Time-Limited Subsidies: Optimal Taxation with Implications for Renewable Energy Subsidies

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January 17, 2023

Abstract

Pigouvian subsidies are efficient, but subsidies with limited durations are not Pigouvian. When using “time-limited” output subsidies, the optimal policy subsidizes output *and* investment, where investment subsidies separately correct for the limit. Because the change in production when the subsidy ends is a sufficient statistic for the optimal duration, we estimate this statistic using the US Renewable Energy Production Tax Credit for wind energy. Wind facilities reduce generation by 5-10% when the ten-year subsidy ends, demonstrating that time limits distort production even in inelastic industries, and suggesting that adapting to limits is key to improving industrial policy elsewhere.

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This research is the product of generous feedback from many helpful people including Catie Hausman, Ash Craig, Joe Aldy, Tatyana Deryugina, Matt Kotchen, Jim Hines, Rich Sweeney, Danny Schaffa, Alecia Cassidy, Yeliz Kacamak, Justin Wolfers, Matt White, Sam Stolper, Sarah Johnston, Ying Fan, Zach Brown, Rich Patterson, Michael Moore, and from seminar and conference participants at the University of Michigan, Brigham Young University, Yale University, the National Tax Association, AERE, the Michigan Tax Invitational, and OSWEET.

1. Introduction

As growing subsidy programs across the world herald a new era in industrial and energy policy, a key question is how to structure subsidies that efficiently correct production externalities. The theoretical answer is simple whether the externalities is innovation, offsetting emissions, or something more nuanced externalities like maintaining supply chain resilience and a strong working class. In each case, the optimal "Pigouvian" correction is to subsidize every unit produced by its marginal external benefit. In practice, however, almost all output subsidies end after a certain amount of time, and therefore do not subsidize all externality-generating units. We call these subsidies "time-limited" output subsidies.

Time-limited subsidies exist across the world and arise naturally from the political and institutional frictions surrounding policy choice. For example, in the United States, the Advanced Manufacturing Production Tax Credit lasts for 7 years and the Renewable Energy Production Tax Credit and Clean Vehicle Credit both create 10 years of subsidies (The White House, 2022; United States Department of the Treasury, 2021). In Germany, feed-in-tariffs for renewable energy last for 20 years and Chinese tax cuts for renewable energy last for 6 (Nyberg et al., 2020; OECD, 2022). Many agricultural policies have even shorter subsidy windows like year-to-year Chinese subsidies for oilseeds or market price supports for dairy in Canada and the United States (Mcdonald, 2022; Congressional Research Service, 2014). Although the same political processes and policy considerations create the policy and the time limit together (such as budget reconciliation in the U.S. or federal mandates in Germany), we know nothing about the implications of having time limits for optimal policy.

Exactly how time limits change policy considerations hinges on how the limits change the incentives for firms and policymakers. Time limits have two major implications. First, because time-limited polices only subsidize output produced during a limited "subsidy period,"[1] firms have incentives to invest less up front and to reduce production after the subsidy period ends. Second, time limits compromise the Pigouvian ideal of subsidizing all externality-generating units, inhibiting policymakers' ability to implement corrective policies. This paper explores how accounting for subsidy duration affects the optimal size of subsidies and the optimal choice of subsidy instruments.

By developing an optimal tax framework for time-limited output subsidies we demonstrate that time limits change which policies a social planner should use. Rather than only subsidizing output, as the canonical Pigouvian policy does, the optimal policy is a combination of output and investment subsidies. This result counters production-efficiency

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[1] We use this generalization of the phrase "credit period" used for tax credits (e.g., United States Department of the Treasury, 2021).

arguments that require subsidizing output only (see Diamond and Mirrlees, 1971). Because directly subsidizing investment can mitigate the inefficiency in investment decisions introduced by time limits, the optimal investment subsidy is strictly positive whenever the subsidy duration is less than the life of the fixed inputs.

Although the optimal output subsidy is larger than the externality when used alone with time limits, combining it with an optimal investment subsidy reduces its size to the external value—for *any* subsidy duration. Large output-only subsidies try to compensate for forgone subsidization after the subsidy period, but investments subsidies make this correction more efficiently, especially when the subsidy period is short. When combined, the optimal output subsidy decreases, but it never falls below the marginal external value. Interestingly, the two subsidies are fully separable: The optimal output subsidy remains exactly calibrated to the marginal externality while the investment subsidy changes with the subsidy duration. An implication is that (all else equal) policymakers should subsidize investment more when output subsidies have shorter durations but output subsidies should be equal to the externality value regardless of the subsidy duration.

After defining the best subsidy size for any given duration, we characterize an intuitive sufficient statistic for the optimal duration in response to political, administrative, or other institutional frictions. We model these frictions as a cost to the policymaker of implementing a longer-running subsidy. As such, a time-limited output subsidy is a second-best policy that is incentive compatible for policymakers—whereas the first-best Pigouvian subsidy may not be.[2] In that case, the efficient duration trades off the marginal external value of increased production under a longer subsidy period against its marginal institutional cost—as in the optimal tax system literature (Dharmapala et al., 2011; Keen and Slemrod, 2017) and politically feasible optimal tax literature (Scheuer and Wolitzky, 2016; Bierbrauer et al., 2021). The sufficient statistic for the optimal subsidy duration is the change in production when the subsidy period ends, which captures the marginal social benefit of a longer output subsidy. This means that all else equal (including the institutional friction), policymakers should set longer-running subsidies in industries where they expect the change in production to be larger.

Although many industries face time-limited subsidies, our empirical application focuses on the US wind industry and the Renewable Energy Production Tax Credit (PTC), one of the largest output subsidies in the world. In addition to the policy relevance of renewable energy subsidies as part of a global energy transition, studying the wind industry is of theoretical interest because of its production technology. In the wind industry turbines are

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[2] For example, a lame duck policymaker might prefer a policy with a short subsidy duration knowing that the official-elect would annul the first-best subsidy upon taking office.

essential, wind is free, and there are only minimal margins to change production when the subsidy period ends (like better maintenance, forecasting, and optimization). This means the change in production should be relatively small in the wind industry. Because having a time-limited subsidy can only be optimal when the change in production is small, the wind industry serves as a limiting case in which we can test the model. If the end of the subsidy period affects firm behavior in the wind industry, policymakers must consider the use of time-limited subsidies even more carefully in industries with more elastic margins of response.

We estimate the change in electricity generation when the PTC's ten-year subsidy period ends using an event study design and show that wind facilities reduce their output by 5-10%. Although this is a significant response, it represents a relatively inelastic one (on the order of 0.15). This response also has large market implications. Each month, PTC ineligibility results in over 500 GWh (Gigawatt hours) of forgone production and externality benefits, and will increase as additional turbines age out of the subsidy period. Furthermore, by plugging the social value of this forgone production into the sufficient statistic, we show that the ten-year duration can only be optimal if the institutional frictions cost policymakers more than $200,000 per firm per year. If this means the PTC subsidy period is too short, then the subsidy periods of time-limited subsidies for many other industries are also likely too short.

Our paper sheds insights on three major strands of economic research. First, we contribute new efficiency results about time limits and investment subsidies to a long literature comparing subsidy instruments, showing that output and investment subsidies are complementary policy tools rather than substitutes. From a general theoretical standpoint, the long-standing production efficiency argument (Diamond and Mirrlees, 1971) advocates only subsidizing output to avoid distorting the lowest-cost input mix. We show this is no longer true when output subsidies have time limits. Empirical case studies have found that investment subsidies do introduce distortions (e.g., Burr, 2016; Aldy et al., forthcoming), but argue that consumer myopia, uncertainty, or other compounding frictions may still justify their use under a criterion of *cost effectiveness* (see Parish and McLaren, 1982; Dunne et al., 2013; De Groote and Verboven, 2019; Yi et al., 2018). Our results reveal an *efficiency* justification for investment subsidies even without these complications whenever the duration of an output subsidy is less than the capital life. Our results show how investment subsidies help firms commit to produce even when output is unsubsidized. Given evidence that price and policy uncertainly are especially likely to produce underinvestment (Kellogg, 2014; Baker et al., 2016; Handley and Li, 2020) and intuition that considerations like market power or managerial myopia in firms may have similar effects, investment subsidies may be even more important for efficiency in general than captured in our analyses.

Our second contribution is extending our understanding of the targeting principle for correcting externalities when not all externality-generating units are targeted. According to the targeting principle, if policymakers can directly subsidize the externality-generating commodity, the optimal policy is separable and equal to the Pigouvian correction plus any other taxes (Kopczuk, 2003).[3] Although this logic is often used to calibrate output subsidies, in the real world, time limits disrupt targeting. We show that that using an investment subsidy restores an optimal policy with a targeting-like calibration—*even when* not all units are targeted. This result builds on renewed interest in imperfect targeting both for externalities (e.g., Jacobsen et al., 2020) and individuals (e.g., Dubois et al., 2020; Miravete et al., 2020) by showing the important role of complementary policy instruments in achieving second-best policy objectives.

Our third contribution is that the empirical results extend the conversation about efficient subsidies for renewable energy by showing how time limits affect production. For over three decades countries across the world have subsidized wind and solar energy production using time-limited output subsidies. Whether the subsidies are tax credits like the US PTC or the feed-in tariffs in China and the EU, these policies have limited subsidy periods. Our paper documents how firms respond to the incentives that these time limits produce. Of the papers studying or comparing subsidies for wind (including Schmalensee, 2012; Johnston, 2019; Abrell et al., 2019; Aldy et al., forthcoming; Helm and Mier, 2021; Petersen et al., 2022), to our knowledge only Hamilton et al. (2020) considers the duration of the PTC, and they focus on degradation leading up to and after the end of the subsidy period. Aldy et al. (forthcoming) and Petersen et al. (2022) document differences in production and intermittency between firms that receive output versus investment subsidies in the United States and Spain. But our contribution is in quantifying how time limits affect production, presenting evidence that firms decrease output by 5-10% when the PTC subsidy period ends.

Note that this contribution also has implications for larger discussions about optimal industrial and energy policy. For example, if subsidies are part of a policymaker's plan for an energy transition, our results show it is critical to account for time limits' effects on production. In our context having a time limit will lead energy markets to forgo enough renewable energy to power every household in the United States for over 18 months. This lost generation needs to be accounted for in choosing an optimal policy. Similarly, industrial policy should expect responses to time limits to be much more important in other industries

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[3] As shown in case studies of commodity taxation (Sandmo, 1975), international tax policy (Dixit, 1985), public good provision (Bovenberg and van der Ploeg, 1994), and joint income and commodity taxation (Cremer et al., 1998), all generalized by Kopczuk (2003).

than in the wind industry. For example, in heavily subsidized industries with more expensive inputs like agriculture and manufacturing, the changes in production after the subsidy period will be even larger. In that case, aptly setting the subsidy periods and accompanying investment subsidies will have even larger welfare implications.

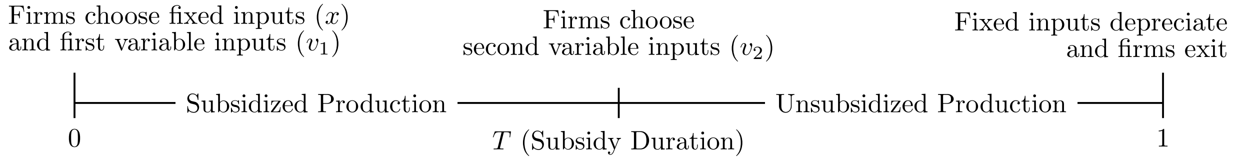
The remainder of the paper is organized as follows: Section 2 presents the two key tensions between subsidy theory and policy that motivate our research; Section 3 estab‘lishes our theoretical framework for time-limited subsidies and our efficiency results; Section 4 presents our event-study design and results in the wind industry; and Section 5 concludes and interprets the broader policy implications of our results.

2. Two Tensions between Subsidy Theory and Policy

This section explores two fundamental results supporting standard Pigouvian subsidies—production efficiency and the targeting principle—and the tensions between these results and standard subsidy practices. Throughout we will use subsidy-oriented language, but corresponding arguments hold for taxes as well.

Figure 1 illustrates how subsidy duration interacts with firms' choices. Because firms know the policy context, they will choose fixed inputs taking the subsidy duration as given. Those fixed inputs will produce both subsidized and unsubsidized units if the capital life is longer than the subsidy duration. Firms will respond to these incentives when choosing variable inputs leading to differences in production between the subsidy period and after.

Figure 1: Example of Time-Limited Subsidy Structure



Note: This figure displays the economic problem presented when output subsidies have time limits. Firms make investment and input decisions with the recognition that only units produced during the subsidy period (before T), will receive the output subsidy.

Considering a social planner who wants to correct a constant production or consumption externality, it is well known that the best solution is to apply a "Pigouvian" subsidy, i.e., one that subsidizes each unit of the externality-generating good by the marginal external value (Pigou, 1920).[4] The policy implication is that subsidies should focus on outputs rather

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[4] Note that because the focus is a constant production externality, these results need not extend to time

than inputs and should be remitted for all units produced rather than only some (e.g., those produced before a time limit). In practice neither of these ideals are observed.

2.1 Common Tax and Subsidy Instruments Violate Production Efficiency

The argument for production efficiency says that subsidizing anything besides output is inefficient. This is because subsidizing inputs will distort the optimal input mix away from the lowest cost combination (Diamond and Mirrlees, 1971; Parish and McLaren, 1982). Recently this intuition has been extended in more generality (see Ganapati et al., 2020) and verified empirically. For example, investment grants for wind turbines lead developers to put too much capacity on too little land and on less windy sites (Aldy et al., forthcoming), and investment tax credits for rooftop solar lead to allocations with relatively less solar irradiance than an output subsidy would have (Burr, 2016; Sexton et al., 2021). Furthermore, the existence of these investment subsidies demonstrates that output subsidies are not used exclusively in the way production efficiency would suggest.

In practice, corrective subsidy instruments vary immensely both across and even within industries. For example, output taxes and subsidies include sin and excise taxes; market price support for agriculture, manufacturing, and energy; and tax credits such at the PTC and electric vehicle tax credit. Although some policies subsidize inputs like R&D subsidies or direct subsidies on labor or (especially in Chinese industrial policy) fuel, many more policies focus on investment such as property and sales taxes or abatements; accelerated and bonus depreciation; loan guarantees and sub-market rates; and direct investment grants or tax credits like the affordable housing, chip manufacturing, and investment tax credits in the US. Counterintuitively (at least from a Pigouvian perspective), multiple subsidies often exist even within the same industry. For example, in the United States wind developers receive the PTC for output and can also claim bonus depreciation on investments and may receive additional local subsidies like selling renewable energy credits or receiving property tax abatements. From 2009-2012 wind facilities could also choose whether to receive the PTC or a direct grant for 30% of the investment costs.[5]

Although there are numerous empirical evaluations of investment subsidies, there are no efficiency justifications for using them in corrective policy or for combining them with output subsidies. For example, in the US context, typical acceleration programs provide an effective subsidy of 7-12% of investment costs.[6] Research finds that accelerated and bonus depreciation have had large effects in countries around the world (Zwick and Mahon, 2017;

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varying externalities like learning spillovers in emerging markets—another plausible rationale for a subsidy. We discuss the implications of our results for more complicated settings like this in the Conclusion.

[5] Over 60% of firms preferred the grant see (Johnston, 2019; Aldy et al., forthcoming).

[6] Compared to a regime with depreciation claimed over 25 years the effective subsidy of accelerating over

Ohrn, 2018; Liu and Mao, 2019; Maffini et al., 2019) but does not consider the corrective justification for the subsidy in the first place. Other research is actively examining the cost effectiveness of different subsidy designs (e.g., Dunne et al., 2013; De Groote and Verboven, 2019; Yi et al., 2018), but on a case-by-case basis and through the lens of cost effectiveness, not efficiency. In part, this focus on cost effectiveness exists because the inefficiency of non-Pigouvian subsidy instruments is assumed—but as we show, that assumption will not hold in light of the empirical reality of time limits in subsidy policy.

2.2 Limiting Subsidy Duration Breaks the Targeting Principle

Another argument in favor of Pigouvian output subsidies is the targeting principle. Targeting results demonstrate that if the social planner can remit the subsidy for all externality-generating units, the optimal externality correction is separable from any other tax considerations, very broadly defined (Kopczuk, 2003). In this case, the optimal calibration for the additional output subsidy is equal to the marginal external value (as in Pigou, 1920; Diamond and Mirrlees, 1971). Exceptions to perfect targeting have usually focused on subsidies that do not directly target the externality-generating unit, for example taxing fuel-efficiency rather than total emissions (Langer et al., 2017; Jacobsen et al., 2020), beverage volume rather than sugar or alcohol content (e.g., Grummon et al., 2019; Dubois et al., 2020; Miravete et al., 2020; O'Connell and Smith, 2021), or using attribute based regulation (Ito and Sallee, 2018; Kellogg, 2020). Targeting will also be compromised, however, if not all externality-generating *units* can be subsidized—a point that has received considerably less attention.

In the presence of time limits, naively calibrating an output subsidy to the marginal external value will have two problems. Both problems result from imperfect targeting after the subsidy period. We call the first problem with a naive Pigouvian calibration *moral hazard*. That is, conditional on production capacity, production will be inefficiently low after the subsidy period. We call the second problem a naive Pigouvian calibration *underinvestment*. Because the fixed inputs will be used to produce subsidized and unsubsidized units, firms will invest in fewer fixed inputs than is socially optimal. Interestingly, these changes to incentives generate production inefficiency even though output is subsidized. As such, time-limited subsidies fundamentally change our optimal tax intuition about both targeting and production efficiency rationales for a Pigouvian policy.

Even though time limits have received relatively little attention from an optimal subsidy

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N years (given corporate tax rate, t and interest rate r) is $t\sum_{n=1}^{N}\frac{1}{N}\left(\frac{1}{1+r}\right)^{n-1} - t\sum_{n=1}^{25}\frac{1}{25}\left(\frac{1}{1+r}\right)^{n-1}$. These numbers come from assuming an interest rate of 0.04 and comparing bonus depreciation, $N = 1$, under a 0.35 marginal tax rate (most generous) and accelerated depreciation to $N = 5$ under a 0.21 rate (least generous).

or industrial policy perspective, in practice time limited output subsidies are ubiquitous. Ignored by standard theory, time-limited subsidies may exist for a variety of reasons. For example, flowing political tides may introduce incomplete policy contracting (e.g., policy-makers might prefer implementing a policy with a shorter duration rather than the first-best subsidy that risks revocation). Similarly, there may be statutory difficulties of making long-term spending commitments, and many countries have policy features that encourage time limits. For example, in the United States, only outlays meeting time-specific objectives can pass via reconciliation (see discussion in Wessel, 2021) and federal mandates in Germany require time limits on subsidies (German Federal Ministry of Finance, 2022).

3. Optimal Time-Limited Subsidies

Motivated by the prevalence of time-limited output subsidies, their implications for firm decision-making, and how they undermine our Pigouvian intuition, this section builds time-limited subsidies into an optimal tax framework. After presenting the firm decision and building intuition for the types of policies that fit within this framework, this section explores three sets of efficiency results. First, it characterizes the optimal subsidy size using only one instrument (either output or investment) given a predetermined subsidy duration. Second, it combines both subsidies, demonstrating that the seemingly counterintuitive combination can combat the problems presented by time limits. Finally, it explores the optimal subsidy duration given the institutional frictions that generate them in practice.

3.1 Model Setup and Intuition

3.1.1 Firm Problem

In our model, firms make decisions about investment in fixed inputs and use of variable inputs, given a set of subsidy policies, θ; market prices; and a production technology, $q()$. We write the following firm profit maximization problem:

$$\max_{x,v_1,v_2} \pi(x,v_1,v_2;\theta) = T[q(x,v_1)+\tau^o q(x,v_1)-mv_1]+(1-T)[q(x,v_2)-mv_2]-x(c-\tau^i) \quad (1)$$

The policy vector $\theta = (\tau^i, \tau^o, T)$ includes the size of an investment subsidy for the fixed input, τ^i; the size of the output subsidy, τ^o; and the duration of the output subsidy T (as a fraction of the capital life). As illustrated in Figure 1, T partitions the life of the fixed input into two portions where output is either subsidized or unsubsidized. In response to these policies, firms choose fixed inputs x and different levels of variable inputs v_1 and v_2, corresponding to production during and after the subsidy period. Fixed and variable inputs are purchased at c and m. Output is produced with a production technology $q(x, v)$ and is sold at a price normalized to one. Because of the subsidies, firm revenue in the subsidized period is $(1 + \tau^o)$ per unit, and investment only costs $(c - \tau^i)$.

We feel that the strongest assumptions imposed by this model relate to dynamics. Because there is no uncertainly, firms can solve this dynamic problem by backward induction and effectively make all decisions at the outset. We consider the case of certainty because we are unaware of efficiency justifications for deviating from Pigouvian corrective policy given perfect certainty (whereas there are such arguments in response to uncertainty—usually based on cost effectiveness, e.g., Yi et al., 2018)). Assuming all depreciation of the fixed input occurs at the end of the capital life gives the model interpretable optimal-policy solutions. The absence of discounting is not a restriction. In Appendix A we show that this intuitive setup is isomorphic to a continuous-time model where firms choose a function $v(t)$ to maximize their net present value with exponential discounting.

The definition of the profit function in Equation 1 imposes a few other restrictions on the economic setting. First, it assumes competitive input and output markets. Second, the cost of entry scales with investment such that there are no additional fixed costs or returns to scale not captured in $q()$. Third, this model can be used to consider changing subsidies, advancing technology, and other dynamics, but only if potential entrants are "short lived" in the sense that they cannot strategically wait to enter later (as in IO methods like Doraszelski and Satterthwaite, 2010). This assumption would be much more restrictive in a setting where the externality of interest is not a constant production externality (such as learning spillovers in emerging industries or solving a coordination problem in new technology adoption). Finally, the use of a representative firm requires there be no significant heterogeneity in prices, costs, or production technologies in the market.

3.1.2 Connecting Theory and Policy

Note how this subsidy framework nests a very general set of output and investment subsidies of interest. The key innovation is to use the subsidy duration, T, to make continuous rather than discrete comparisons between output subsidies, investment subsidies, or their combinations. For example, a Pigouvian policy is an output subsidy calibrated to the externality that subsidizes all units produced by a firm. It requires no investment subsidy. If the externality is γ, this would be written as $\theta^{Pigou} = (0, \gamma, 1)$ because it remits $\tau^o = \gamma$ for the entire capital life of the fixed inputs, $T = 1$. It is well known that this is policy generates the first-best allocation (e.g., Pigou, 1920; Diamond and Mirrlees, 1971; Diamond, 1973). On the other extreme, common policies that only subsidize investment could be written as $\theta^i = (\tau^i, 0, 0)$. The duration of the output subsidy is zero, $T = 0$. Common time-limited output subsidies could only subsidize output $\theta^o = (0, \tau^o, T)$, or could subsidize both output and investment $\theta = (\tau^i, \tau^o, T)$.

With the model defined, we can also see the inefficiencies that certain policies could generate more clearly. For example, the intuition about production efficiency can be seen in how the investment subsidy reduces the marginal cost of fixed inputs. This will distort the efficient input mix. Similarly, time limits generate underinvestment because the subsidy only increases the marginal return of fixed inputs for some of the capital life. In addition to the underinvestment, the presence of the time-limited output subsidy will distort production to be relatively larger during the subsidized period and firms will reduce production thereafter—this is the moral hazard channel discussed above.

3.1.3 Policymaker Problem

The policymaker tries to design a subsidy system to maximize welfare given firm responses to policy, (x^f, v_1^f, v_2^f), the size of the externality, and the costs imposed by current institutional features. We write the following maximization problem:

$$\max_{\tau^i,\tau^o,T} \mathcal{W}(\tau^i, \tau^o, T) - \phi(T) \equiv \max_{\tau^i,\tau^o,T} \Pi(\theta) + \gamma Q(\theta) - \lambda\big[x^f \tau^i + T\tau^o q(x^f, v_1^f)\big] - \phi(T) \qquad (2)$$

The $\mathcal{W}$ function is the social welfare, and consists of three terms. The first represents firm profits, $\Pi(\theta) = \pi(x^f, v_1^f, v_2^f; \theta)$. Second, is the external benefit of total production, where $Q(\theta) = Tq(x^f, v_1^f) + (1 - T)q(x^f, v_2^f)$. The third term is the product of the marginal cost of public funds λ and the total tax expenditures on the investment and output subsidies. Policymakers maximize welfare subject to a cost associated with subsidy duration, $\phi(T)$. This term captures the institutional frictions that make the first-best allocation politically difficult to attain and reflect the direct cost to the policymaker from a subsidy period with duration T. For example, it could reflect political constraints, incomplete contracting, or statutory limitations that make *ad infinitum* subsidies complicated to implement in practice. Having the $\phi(T)$ term can be thought of as the social costs of satisfying an incentive compatibility for the policymaker.

There are two main economic restrictions implied by this welfare function. First, it implies that all units produced, whether in the subsidized or unsubsidized periods, have the same external social value. As discussed earlier, constant externalities rule out some interesting cases. We focus on the constant externality case since it most closely reflects the tension between the Pigouvian ideal for production and consumption externalities and the policies observed in practice. Second, this welfare function suggests that the quantity of the externality good produced does not affect output prices as would be the case when the externality-generating firms are a small fringe relative to other firms using externality-free technology, or when domestic externality-generating firms are facing a fixed world price. Note that λ can be interpreted very generally as capturing the social value of \$1 of government revenue (and possible subsidization or redistribution) relative to \$1 of profits (or firm-owner consumption).

3.2 Optimal Subsidy Policies

This section solves four optimal policy problems. To build intuition for the moving pieces involved, they are presented in order of increasing complexity. First, this we describe the optimal investment subsidy, providing a new (to our knowledge) characterization of the tradeoff between externality generation and production efficiency. Second, we describe the optimal policy response to a given subsidy duration using only an output subsidy. As the subsidy duration changes from $T = 1$ to $T = 0$, the value of the output subsidy increases to infinity. This policy may perform very poorly because when the output subsidy has a short duration it cannot correct the underinvestment and moral hazard problems.

After considering the policies separately, we describe the optimal policy given a time-limited output subsidy using both subsidy instruments. We show that even though each subsidy cannot respond well to a given time limit, combining them compensates for the problems time limits create. This third proposition produces a striking separability result: when used together with an investment subsidy, the output subsidy remains constant at the marginal externality of production. As the duration of the output subsidy changes from $T = 1$ to $T = 0$, the value of the investment subsidy increases to compensate for the reduction in the total value of the output subsidy, but the per-unit value of the output subsidy does not change.

Finally, we explore the (second-best) optimal subsidy duration given the social costs associated with the institutional frictions that generate them in practice. We show that the efficient subsidy duration must trade off the marginal external value of increased production against the marginal institutional costs of the longer duration. This comparison provides a sufficient statistic for subsidy duration, which is how much production changes when the subsidized period ends.

We solve the optimal tax problem given one main assumption. Assumption 1, stated formally in Appendix B, assumes that $\lambda = 1$ and standard regularity conditions hold.[7] We make this assumption to focus our attention on correcting the production externality rather

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[7] These conditions guarantee that $q(x, v)$ generates a unique solution given prices and subsidies and ensures that the conditions of the Implicit Function Theorem are met. The solution to the firm's problem under these conditions is also in Appendix B.

than correcting the fiscal externality as well (a common argument in optimal corrective taxation, e.g., Griffith et al., 2019). This assumption would be met if the tax and redistribution system is optimally calibrated (Jacobs, 2018), or if revenue for the subsidies is raised using non-distortionary lump-sum taxes.[8]

3.2.1 Optimal Investment-Only Subsidy

A social planner trying to maximize welfare with only an investment subsidy will face a tradeoff between increasing the quantity of externality-generating units and raising costs by distorting production efficiency.

Proposition 1. Optimal Investment-Only Subsidy. Under Assumption 1, if $\tau^o = 0$, then for any T

$$\tau^{i*} = \frac{\gamma \frac{\mathrm{d}q(x^f, v_2^f)}{\mathrm{d}\tau^i}}{\frac{\partial x^f}{\partial \tau^i}}$$

Proof in Appendix B.

In addition to being the first (to our knowledge) theoretical result about optimal investment subsidies, Proposition 1 captures the intuitive tradeoff faced by the social planner. Because $\tau^o = 0$, production is the same during and after the subsidy period and all production is captured in the $q(x^f, v_2^f)$ term. As such, $\gamma \frac{\mathrm{d}q(x^f, v_2^f)}{\mathrm{d}\tau^i}$ captures the marginal external benefit of increasing τ^i. The optimal investment subsidy will be larger in settings when the externality or the production response are large. On the other hand, the $\frac{\partial x^f}{\partial \tau^i}$ term reflects the marginal production distortion induced by changing τ^i. The more responsive investment is to the subsidy, all else equal, the smaller the optimal subsidy.[9]

3.2.2 Optimal Output-Only Subsidy with a Given Duration

On the other extreme, given some fixed subsidy duration, responding to the externality with only an output subsidy trades off production in the subsidized and unsubsidized periods. Because the output subsidy only targets some units, it may lead to over-reliance on variable inputs in the subsidized period,[10] but increasing the subsidy to increase investment may widen the gap between production before and after the end of subsidy eligibility.

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[8] In the case that $\gamma < 0$ and the optimal policies are a tax, this also means that the government will not try to reduce the fiscal externality by raising additional taxes on the externality generating industry.

[9] Multiplying both sides by $\frac{\partial x^f}{\partial \tau^i}$ reveals that the marginal external benefits will be set equal to the marginal distortion in investment costs.

[10] Not inefficiently high from a static production efficiency sense, but in a social sense

Proposition 2. Optimal Output-Only Subsidy. Under Assumption 1, if $\tau^i = 0$ and T is fixed, then

$$\tau^{o*} = \gamma \left(1 + \frac{1-T}{T} \frac{\frac{\mathrm{d}q_{(}x^f, v_2^f)}{\mathrm{d}\tau^o}}{\frac{\mathrm{d}q_{(}x^f, v_1^f)}{\mathrm{d}\tau^o}} \right)$$

Proof in Appendix B.

This characterization of output subsidy size as a function of subsidy duration captures the tradeoff induced by the time limits. If $T = 1$ and all units can be subsidized, the ideal subsidy simplifies to $\tau^o = \gamma$, the Pigouvian first best. This intuitive Pigouvian policy breaks down, however, when the subsidy period is shorter; in fact, as T approaches 0, the optimal subsidy diverges to infinity. The speed at which τ^{o*} diverges depends on the ratio $\frac{\frac{\mathrm{d}q_{(}x^f, v_2^f)}{\mathrm{d}\tau^o}}{\frac{\mathrm{d}q_{(}x^f, v_1^f)}{\mathrm{d}\tau^o}}$. This ratio, which is weakly less than 1, reflects how much less a change in τ^o will affect production after the subsidy period relative to during the subsidy period. This ratio is close to zero when $\frac{\partial x}{\partial \tau^o}$ is small and when fixed and variable inputs are relatively more substitutable. In this case, τ^{o*} diverges slowly, remaining close to γ. On the other hand, the ratio is close to 1 when $\frac{\partial x}{\partial \tau^o}$ is large or when fixed and variable inputs are better complements, so τ^{o*} diverges more quickly.

In Section 3.3 we compare the welfare under these two policies and show that in many cases the welfare under an investment-only subsidy is higher than the welfare under the optimal output-only subsidy for a broad range of possible durations.

3.2.3 Optimal Combined Subsidy with a Given Duration

This subsection explores the joint choice of investment and output subsidies in response to a given output subsidy duration. The previous two propositions demonstrated the shortcomings of subsidizing just investment or just output when there are time limits. Whereas the investment subsidy can target x, it cannot affect q_1 or q_2 (resulting in the breakdown of production efficiency). On the other hand, the time-limited output subsidy can target q_1, but it cannot directly affect x or q_2 (resulting in underinvestment and moral hazard). But are there benefits to combining the two policy instruments?

Whether there are gains from having multiple instruments is not *ex ante* obvious. For example, in the traditional setting, the availability of an investment subsidy yields nothing beyond the efficient output subsidy (Diamond and Mirrlees, 1971). However, we show that this is no longer the case when output subsidies are time limited:

Proposition 3. Optimal Combined Subsidy. Under Assumption 1, if T is fixed, then in general the optimal subsidies are

$$\begin{aligned}\tau^{i*} =&(1-T)\frac{\gamma\frac{\mathrm{d}q(x^f,v_2^f)}{\mathrm{d}\tau^i}}{\frac{\partial x^f}{\partial \tau^i}}\\ \tau^{o*} =&\gamma\end{aligned}$$

Proof in Appendix B.

This result (which we found somewhat breathtaking) has two major implications. First, it shows that only the investment subsidy should be used to correct the problems created by the time limits. Note that τ^{i*} is strictly decreasing in T whenever the marginal product of capital is positive. When $T = 0$, and all output is unsubsidized, τ^{i*} takes the same form as in Proposition 1. When $T = 1$, the $\tau^{i*} = 0$—reflecting the Pigouvian intuition of Diamond and Mirrlees (1971) that under perfect targeting there is no need for an investment subsidy.[11] As explored in Proposition 2, a shorter subsidy period creates an underinvestment problem. We now show that that inefficiency that can be directly countered with an investment subsidy. Although still somewhat costly in terms of production efficiency, the investment subsidy addresses underinvestment much more effectively than increasing the value of the output subsidy in the subsidy period (as in Proposition 2)—and without amplifying moral hazard problems.

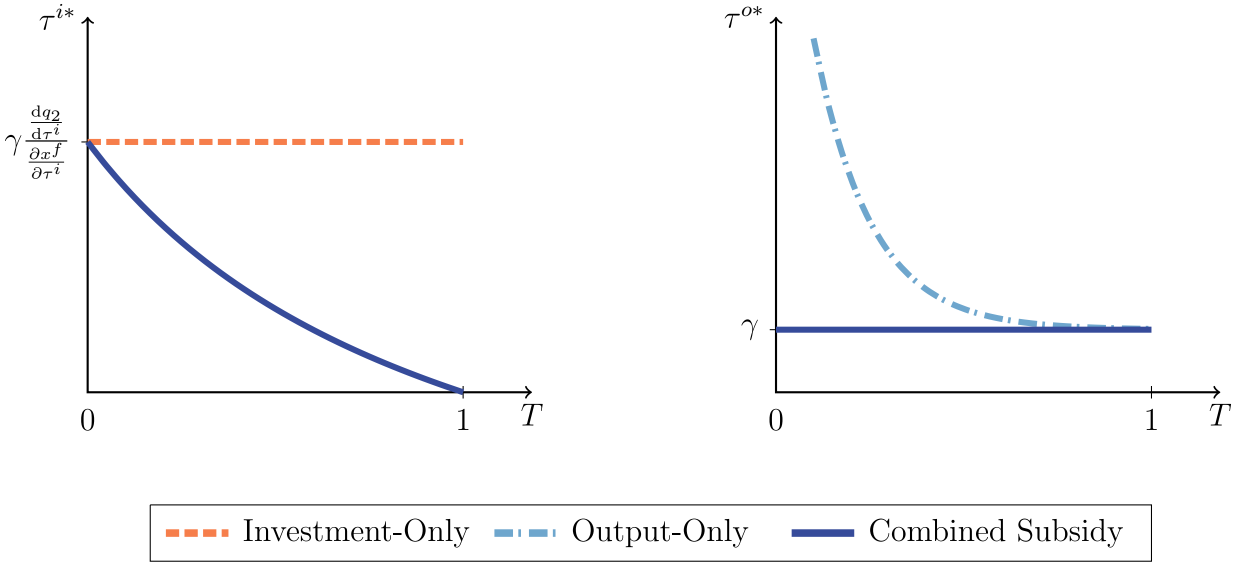
Second, this combination of subsidy instruments also restores a targeting-like calibration even though not all production can be targeted. The optimal output subsidy is $\tau^{o*} = \gamma$ for all values of T—whether all or almost none of the production is subsidized. Whereas the τ^{o*} in Proposition 2, increased above the marginal externality when the output subsidy was time-limited, now it remains constant. The optimal response to changes in subsidy duration is fully separable from τ^{o*} and is captured in τ^{i*} instead. This "separability" is reminiscent of many other results in the targeting literature (e.g., Sandmo, 1975; Dixit, 1985; Bovenberg and van der Ploeg, 1994; Cremer et al., 1998; Kopczuk, 2003), but here we show that (with the appropriate instruments) a targeting-like result holds *even without perfect targeting.*

For intuition, Figure 2 depicts a comparison of the three policies presented in Propositions 1-3. It depicts the size of the investment subsidy and the output subsidy as functions of T for cases where the social planner is restricted to only one of the instruments or has both available. Although the degree of curvature will depend on the production technology $q(\cdot)$, intercepts and limits reflect the optimal policies in general.

---

[11] Technically this is an extension since Diamond and Mirrlees (1971) assumes constant returns to scale and Parish and McLaren (1982) show that decreasing returns to scale is the best case to justify input subsidies.

Figure 2: Comparing Optimal Time-Limited Subsidies



Note: This figure shows the optimal calibrations of τ^i and τ^o as functions of T the subsidy duration. Three policies are represented; the optimal investment-only subsidy, the optimal output-only subsidy, and the optimal combined subsidy.

3.2.4 Optimal Subsidy Duration Choice

We now turn our consideration to the optimal choice of subsidy duration. Because the investment subsidy can only directly affect x and the output subsidy only q_1, the choice of subsidy duration affects how well the other instruments target the externality. Intuitively, the ideal would be to choose $T = 1$ and target perfectly, but revealed preference suggests real constraints to implementing this policy. We model these constraints as the political costs, $\phi(T)$.

A policymaker choosing the subsidy duration for a given policy must weigh the welfare from better externality targeting against the political costs of a longer duration. We use a second-best interpretation of the results that follow, where because of the institutional frictions, the first-best policy is not incentive compatible to the policymakers (although in a sense the choice of subsidy duration is a technically one of “first-best” optimality like other questions with optimal tax systems e.g., Keen and Slemrod, 2017). In either case the economics of the optimization problem reflect the decision of policymakers who inherit a set of bureaucratic or institutional frictions and who are attempting to implement the best corrective policy they can given those constraints.

Proposition 4. Optimal Subsidy Duration. Under Assumption 1, and a first order Taylor approximation where $\Delta v = v_2 - v_1$ is small and q_v is locally linear, and if $\phi(T)$ is positive, convex, and twice differentiable, then the optimal subsidy duration is unique and satisfies the following at interior solutions:

$$\phi'(T^*) = -\gamma\big[q(x^f, v_2^f) - q(x^f, v_1^f)\big] \equiv -\gamma\Delta q(\theta^*)$$

with corner solutions are characterized by

$$\begin{aligned} T^* &= 1 \quad \text{if } \phi'(1) \leq -\gamma\Delta q(\theta^*|_{T=1}) \\ T^* &= 0 \quad \text{if } \phi'(0) \geq \gamma\Delta q(\theta^*|_{T=0}) \end{aligned}$$

Proof in Appendix B.

This characterization of the optimal T captures the intuitive tradeoff between the costs and benefits of a longer subsidy duration. A longer subsidy period will increase the amount of the externality good produced. At the same time, it will also cost the policymaker more to implement. We assume that $\phi(T)$ is convex because as the costs to policymakers of incomplete contracting and political economy become increasingly more pronounced the longer the proposed subsidy duration.

This solution also reveals a sufficient statistic for the optimal subsidy duration. For a policymaker who values production at γ but pays $\phi(T)$ to implement the subsidy, the change in production when the subsidy period ends (Δq) is a sufficient statistic for T^*. In corner solutions the externality benefits are greater than all costs ($T = 1$) or less than any costs ($T^* = 0$). This implies a Ramsey-like argument for optimal subsidy durations: policymakers should choose a longer subsidy duration in industries with more elastic changes in production (because externality generation decreases more when the subsidy period ends) and a shorter subsidy duration in markets with less elastic production.

3.3 Welfare Implications of the Second-Best

These theoretical results are powerful in their generality, but there remains a substantive question about how economically meaningful deviations from optimal policy may be. In that spirit, this subsection presents a simple calibration to illustrate some of the welfare implications of various policies—hopefully providing some theoretically-grounded benchmarks for interpreting the empirical results that will follow.

All calibrated results all come from a Cobb-Douglas-inspired production function that assumes the following technology with decreasing returns to scale.[12]

$$
\begin{aligned}
&Q = Tx^a v_1^b + (1-T)x^a v_2^b \\
&1 > a + b
\end{aligned}
$$

Note that this function is *not* Cobb-Douglas, nor even is it CES because v_1 and v_2 are not substitutable with constant elasticities. Appendix C reports the analytical expressions of the optimal policy parameters.

We use this model to suggestively quantify the size of welfare losses resulting from sub-optimal policies. In addition to exploring the welfare losses imposed by time limits, we also examine a larger set of improperly calibrated subsidies under three classes of policies:

$$
\mathcal{W}(\tau^i, \tau^o, T) = \begin{cases} \mathcal{W}(\tilde{\tau}^i(T), \gamma, T) & \text{Combined Subsidy (Second Best Given } T\text{)} \\ \mathcal{W}(0, \tilde{\tau}^o(T), T) & \text{Output-Only Subsidy} \\ \mathcal{W}(0, \gamma, T) & \text{Naive Pigouvian Subsidy} \end{cases}
$$

Each function corresponds with the total welfare under a certain type of policy. The first policy is the (second-best) combined subsidy policy for a given T. It allows τ^i to vary based on the output subsidy duration and holds $\tau^o = \gamma$ as suggested by Proposition 3. The second policy is constrained to only use a time-limited output subsidy, allowing τ^o to vary with T to compensate for underinvestment as suggested by Proposition 2. Finally, the third policy is a naive Pigouvian time-limited output subsidy, $\tau^o = \gamma$, but no investment subsidy.

Figure 3 reports the result welfare for each possible policy for a given subsidy duration T. For all results, welfare is scaled so that $\mathcal{W} = 1$ represents the first-best allocation and that $\mathcal{W} = 0$ represents the competitive equilibrium that would arise without subsidization. Panel (a) shows the case where the production is relatively intensive in fixed inputs ($a = 0.7$ and $b = 0.2$) and Panel (b) the case where the production is relatively intensive in variable inputs ($a = 0.2$ and $b = 0.7$). Both are calibrated assuming $c = 0.5$, $m = 0.2$, $\gamma = 0.5$, and $\phi(T) = 0$ everywhere. Appendix Figure D.1 shows similar results assuming a lower degree of homogeneity.

Two striking patterns emerge from these results. First, there is a strict ordering and large differences between the policies on the interior $T \in (0, 1)$. The combined subsidy is better than the output-only subsidy which is better than the naive subsidy. The differences in welfare have clear economic interpretations as well. The wedge between the optimal combined

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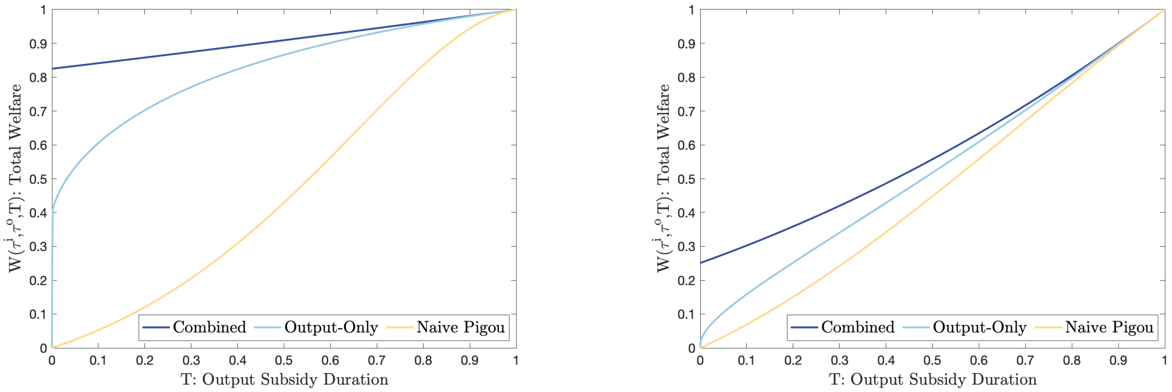
[12] As in Assumption 1 assuming decreasing returns is necessary for an internal solution. Note that this assumption isomorphic to a constant-returns-to-scale technology with convex costs. We model it this way because wind facilities do show (slight) decreasing returns in our data and in other research (Tsolas, 2020).

Figure 3: Welfare Losses from Sub-Optimal Policies



(a) Fixed-Input Intensive Production

(b) Variable-Input Intensive Production

Note: This figure shows what percent of total welfare is lost from suboptimal policy. The allocation under first-best, Pigouvian policy is normalized to one and the competitive (unsubsidized) allocation is normalized to zero. Three policies are plotted: (1) a (second-best) combined subsidy that chooses τ^i and τ^o given T, (2) an output-only subsidy that chooses τ^o optimally given T and $\tau^i = 0$, and (3) a naive Pigouvian policy that chooses $\tau^o = \gamma$ and $\tau^i = 0$ for every value of T. Results from a Cobb-Douglas-like calibration $Tx^a v_1^b + (1-T)x^a v_2^b$. Calibrated values: $(a, b) \in \{(0.7, 0.2), (0.7, 0.2)\}$, $c = 0.5$, $m = 0.2$, and $\gamma = 0.5$.

subsidy and the output-only subsidy measures the value of having an investment subsidy to correct for underinvestment.[13] The second wedge between the output-only subsidy and the naive Pigouvian policy measures the value of adapting to the subsidy duration. Note that even though this ordering is strict for a given duration (e.g., comparing all three subsidies at $T0.4$), there are subsidy durations where the second-best policy is worse than the output-only and naive allocations (e.g., the second best at $T = 0$ and the others at $T = 0.9$). Additionally, the magnitude of the differences may change. For example, when production is more intensive in the variable input the output-only subsidy captures a much smaller percentage of the gains from the combined subsidy. This is because it cannot affect much investment because of the nature of production.

A second pattern can be seen from examining the intercepts at either extreme. All three policies are equivalent when $T = 1$ and produce the same allocation and the same welfare. But they are very different at $T = 0$. The welfare under the combined subsidy at $T = 0$ reflects the best that the social planner could do with only an investment subsidy. Note how the height of this intercept depends crucially on fixed-input share. This captures the intuition that if output is capital intensive, the social planner can always do relatively well as long as an investment subsidy is utilized, but that the investment subsidy contributes much

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[13] In general the combination will be strictly better the output-only subsidy (evaluated at the same subsidy duration $T < 1$) as long as $a > 0$.

less when capital is less important. The steep slope of the second-best combined subsidy in Panel (b) shows how much a marginal increase in T could improve welfare when b is larger (this is the argument behind Proposition 4 because in Cobb Douglass b determines Δq). The other intercept reflects the unsubsidized equilibrium where both the optimal output only subsidy and the naive Pigouvian subsidy converge as $T \to 0$ (since the they do not generate additional investment that will be used after subsidy period).

These results imply that the qualitative sizes of differences in welfare may be large. For example, in both calibrations, the welfare attained is immensely reduced by a naive policy incorrectly applying Pigouvian logic. This gap is particularly pronounced when production is intensive in the fixed inputs when a naive policy could be leaving 50-70% of welfare gains on the table. Similarly, when the subsidy duration is shorter, the welfare gained using a combined subsidy is often much greater than the welfare under an output-only subsidy. For a subsidy duration in the range of 20% of the capital life, the gains from having an appropriately calibrated investment subsidy are 30-50% the gains from the best output-only subsidy. Given how (relatively) small investment subsidies like accelerated depreciation are in practice, this could have large implications for policy.

Interestingly, this calibration also sheds light on which policy levers are most important for improving welfare—an answer which depends on the nature of production. When fixed inputs are key determinants of production, it is the availability of the investment subsidy that strongly affects welfare. Even under a subsidy duration of 10% of the capital life, more than 80% of the policy gains are still available. On the other hand, when variable inputs matter more, having an investment subsidy generates smaller welfare gains than extending the subsidy duration would.

Stepping back, we consider three main messages from these calibrations and related propositions. First, given a fixed subsidy duration, combining investment subsidies and output subsidies compensates for the frictions the time limit imposes—despite the real welfare losses that result from using either on its own—and the welfare implications of not having both policies can be very large. Second, when policymakers face institutional frictions, having a time limit is the efficient second-best response (as long as the two subsidy instruments can be combined). Third, because the production technology matters, the optimal subsidy duration, and thus the overall optimal policy structure is characterized by the change in production when the subsidy period ends—an object that can be recovered from engineering, calibration, or quasi-experimental estimates.

4. Wind Energy and the PTC Subsidy Period

Given the theoretical results in Section 3, whether time-limited subsidies are justified hinges on an empirical question: How big are changes in production? For a social planner facing some cost function, $\phi(T)$, having a time limit only makes sense if the change in production is relatively small or if the costs are large. This section explores this question in the context of the US wind energy industry. We first describe the relevant features of the industry, then estimate the change in production when the subsidy period ends and explore the implications for our theory and for markets.

4.1 Background, Motivation, and Data on the US Wind Industry

Wind developers make investment and production decisions, deciding how many turbines to build and how much to produce by operating them. In the United States investment costs average \$0.8-1.5 million per megawatt (MW) of capacity and are paid at the outset of the project (Wiser and Bolinger, 2021). These costs include turbine purchase and installation, interconnection costs, and balance of plant. In the years in our sample, the average ratio of production to capacity, called the capacity factor, was between 30-36% (Wiser and Bolinger, 2021). Production depends on wind speed—which is free—as well as on maintenance, repair, forecasting, optimization, and paying land rent and worker wages. These (fixed and variable) operation and management costs average \$7-10 per MWh and are small relative to revenues (Wiser and Bolinger, 2021);[14] wind farms sell electricity they produce for around \$40 per MWh on average and receive an additional \$25-40 per MWh in subsides.

This capital-intensive production technology makes wind a theoretically interesting application for our model. Recall that time-limited subsidies are most likely to be justified when the change in production is small. Because wind energy generation is fixed-input intensive, and because wind is free, the change in production should be relatively small. In this sense, we think of the wind energy generation technology as a limiting case in which we can test the model. If wind facilities respond to the end of subsidization, the social burden of time-limited subsidies may be much more costly in industries with more elastic margins of production response.

As discussed in Section 2, the wind industry is also a central part of the worldwide energy transition that has been widely subsidized. In the US (as in many other countries across the world) the industry receives many subsidies for both output and investment. The largest subsidy is the Renewable Energy Production Tax Credit (PTC), which since 1992

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[14] Wiser and Bolinger (2021) report that in 2020 average costs are \$25 per kW-year. Assuming a capacity factor between 0.3 and 0.4 implies average costs of \$7-\$9.5 per MWh.

has awarded non-refundable tax credits for every MWh of electricity a turbine produces in a limited subsidy period of its first 10 years of operation.[15] The amount of the credit is indexed to inflation and was $25 per MHh in 2020. Over these 30 years, investment has usually been subsidized by accelerated or bonus depreciation, worth roughly 10% of investment costs, but between 2009 and 2012 new turbines could claim an investment grant (called a Section 1603 grant) worth an additional 30% of the investment costs in cash instead of the stream of credits provided by the PTC.[16] Sub-national policies also subsidize both output and investment, such as Renewable Energy Credit markets in states with Renewable Portfolio Standards and tax abatements on land and turbine sales.

4.1.1 Data and Sample Construction

We use administrative data about wind facilities and their decisions, including investment, production, and subsidy receipt. Data on investment and production are available from the Energy Information Administration (EIA). The EIA data are a census of all utility-scale wind facilities in the United States. The annual EIA-860 form contains information on first date of operation, location, and investment information like the nameplate capacity (United States Energy Information Administration, 2001-2021a). Realized production data come from the monthly EIA-923 form, which reports monthly net generation at the facility level. We calculate monthly capacity factors by dividing realized generation by the potential generation implied by capacity (United States Energy Information Administration, 2001-2021b).[17]

Empirically we are interested in the change in production when the PTC subsidy period ends. Because the administrative data do not include tax filings, receiving the PTC is not directly observable. Instead we use the policy rule to determine eligibility. Specifically, we identify the first month each facility reports positive net-generation in the EIA-923 and impute subsidization from that 1st month until the 120th month thereafter. This measure should be valid for all firms for whom we can identify a first month and who received the

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[15] Research on the effects of these subsidies on firms has shown that production degradation accelerates in the years after passing the end of the subsidy (Hamilton et al., 2020, though we know less about the immediate effects) and that because the subsidy is nonrefundable and politically uncertain, it's real value is less than $25 per MWh (Grobman and Carey, 2002; Johnston, 2019).

[16] Aldy et al. (forthcoming) describe the history and implications of this policy and show that although the subsidy may have made some marginal entrants profitable, firms who were induced to take up the investment subsidy produced less and invested less efficiently (as predicted by Diamond and Mirrlees, 1971; Parish and McLaren, 1982). They also show that for a wide range of quantity targets the 30% investment subsidy would be relatively less cost effective than the existing PTC.

[17] Note that this means we drop 41 facilities with missing capacity information. We also truncate the resulting capacity factor above and below at 0 and 100, and impute periods of missing generation with 0 generation, but results are not sensitive to these inclusions and specifications.

PTC and not the 1603 grant.

With these considerations in mind, we make four sample restrictions. First, we exclude firms who received the 1603 investment grant instead of the PTC from our baseline analysis (using the list from the replication data of Aldy et al., 2021). Second, because the EIA data cover production in 2001-2021, we focus on firms who began producing in or after 2002 so that we can identify their first month of production. Third, we drop facilities who renovated their turbines, called "repowering," during the sample period because we cannot determine their new capacity from the EIA data. To do this, we exclude firms that report repowering in the American Clean Power Association's CleanPowerIQ data (American Clean Power Association, 2020). Finally, we drop observations from the first 24 months of production because the staggered construction of turbines within a facility means that not all capacity is online in the first month of facility operation.

4.2 Measuring Production Responses after the PTC Subsidy Period

We now consider if and how much energy generation changes at wind facilities when the PTC subsidy period ends. In theory, reducing the after-tax revenue per MWh should incentivize less production, but it is an empirical question whether wind facilities actually respond to this incentive. On one hand, investment decisions are made only once, and firms have no control over how much then wind blows. On the other hand, firms may still be able to respond by optimizing or maintaining their capital less effectively, engaging in curtailment in the face of low or negative prices, or choosing to exit. In this subsection we present our empirical strategy and demonstrate that facilities do decrease production when the PTC subsidy period ends. In the appendix, we present evidence that the effect is not driven by exit or curtailment.

4.2.1 Event Study Design

To estimate the effect of output subsidies on net generation, we estimate an event study of production around the 120-month end of the PTC. Our main outcome of interest is the capacity factor, but in the appendix, we show results with net generation, capacity, and exit. We estimate the following specification:

$$\begin{aligned}\text{Capacity Factor}_{jst} = {} & \theta_j + \psi_{s,t} \\ & + \sum_{v' \in \mathcal{V}} \sum_{m' \in \mathcal{M}} \beta_{m',v'} \mathbb{1}[\text{First Month}_j \in v'] \mathbb{1}[m' = t - \text{First Month}_j] + \varepsilon_{jst}\end{aligned} \tag{3}$$

Here, capacity factor is indexed by firm j producing in state s during (monthly) time period

t. The event study sums over vintage v (in which each v' is calendar year the facility started operation) and the month of operation m. The set $\mathcal{V}$ is partitioned into years, and the set of included event indicators is $\mathcal{M} = [\underline{m}, 60, 61, ..., 119, 121, ..., 180, \bar{m}]$. We exclude $m = 120$ because it is not included so it is the reference period. Because there are no never treated units we bin $m < 60$ and $m > 180$ together for a second normalization (see details in Sun and Abraham, 2021). We also include facility fixed effects θ_j and state-by-month-by-year fixed effects $\psi_{s,t}$. Note that the data are not a balanced panel because we only observe firms after their first month of production (i.e., $t >$ First Month$_j$).

There are five empirical considerations that motivate this specific characterization of the event study. The first is the simplest: Wind speeds vary across time and space. There are seasonal patterns (windy and slow months), annual patterns (windy and slow years), and geographic patterns (windy and slow locations). But because these three dimensions of variation are correlated, naive time-period fixed effects or controls for seasonality will not capture the true heterogeneity and could leave spurious residual correlations between the event indicators and the error term. To account for this, we estimate the model with state-by-month-by-year fixed effects.[18]

Second, heterogeneity in the effects by vintage may bias the effects of a naive event study estimator. A rich literature on event study estimation has documented the importance of allowing for heterogeneous effects by treatment cohort (see Callaway and Sant'Anna, 2021; Sun and Abraham, 2021; Wooldridge, 2021). We operationalize this by using the estimator proposed by Sun and Abraham (2021) and estimating effects for each month of production separately by vintage, or the year in which production was first reported to the EIA. Following Sun and Abraham (2021), we report vintage-weighted averages of the heterogeneous effects:

$$\beta_m = \sum_{v'} \omega_{m,v'} \beta_{m,v'}$$

where $\omega_{m,v}$ is the share of firms that entered in v' among those who produce for m months.

Third, the timing of PTC eligibility is unobserved. PTC eligibility occurs at the turbine level, but our data are only available at the facility level, introducing "fuzziness" in the defined treatment. This could happen in two ways. First, turbines that are completed after the first month of facility generation will still be subsidized after the 120th month of facility production. Second, when tax filing dates do not line up with the month of first reported generation, some observations before the 120th observed month may be unsubsidized and some observations after may be subsidized.

---

[18] The effects estimated in this way are similar to those using facility-by-month and month-by-year fixed effects, and both yield much less variable estimates of the event indicators compared to estimators that ignore this heterogeneity.

Because each of these measurement imperfections will attenuate our estimated effects, we report both short- and long-term effects:

$$\beta_{short} = \sum_{m'=121}^{144} \sum_{v'} \omega_{m',v'} \beta_{m,v'} \qquad \beta_{long} = \sum_{m'=145}^{180} \sum_{v'} \omega_{m',v'} \beta_{m',v'}$$

where the $\omega_{m,v}$ weights are now the unconditional share of firms with (m', v') among the short- or long-run period. Here the first effect represents the average change in production in the two years immediately after the subsidy period. To the extent to which staggered turbine completion is driving the attenuation, this will be limited to the short-run effect since all turbines seem to be completed by the end of year two. We also estimate a long-run effect for the years thereafter, which will not be biased from the staggered turbine completion, but may still be attenuated if some facilities enter the unsubsidized period before their 120th month of reported production because of tax filing reasons.

The final concern is that event study estimates will capture any acceleration in depreciation over time. Interestingly, other research has shown that the end of the PTC subsidy period is a main determinate of heterogeneous degradation in wind turbine generation (Hamilton et al., 2020). In the presence of accelerating depreciation, we would expect to see a negative pretrend that accelerates approaching the end of eligibility from the left. Interestingly, whereas this pattern is visible in other countries that don't have the PTC, it is absent in the US (see discussion in Hamilton et al., 2020). This insight suggests that we should interpret changes in depreciation as part of the long-term treatment effect on production after the PTC subsidy period.[19]

4.2.2 Wind Facilities Reduce Produce when the PTC Subsidy Period Ends

Figure 4 presents the results from our event study analysis. This figure presents the vintage-weighted average event estimates for each month of production, β_m, relative to the 120th month. The shaded area behind the series of estimates are two-way clustered, 95% pointwise confidence intervals computed using the delta method, clustering by facility and month-of-year. Looking at the patterns in these estimates, we see that the capacity factor essentially remains constant during the subsidy period up through the 120th month. The average capacity factor in year 10 is 31.3%. After the subsidy period, production jumps down by just under 1 percentage point and begins sloping downward. In the first two years after the end of the PTC, the average decrease in the capacity factor is 1.5 percentage points (4.6%);

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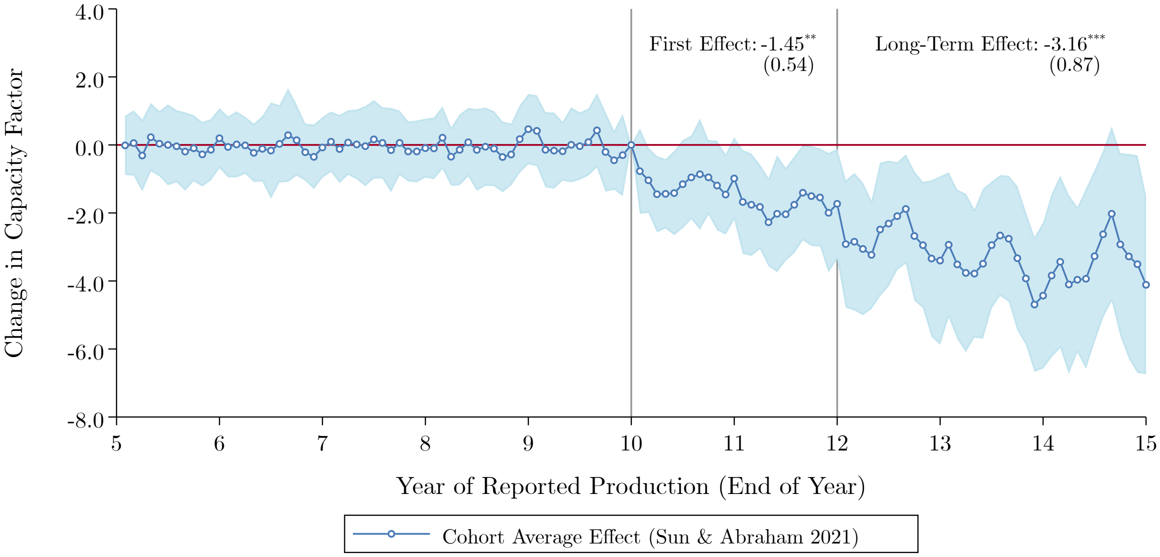
[19] Note that the results we find could still be driven by accelerating depreciation and not the PTC, but the process would have to be nonlinear or discontinuous in ways that seem implausible.

this effect grows and stabilizes to 3.2 percentage points (10.1%) in the years thereafter.

Figure 4: Production Decreases after When Production Tax Credit Subsidization Ends



Note: This graph shows event-study estimates of the change in production when the PTC subsidy period ends. The sample are 65,861 non-singleton, facility-month observations from 2002-2021, including 763 firms, 307 of which produced for more than 10 years. The series present vintage-weighted average of the event coefficients from equation 3, with the first and long-run effects reported as well. Standard errors and 95% confidence intervals are computed with the delta method with two-way clustering by facility and month-of-year. The average capacity factor in the tenth year of production is 31.3.

The first identifying assumption required to interpret these estimates as causal effects is parallel trends in baseline outcomes (Sun and Abraham, 2021). In our setting, this means that the subsidized production of all firms would be evolving in parallel in the absence of the PTC time-limit. This assumption requires that the state-by-month-by-year fixed effects reflect generalizable changes for the relevant firms on average. In other words, we assume that the counterfactual changes in production had a facility still been subsidized are characterized by the changes in production for other still-subsidized firms in the same state. Because the identifying variation for the event indicators after 120 months comes from relatively older firms, the fixed effects capturing the geo-temporal variation in wind resource are identified by changes in the newer firms (in that sense they act as "control" units). The possibility of heterogeneous responses to seasonality by newer and older firms is why we measure output in capacity factor and not MWh. Models with facility-by-month fixed effects are noisier but also suggest that this is not a problem. As discussed above, we consider heterogeneity in depreciation part of the causal effect because evidence suggests that subsidized production is indeed parallel despite the potential for degradation.

The second identifying assumption is that there is no treatment effect in pre-treatment periods (Sun and Abraham, 2021). This could be violated if subsidized production ends for some turbines before the 120th month of reported production, biasing the effects towards zero as discussed. This identifying assumption could also be violated if firms engaged in strategic maintenance decisions or change their capacity as the end of PTC eligibility approaches.[20] Fortunately, the average level in the pre-treatment periods is very close to zero and does not drop until the subsidy period ends, suggesting that neither noise between tax filing and reported generation, nor reduced repairs before the end of PTC eligibility is a significant source of bias.

In addition to concerns about identification and internal validity, we want to raise three important points about external validity. First, we show that the reduction in production represents an intensive- rather than extensive-margin response to the difference in prices after the revenue. Appendix Table D.1 shows that although both capacity factor and net generation decrease when the PTC subsidy period ends, the change in the probability of exit, measured by zero-generation, is almost zero and statistically insignificant [$p = 0.83$].

Second, we consider the difference between our short- and long-run effects. Because the event-study estimates are weighted by cohorts, the effects in periods farther from the 120th month (e.g., months 168-180) are identified off of firms from earlier vintages (e.g., 2002-2007).[21] In this case, the estimated effect in month 180 may not generalize to firms from later vintages, and the difference in long-term and short-term effects may be driven by composition rather than dynamics. To assess this concern, we estimate our event-study separately for three terciles of vintage: 2002-2006, 2007-2008, and 2009-2011. When we compare the short-term effects, the effects on the oldest and newest vintages are almost the same and there are no statistical differences between any group (see Appendix Table D.1).[22]

A third concern about external validity is that the reduction in production occurs because energy markets occasionally face negative prices. In very windy hours, turbines may generate more energy than needed but will want to still produce to capture the PTC, driving prices below zero. Although Aldy et al. (forthcoming) document that curtailment accounts for at most one third of the difference in production between facilities that receive the PTC and 1603 investment grant, we also consider it in our data. Because firms selling to lower-price markets are most likely to face negative prices, we estimate our event-study separately for

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[20] Under the 80/20 rule investments that are updated at a cost of more than 80% of the original investment cost re-qualify for another 10 year of the PTC. This is another reason why we drop firms that report repowering.

[21] This is why the standard errors grow larger in Figure 4 the farther the series progresses to the right.

[22] The fact that the effect in the 2007-2008 tercile is smaller seems to be driven by firms that began production in 2008 that may be producing more when the subsidy period ends. We conjecture that this is due to a repowering decision not observed in our data.

facilities that sold at above and below median average wholesale prices in their tenth year of operation. We find similar reductions in production for both groups (see Appendix Table D.1), suggesting that negative prices and curtailment do not limit the interpretation of our results.

Considering this evidence, we conclude that wind facilities reduce production by 5-10% when the PTC subsidy period ends and that this represents a causal response to the marginal incentives to produce. Given the important role of fixed inputs like turbines, some readers may find it striking that there is any response at all. It is important to note then, that because the end of the subsidy period essentially creates a 30% reduction in prices, the implied elasticity is still quite small (about 0.1-0.25). Our event-study estimates are also smaller than the differences in Aldy et al. (forthcoming) who show that in a subset of large facilities, facilities receiving the PTC produce 10-12% more than those receiving the 1603 investment grant. They point out and discuss the important margins of endogenous decisions about maintenance, repairs, forecasting, and optimization,[23] concluding that effects even larger than ours could be very realistic.

4.3 Assessing the Optimality of Renewable Energy Subsidies

Having measured how energy production changes when the PTC subsidy period ends, we can return to the theory to consider whether existing subsidies for wind energy are designed optimally. To assess the optimality, we will assume that the current policy is calibrated appropriately and will consider what model primitives would justify each policy.

First, we consider the \$25 value of the PTC which can only be justified by a small value of the externality. According to Proposition 3, if all policy parameters are optimally chosen, the output subsidy should be $\gamma = \tau^o$; thus, optimality requires that $\gamma =$\$25/MWh. Although there are additional external benefits to offsetting other pollutants, reducing CO_2 is the main benefit in most locations (see calculations in Cullen, 2013). If 1 MWh of wind energy reduces average CO_2 emissions by 0.709 metric tons (as estimated by United States Environmental Protection Agency, 2022), a \$25/MWh benefit implies a social cost of carbon of \$36 per ton. This estimate is low relative to the EPA's estimate (\$51 per ton) and recent academic work (\$59 to \$99 in Cai and Lontzek (2019) or \$185 in Rennert et al. (2022)). Note that computing the true external value of wind from these average figures is complicated by two considerations. First, the average CO_2 and pollution offsets reported by the EPA may not reflect the marginal offset in the short run (Cullen, 2013, although in the long run the

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[23] Another endogenous mechanism could be strategically choosing cut-in speeds at which to operate the turbines because, as one reader pointed out, wear and tear may be more closely related to hours of operation than to MWh produced.

"marginal" effect of clean energy will be the average difference in pollution as dirty firms exit). Second, there is heterogeneity across time and space in the value of one MWh of wind energy (e.g., Hollingsworth and Rudik, 2019; Fell et al., 2021; Sexton et al., 2021). This could positively or negatively affect γ. Despite these complications, the average value of the externality is so much larger than the current value of the PTC, we think it is likely that the \$25 PTC is probably too low for $\gamma = \tau^o$ to hold, even on average.[24]

Second, we consider the policy of accelerated and bonus depreciation, and show it is only an optimal investment subsidy if the average capital share of output is very small. This subsidy was probably worth about 7-12% of investment costs in our sample period. Recall that the optimal investment subsidy should be $\tau^i = (1-T)\frac{\gamma \frac{\mathrm{d}q}{\mathrm{d}\tau^i}}{\frac{\partial x^f}{\partial \tau^i}}$. Given an output subsidy with a ten years time limit, and assuming the life of a wind turbine is twenty five years, $T \approx 0.4$. If the average investment cost for producing an additional MWh over the capital life is between \$10-20,[25] and if the PTC is optimally chosen such that the average marginal externality really is worth \$25, then the bonus depreciation is optimally subsidizing investment only if $\frac{\frac{\mathrm{d}q}{\mathrm{d}\tau^i}}{\frac{\partial x^f}{\partial \tau^i}} < 0.16$ (under the most generous calibrations).[26] Whereas such a small fixed-inputs share on the margin might be true in some industries, it seems implausible in the wind industry.

Finally, we consider the PTC's ten-year subsidy period and show that it could be optimal under large political frictions. Recall, that at the optimum $\phi'(T) = -\gamma \Delta q$. We estimate that the average change in production is about 1000 MWh/month/firm. For context, this means that (again assuming $\gamma = \$25$) extending the PTC by one year would cost policymakers over \$244 million.[27] Because the $\phi(T)$ term captures institutional frictions, it is hard to benchmark this number to consider whether it is reasonable. Perhaps one way to think of it is that the value of winning a US Senate race is \$15 million (assuming the total cost represents a willingness to pay), and there are about 10 "swing" races every two years. If successfully passing policies through reconciliation is another way of working towards re-election, then passing time-limited subsidies may be an optimally chosen strategy with costs

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[24] Even considering REC prices as an added output subsidy, implies externality values in the range of \$25-\$40 per MWh, which could possibly account for the social cost of carbon in some states.

[25] If 1 MW of capacity operates for 8760 hours a year for 25 years with an average capacity factor of 31.3 (the average in the year before the end of eligibility in our sample), it will produce just under 70,000 MWh, so to produce 1 Mwh over the capital life it requires $\frac{1}{70{,}000}$ MW of capacity. Recalling that 1 MW of capacity costs about \$0.8-1.5 M, this means the cost will be \$11-20.

[26] If $\frac{\tau^i}{c} \in [0.07, 0.12]$ is optimal, then Plugging in $T \approx 0.4$, $\gamma = \$25$, and $c \in \{10, 20\}$ for bounds we can simplify $\frac{(1-T)\gamma}{c}\frac{\frac{\mathrm{d}q}{\mathrm{d}\tau^i}}{\frac{\partial x^f}{\partial \tau^i}}$ to $\frac{\frac{\mathrm{d}q}{\mathrm{d}\tau^i}}{\frac{\partial x^f}{\partial \tau^i}} \in [0.09, 0.16]$.

[27] That is, \$25 in value for about 12,800 MWh forgone in the eleventh year for each firm. This linear approximation of $\phi(T)$ around $T = 0.4$ underestimates the administrative cost from a convex $\phi(T)$ (and convexity is necessary for an interior solution like $T = 0.4$ to be optimal).

of a similar order of magnitude as campaigns.

Overall this analysis suggest that large costs and small external values are necessary to justify the policies, but with the exception of using accelerated depreciation to subsidize investment, the current calibrations are not outlandishly far from the theoretical optima. Interestingly, although intuition based on production efficiency might suggest that offering accelerated depreciation is too generous a subsidy (Diamond and Mirrlees, 1971), our results suggest that it is in fact too small. This finding reemphasizes the critical role of using investments subsidies as corrective instruments when the accompanying (politically feasible) output subsidy is time limited.

4.4 Implications for Energy Markets and Welfare

Having discussed the implications of the PTC subsidy duration for optimal policy, we now explore its implications on energy markets. Wind facilities are a quickly growing feature of energy markets in the United States, and in just the next five years over 28,700 MW of wind capacity will age out of the PTC subsidy period. This subsection explores the magnitude of the total change in wind energy production due to the PTC time limit.

We quantify the dynamic production response attributable to PTC ineligibility with a simple extrapolation exercise using the event study estimates. For each month that firms produce after the subsidy period, we assume that their average net generation would have been lower by 733 MWh in the first two years after the subsidy period and by 1405 MWh in subsequent years. If anything, this will underestimate the total effect if the loss of the PTC leads to continued degradation beyond the 5-year window we estimate effects over (as suggested by Hamilton et al., 2020) and because newer firms have larger name plate capacity (we are using MWh estimates rather than capacity factor estimates to be conservative). We estimate the cumulative effect to date and also project the effect forward in time on the existing fleet through the year 2045, assuming a capital life of 25 years.[28]

We compare the effects of the existing policy with two counterfactual policies that extend the duration of the PTC subsidy period. For these counterfactuals, we estimate the energy production that would be forgone if in January 2022 the United States had extended the PTC to either 15 or 20 years. To be conservative, we assume that firms who “requalify” for the PTC after this policy return to full production and experience the short-term effects again when the policy expires rather than resuming where they had been in the dynamics. If there are persistent effects from the degradation that firms allow to occur after the end of subsidy eligibility, it will lead us to underestimate the value of extending the subsidized period.

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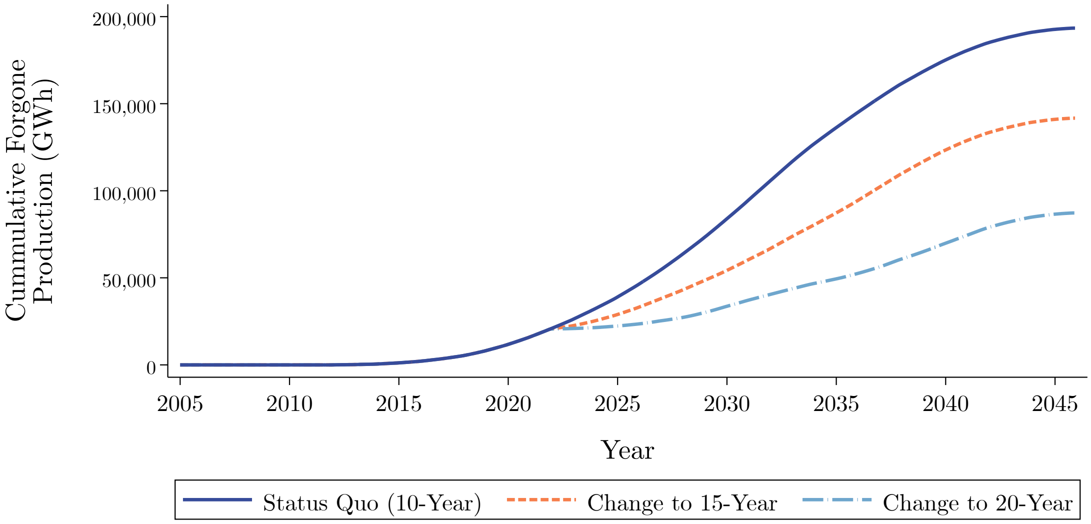
[28] Which, if too short, would also lead us to understate the total forgone energy.

Figure 5: Forgone Clean Energy Production from PTC Ineligibility



Note: This figure shows the energy production that was lost from PTC ineligibility and projections for the amount of forgone energy resulting from different possible changes to the PTC for the existing fleet of wind facilities. To calculate these estimates, we apply the short- and long-term effects on net generation to each month and sum up the total effects. For the counter-factual policies we assume the same responses as estimated at the ten-year time limit, even though this is likely an underestimate of the true effect. Note that these estimates only capture the production lost along the intensive margin for the existing fleet, not for firm entry and investment decisions as new capacity comes online.

Figure 5 shows how the amount of forgone energy is increasing rapidly and will continue to do so. By December 2021, energy markets forwent over 420,000 MWh/month of energy produced by wind. This corresponds to the power used by over 470,000 homes (using the EIA's estimate that the average household uses 0.893 MWh/month United States Energy Information Administration, 2022) and a social externality value between $17 and $30 million dollars per month—figures that will more than double by 2030 under the current policy. By the end of 2045, when the last of the current fleet will retire, the energy market will have forgone over 190,000 GWh of clean energy from wind—enough energy to power every home in the US for over 18 months.

Figure 5 also shows how extending the PTC subsidy duration could reduce the amount of forgone energy. Although the exact values of the estimates should be treated as suggestive since a lot of extrapolation is required, the overall patterns are striking. Lengthening the PTC subsidy duration would reduce the amount of forgone energy and would strongly reduce the rate at which that amount is increasing. Our estimates suggest that increasing the PTC time limit by 40% (20%) of the capital life could cut forgone production by more than 55% (25%). Interestingly, these results are calibrated to the $25 PTC, so they hold even though the value of the subsidy is probably less than the value of the externality.

While these implications for markets are striking, we want to make two cautions about extrapolating from these production-based results to analyses of welfare. First, although the marginal externality per MWh is almost surely bigger than the current cost of the PTC, a longer subsidy duration would transfer surplus to firms because most of their production after the subsidy period is inframarginal. If the social value of a dollar to the government is equal to a dollar to firms, then this transfer is welfare neutral, but if there are concerns about the marginal cost of public funds, then tax dollars spent by extending the PTC have a relatively smaller welfare impact. Second, although we can quantify the externality today and the amount of production forgone in the next 20 years, we consider it very unlikely that the external value of a MWh of wind will stay constant over this period. As the US transitions to cleaner energy, the pollution offset by wind energy will decrease toward zero, suggesting that the social cost of forgone production will also be decreasing.

5. Conclusion and Policy Discussion

Motivated by the observation that "nothing is permanent," this paper explores the optimal tax implications of subsidy duration in the case of constant production and consumption externalities. It shows the critical importance of investment subsidies as a policy tool when a ("Pigouvian") output subsidy with no time limit is infeasible. Because the change in production when the subsidy period ends informs the optimal subsidy duration, we document that the end of the Renewable Energy Production Tax Credit subsidy period results in a 5-10% decrease in wind energy production and conclude that the current subsidies for wind energy are somewhat difficult to justify. In this section, we conclude by considering ways that policymakers might apply these results or extend them to inform policies for other subsidies in industrial and energy policy. We also consider the implications for policies in more complicated situations than explored in this paper, pointing to important limitations and extensions.

Before making our recommendations, we want to emphasize that many current features of subsidy policy reflect aspects of the optimal theoretical results we derived. For example, although traditional intuition focused on the first best (e.g., Diamond and Mirrlees, 1971) would frown on the use of investment and output subsidies together—and on investment subsidies at all—our model shows that subsidizing investment is the optimal response to the institutional frictions that generate time-limited output subsidies. These investment subsidies correct the underinvestment that results from unsubsidized production created by time limits. With that noted, we illustrate four policy considerations: using estimates of externalities to calibrate policy, the importance of investment subsidies, choosing subsidy duration, and designing the institutions that generate them. Although our empirical application focused on renewable energy, we hope these considerations are general enough to inform any externality-correcting policy.

First, having credible estimates of the external benefit of production is crucial for determining the optimal policy. No matter the subsidy duration, the optimal output subsidy is always exactly equal to the externality—and even when no investment subsidy is feasible, they are closely related. Not only do the optimal calibrations of the output and investment subsidy depend on the size of the externality, but so does the optimal duration. All else equal, a larger externality means that it's socially optimal to have a longer subsidy duration. This is true of environmental externalities (Cai and Lontzek, 2019) as well as for other possible production externalities like maintaining a strong working class (Autor et al., 2019).

A fruitful, policy-relevant direction for future research might be extending the motivation for investment subsidies to more general contexts, for example when the externality value may vary. Then, rather than uniform electric vehicle subsidies, policymakers might want to subsidize purchasing more in markets where electricity is produced from cleaner means (for reference see external benefits quantified in Holland et al., 2016). Similarly, if the production externality value will decrease over time, the subsidy value should change. For example, if the benefit of renewable energy generation is avoiding carbon and sulfur emissions (Cullen, 2013; Sexton et al., 2021), their external value will diminish as the share of energy generated by renewables grows. These are considerations policymakers should keep in mind if using our results to structure subsidies.

The second implication of our results for policymakers is the importance of externality-specific investment subsidies. Our theoretical results show that investment subsidies are critical when output subsidies are time limited—as investment subsidies avoid underinvestment much more effectively than scaling up the value of the output subsidy. Many countries use tax benefits to subsidize investment, but the value of the subsidy is tied up in the cost of capital, deviations from scheduled depreciation, and the corporate tax rate. As such, the subsidy value cannot be closely tied to the externality, production technology, or subsidy duration in a given industry. Replacing these tax benefits with industry-specific investment subsidies could improve the synergy between the investment and output subsidies. Additionally, our results clearly show that forcing firms to choose between output and investment subsidies (as with wind and geothermal energy PTC and ITC) is less efficient than allowing them to claim both (as with subsidies for low income housing, healthcare or research and development).

Because our baseline model likely understates the usefulness of investment subsidies relative to settings with more complex dynamics, formalizing the optimal tax implications of these dynamic tradeoffs is another pressing area of future research. For example, when the externality of interest is not a constant production externality but an externality based on the decisions of early adopters (such as learning spillovers in new industries or agglomeration effects), early adoption is critical. We show that even without dynamics it is much more effective to spark investment with an investment subsidy than with an output subsidy. Similarly, our model considers the case of perfect certainty (in regard to prices and future policy), but uncertainty about either could easily generate underinvestment problems similar to those caused by certain time limits. In this case an investment subsidy would be a doubly important mechanism for guaranteeing commitment to externality generation because it cannot be revoked by future policy changes or undermined by future pricing changes.

Third, policymakers interested in correcting externalities should carefully consider the optimal subsidy duration. While not socially optimal from a first-best point of view, we show the presence of time-limited subsidies arise naturally from existing political systems. Unfortunately, our impression is that often time limits are not chosen based on a judicious comparison of social costs and benefits. Fortunately, our results describe how to optimally calibrate subsidy duration. Holding the externality size constant, the subsidy duration should be longer in industries with larger margins of response. This is a good justification for having time-limited subsidies for renewable resources that are fueled by natural phenomena like wind, sun, waves, water, and geothermal heat. On the other hand there is emerging evidence that manufacturing industries respond very strongly to time-limited subsidies and quotas (e.g., electric vehicles Lohawala, 2022). Our results suggest that longer subsidy durations will be important in these industries. We also note that credits like the Renewable Energy Production Tax Credit (which subsidizes other energy sources besides wind) have the same subsidy duration for energy produced by different technologies. We are skeptical that having the same duration for both renewable-energy and biomass-based subsidies is optimal. For example, this would suggest that both industries have equal social externalities (even though burning biomass emits carbon and can emit particulate matter) and equal changes in production (even though biomass resources have fuel inputs that are not free or exogenous). We note that policymakers concerned with efficiency should allow subsidy duration to vary by externality size and response size.

Finally, we point out the value of considering institutional changes that could reduce the frictions that generate time-limited subsidies in the first place. Depending on the production technology, our results show that there can be very real welfare differences between the first-best policy and the second-best response given political and institutional frictions. As policymakers' decisions affect subsidies for many, many markets, there may be great utility in reducing the costs of implementing longer (or first-best) policies. Whatever the reason behind making subsidies time-limited, reducing these frictions could generate increased externality production in numerous markets and large welfare gains overall.

These policy recommendations underscore the fact that while there are real stakes to implementing time-limited subsidies, there are also substantial opportunities for gains. By connecting output and investment subsidies in this framework of time-limited subsidies, we articulate reasons why using investment subsidies can be critical despite the intuition we inherit from the first-best. These insights are crucial for effectively designing subsidies in an era of increasing attention to industrial and energy policy. To this end, much more research is needed to quantify externality sizes, determine the responsiveness of production technologies, and extend our results to scenarios with more real-world nuance and complication. Our surprising results from the US wind industry reflect the large and important role that subsidy design has on equilibrium allocations and suggests that time-limited subsidies may have even greater consequences in industries with larger changes in production. Better understanding these details will allow policymakers to improve policy and enable subsidies to better target the goods they are designed to support.

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A. Continuous Time Model - For Online Publication

In this appendix, we prove that the two-stage model is isomorphic to a continuous time model with exponential discounting. In a continuous time framework, the firm discounts profits at a rate β and chooses capital x and variable inputs v_t for $t \in [0,1]$ to maximize the continuous time firm's problem:

$$\max_{x,v_t} \int_0^T \exp\{-\beta t\}\Big[q(x,v_t)(1+\tau^o) - mv_t\Big]dt + \int_T^1 \exp\{-\beta t\}\Big[q(x,v_t) - mv_t\Big]dt - x(c-\tau^i)$$

Lemma 1. The Firm's optimal variable inputs v_t will be a constant piece-wise function for $t < T$ and $t \geq T$ defined by

$$\begin{cases} q_v(x,v_1^f) - \frac{m}{1+\tau^o} = 0 & t < T \\ q_v(x,v_2^f) - m = 0 & t \geq T \end{cases} \tag{4}$$

Proof. For any t, the first order condition with respect to v_t:

$$\exp\{-\beta t\}\Big[q_v(x,v_t)(1+\tau^o) - m\Big]\cdot \mathbb{1}(t<T) + \exp\{-\beta t\}\Big[q_v(x,v_t) - m\Big]\cdot \mathbb{1}(t \geq T) = 0$$

The above equation holds with equality for v_t defined by

$$\begin{cases} q_v(x,v_1^f) - \frac{m}{1+\tau^o} = 0 & t < T \\ q_v(x,v_2^f) - m = 0 & t \geq T \end{cases}$$

□

Lemma 2. The Firm's optimal investment decision is defined by

$$\tilde{T}q_x(x^f,v_1^f)(1+\tau^o) + (1-\tilde{T})q_x(x^f,v_2^f) - (\tilde{c} - \tilde{\tau}^i) = 0 \tag{5}$$

Where $\tilde{T}$, $\tilde{c}$, and $\tilde{\tau}^i$ are defined as

$$\tilde{T} = \frac{1 - \exp\{-\beta T\}}{1 - \exp\{-\beta\}}$$
$$\tilde{c} = \frac{\beta}{1 - \exp\{-\beta\}} c$$
$$\tilde{\tau}^i = \frac{\beta}{1 - \exp\{-\beta\}} \tau_i$$

Proof. From lemma 1 we can write the firm profits as

$$\max_x \left\{ \Big(\frac{1 - e^{-\beta T}}{\beta}\Big) \Big[q(x, v_1^f)(1 + \tau^o) - mv_1^f\Big] + \Big(\frac{e^{-\beta}(e^{\beta(1-T)} - 1)}{\beta}\Big) \Big[q(x, v_2^f) - mv_2^f\Big] - x(c - \tau^i) \right\}$$

The first order condition is therefore

$$\Big(\frac{1 - e^{-\beta T}}{\beta}\Big) \Big[q_x(x, v_1^f)(1 + \tau^o)\Big] + \Big(\frac{e^{-\beta}(e^{\beta(1-T)} - 1)}{\beta}\Big) \Big[q_x(x, v_2^f)\Big] - (c - \tau^i) = 0$$

Multiplying through by $\frac{\beta}{1-e^{-\beta}}$ the first order conditions becomes

$$\tilde{T} q_x(x^f, v_1^f)(1 + \tau^o) + (1 - \tilde{T}) q_x(x^f, v_2^f) - (\tilde{c} - \tilde{\tau}^i) = 0$$

□

Proposition 5. The two-stage model is isomorphic to the continuous time model with exponential discounting.

Proof. From lemmas 1 and 2 the firm's problem in continuous time is defined by equations 4 and 5 and is identical to the two-stage firm's problem with T, τ^i and c replaced with $\tilde{T}$, $\tilde{\tau}^i$ and $\tilde{c}$.

The continuous time welfare function is

$$\begin{aligned} W = \max_{x, v_t} & \int_0^T \exp\{-\beta t\} \Big[q(x, v_t)(1 + \tau^o) - mv_t\Big] dt + \int_T^1 \exp\{-\beta t\} \Big[q(x, v_t) - mv_t\Big] dt - x(c - \tau^i) \\ & + \gamma \Big(\int_0^T \exp\{-\beta t\} q(x, v_t) dt + \int_T^1 \exp\{-\beta t\} q(x, v_t) dt \Big) - \lambda \Big(x\tau^i + \tau^o \int_0^T q(x, v_t) dt \Big) - \phi(T) \end{aligned}$$

Using Lemma 1 and evaluating the integrals the welfare function becomes

$$
\begin{aligned}
W =& \Big(\frac{1-e^{-\beta T}}{\beta}\Big)\Big[q(x^f,v_1^f)(1+\tau^o)-mv_1^f\Big]+\Big(\frac{e^{-\beta}(e^{\beta(1-T)}-1)}{\beta}\Big)\Big[q(x^f,v_2^f)-mv_2^f\Big]-x^f(c-\tau^i)\\
&+\gamma\Bigg(\Big(\frac{1-e^{-\beta T}}{\beta}\Big)q(x^f,v_1^f)+\Big(\frac{e^{-\beta}(e^{\beta(1-T)}-1)}{\beta}\Big)q(x^f,v_2^f)\Bigg)\\
&-\lambda\Bigg(x^f\tau^i+\tau^o q(x,v_1)\Big(\frac{1-e^{-\beta t}}{\beta}\Big)\Bigg)-\phi(T)
\end{aligned}
$$

Next consider the (monotonically) transformed welfare function $\tilde{W}=\frac{\beta}{1-e^{-\beta}}W$:

$$
\begin{aligned}
\tilde{W} =& \tilde{T}\Big[q(x^f,v_1^f)(1+\tau^o)-mv_1^f\Big]+(1-\tilde{T})\Big[q(x^f,v_2^f)-mv_2^f\Big]-x^f(\tilde{c}-\tilde{\tau}^i)\\
&+\gamma\Big(\tilde{T}q(x^f,v_1^f)+(1-\tilde{T})q(x^f,v_2^f)\Big)-\lambda\Big(\tilde{\tau}^i x^f+\tilde{T}\tau^o q(x^f,v_1^f)\Big)-\frac{\beta}{1-e^{-\beta}}\phi(T)
\end{aligned}
$$

Defining $\tilde{\phi}(\tilde{T})=\frac{\beta}{1-e^{-\beta}}\phi(T)$, maximizing the continuous time welfare function W with τ^o, τ^i, and T is identical to maximizing the transformed welfare function $\tilde{W}$ with respect to τ^o, $\tilde{\tau}^i$, and $\tilde{T}$.

The continuous time model with exponential discounting is therefore isomorphic to the two-stage model. $\square$

B. Proofs for the Optimal Tax Model - For Online Publication

Assumption 1. Assume (1) $\lambda = 1$ (2) that $q(x, v)$ is increasing in both arguments with decreasing returns such that there exists an interior solution (x^f, v_1^f, v_2^f); and (3) that the firm choices (x^f, v_1^f, v_2^f) are implicit functions of the policy parameters (τ^i, τ^o, T) such that all first order conditions are continuously differentiable with respect to all arguments and produce a matrix $F = (f_x, f_{v_1}, f_{v_2}) = 0$ with a non-singular Jacobian with respect to x and v_t.

In order to prove the main results in proposition 3, we first prove a helpful lemma.

Lemma 3. Under assumption 1, the marginal increase in the firm's variable input (v_2^f) with respect to a marginal change in a policy parameter is equal to the marginal increase in the capital input (x^f) scaled by the ratio of the second derivatives of the production function.

$$\frac{\partial v_2^f}{\partial \tau^i} = -\frac{q_{xv}(x^f, v_2^f)}{q_{vv}(x^f, v_2^f)} \frac{\partial x}{\partial \tau^i}$$
$$\frac{\partial v_2^f}{\partial \tau^o} = -\frac{q_{xv}(x^f, v_2^f)}{q_{vv}(x^f, v_2^f)} \frac{\partial x}{\partial \tau^o}$$
$$\frac{\partial v_2^f}{\partial T} = -\frac{q_{xv}(x^f, v_2^f)}{q_{vv}(x^f, v_2^f)} \frac{\partial x}{\partial T}$$

Proof. Under assumption 1, if there exists an interior solution to the firms problem for a given choice of policy parameters (τ^i, τ^o, T), the firm's solution can be defined as the choice of x^f,v_1^f,v_2^f such that $F = \begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix} = 0$.

$$\begin{aligned}
f_1(x^f, v_1^f, v_2^f; \tau^i, \tau^o, T) =& q_v(x^f, v_1^f)(1 + \tau^o) - m \\
f_2(x^f, v_1^f, v_2^f; \tau^i, \tau^o, T) =& q_v(x^f, v_2^f) - m \\
f_3(x^f, v_1^f, v_2^f; \tau^i, \tau^o, T) =& T q_x(x^f, v_1^f) + (1 - T) q_x(x^f, v_2^f) + T\tau^o q_x(x_1^f, v_1^f) - c(1 - \tau^i)
\end{aligned}$$

Using the implicit function theorem, we can define a function g such that

$$\begin{pmatrix} x^f \\ v_1^f \\ v_2^f \end{pmatrix} = g \begin{pmatrix} \tau^i \\ \tau^o \\ T \end{pmatrix}$$

and furthermore

$$\frac{\partial g}{\partial \tau} = -[J_{f,y}(\tau, g(\tau))]^{-1} \frac{\partial f}{\partial \tau}$$

Evaluating the expressions for $\frac{\partial x^f}{\partial \tau}$ and $\frac{\partial v_2^f}{\partial \tau}$ proves the lemma. $\square$

Proof. Proof of Proposition 1, 2, and 3

The optimal investment and output subsidies for a given T are derived from the first order conditions from equation 2. Taking the derivatives and setting $\lambda = 1$, τ^{o*} and τ^{i*} are defined by the following equations:

$$\tau^{o*} = \frac{\gamma \frac{\mathrm{d}Q}{\mathrm{d}\tau^o}}{T \frac{\mathrm{d}q(x^f, v_1^f)}{\mathrm{d}\tau^o}} - \tau^i \frac{\frac{\partial x^f}{\partial \tau^o}}{T \frac{\mathrm{d}q(x^f, v_1^f)}{\mathrm{d}\tau^o}} \tag{6}$$

$$\tau^{i*} = \frac{\gamma \frac{\mathrm{d}Q}{\mathrm{d}\tau^i}}{\frac{\partial x^f}{\partial \tau^i}} - \tau^o \frac{T \frac{\mathrm{d}q(x^f, v_1^f)}{\mathrm{d}\tau^i}}{c \frac{\partial x^f}{\partial \tau^i}} \tag{7}$$

Setting $\tau^o = 0$ and $T = 0$ in equation 7 and simplifying proves Proposition 1. Setting $\tau^i = 0$ in equation 6 and simplifying proves Proposition 2.

To prove Proposition 3, substitute 6 into 7 and rearrange for τ^i:

$$\tau^{i*} = \gamma \left(\frac{\frac{\mathrm{d}Q}{\mathrm{d}\tau^i} \frac{\mathrm{d}q(x^f, v_1^f)}{\mathrm{d}\tau^o} - \frac{\mathrm{d}Q}{\mathrm{d}\tau^o} \frac{\mathrm{d}q(x^f, v_1^f)}{\mathrm{d}\tau^i}}{\frac{\partial x^f}{\partial \tau^i} \frac{\mathrm{d}q(x^f, v_1^f)}{\mathrm{d}\tau^o} - \frac{\partial x^f}{\partial \tau^o} \frac{\mathrm{d}q(x^f, v_1^f)}{\mathrm{d}\tau^i}} \right)$$

Expanding, cancelling terms and using Lemma 3 to further simplify leads to the following:

$$\tau^{i*} = \gamma \frac{(1-T)\Big(q_v(v_1^f) q_x(v_1^f) [\frac{\partial v_1}{\partial \tau^o} \frac{\partial x}{\partial \tau^i} - \frac{\partial v_1^f}{\partial \tau^i} \frac{\partial x}{\partial \tau^o}] + q_v(v_1^f) q_v(v_2^f) [\frac{\partial v_1}{\partial \tau^o} \frac{\partial v_2^f}{\partial \tau^i} - \frac{\partial v_1^f}{\partial \tau^i} \frac{\partial v_2^f}{\partial \tau^o}] \Big)}{q_v(v_1^f) [\frac{\partial v_1}{\partial \tau^o} \frac{\partial x}{\partial \tau^i} - \frac{\partial v_1^f}{\partial \tau^i} \frac{\partial x}{\partial \tau^o}]}$$

Using Lemma 3 to simplify further leads to the following final expression:

$$\tau^{i*} = \gamma \frac{(1-T)\frac{\mathrm{d}q(v_2^f)}{\mathrm{d}\tau^i}}{\frac{\partial x}{\partial \tau^i}} \tag{8}$$

To solve for τ^{o*}, substitute equation 8 into equation 6:

$$\tau^{o*} = \frac{\gamma}{T} \frac{\frac{\mathrm{d}Q}{\mathrm{d}\tau^o}\frac{\partial x^f}{\partial \tau^o} - (1-T)\frac{\partial x^f}{\partial \tau^o}\frac{\mathrm{d}q(v_2^f)}{\mathrm{d}\tau^i}}{\frac{\mathrm{d}q(v_1^f)}{\mathrm{d}\tau^o}\frac{\partial x^f}{\partial \tau^i}}$$

Again expanding $\frac{\mathrm{d}Q}{\mathrm{d}\tau^o}$, cancelling terms and simplifying with Lemma 3 gives the final result

$$\tau^{o*} = \frac{\gamma}{T} \frac{T\frac{\mathrm{d}q(v_1^f)}{\mathrm{d}\tau^o}\frac{\partial x^f}{\partial \tau^i}}{\frac{\mathrm{d}q(v_1^f)}{\mathrm{d}\tau^o}\frac{\partial x^f}{\partial \tau^i}} = \gamma$$

□

Proof. Proof of Proposition 4 Interior Solution

The optimal subsidy duration, T, is found by differentiating equation 2 with respect to T. Setting $\lambda = 1$, the first order condition is

$$\begin{aligned}\frac{\partial W}{\partial T} =& q(x^f, v_1^f) - q(x^f, v_2^f) - m(v_1 - v_2) + \gamma\Big(q(x^f, v_1^f) - q(x^f, v_2^f)\Big) + \\ & \gamma\Big(T\frac{\mathrm{d}q(x^f, v_1^f)}{\mathrm{d}T} + (1-T)\frac{\mathrm{d}q(x^f, v_2^f)}{\mathrm{d}T}\Big) - \frac{\partial x^f}{\partial T}\tau^{i*} - T\tau^{o*}\frac{\mathrm{d}q(x^f, v_1^f)}{\mathrm{d}T}\end{aligned}$$

Using the expressions for τ^{i*} and τ^{o*} from Proposition 3 and the result from Lemma 3 to simplify $\frac{\partial x^f}{\partial T}\tau^{i*}$ the first order condition becomes

$$\frac{\partial W}{\partial T} = -(\Delta q - m\Delta v) - \gamma\Delta q - \phi'(T)$$

Here $\Delta q = q(x^f, v_2^f) - q(x^f, v_1^f)$ is used to denote the change in output at the end of the output subsidy resulting from a change in the variable input $\Delta v = v_2 - v_1$.

For small changes in v, we can Taylor expand $q(x, v_1^f)$ around $q(x, v_2^f)$. This leads to $\Delta q = \Delta v q_v(x^f, v_2^f) = m\Delta v$. The first order condition therefore simplifies further and the optimal T is defined by

$$\phi'(T) = \gamma \Delta q$$

□

Proof. Sufficient Conditions for Uniqueness and Corner Solutions for Proposition 4

Proposition 4 provides a unique solution if $\frac{\partial^2 W}{\partial T^2} < 0 \; \forall T \in [0,1]$.

$$\frac{\partial^2 W}{\partial T^2} = \gamma \frac{\partial \Delta q}{\partial T} - \phi''(T)$$

By assumption ϕ is convex so $\frac{\partial \Delta q}{\partial T} \leq 0$ is a sufficient condition for a unique solution.

$$\begin{aligned}\frac{\partial \Delta q}{\partial T} =& \frac{\partial q(x, v_1)}{\partial T} - \frac{\partial q(x, v_2)}{\partial T} = q_x(x, v_1)\frac{\partial X}{\partial T} + q_v(x, v_1)\frac{\partial v_1}{\partial T} - \Big(q_x(x, v_2)\frac{\partial X}{\partial T} + q_v(x, v_2)\frac{\partial v_2}{\partial T}\Big) \\ =& \Big(q_x(x, v_1) - q_x(x, v_2)\Big)\frac{\partial X}{\partial T} + q_v(x, v_1)\frac{\partial v_1}{\partial T} - q_v(x, v_2)\frac{\partial v_2}{\partial T}\end{aligned}$$

For small changes in v we can use the following Taylor expansions of $q_v(x^f, v_1^f)$ and $q_x(x^f, v_1^f)$ around (x^f, v_2^f):

$$\begin{aligned} q_v(x^f, v_1^f) &\approx q_v(x^f, v_2^f) - \Delta v \, q_{vv}(x^f, v_2^f) \\ q_x(x^f, v_1^f) &\approx q_x(x^f, v_2^f) - \Delta v \, q_{xv}(x^f, v_2^f) \end{aligned}$$

Using the firm's first order conditions and the Taylor expansion of q_v, we find that

$$\Delta v = -\frac{m\tau^o}{q_{vv}(x^f, v_2^f)(1+\tau^o)}$$

Therefore, if q_v is locally linear then Δv does not depend on T and $\frac{\partial v_1}{\partial T} = \frac{\partial v_2}{\partial T}$. Using the implicit definitions of v_1 and v_2, as well as the Taylor expansion of $q_x(x, v_1)$, the expression simplifies to

$$\frac{\partial \Delta q}{\partial T} = -q_{xv}(x^f, v_2^f)\Delta v \frac{\partial X}{\partial T} - \frac{m\tau^o}{1+\tau^o}\frac{\partial v_2}{\partial T}$$

Substituting in the expression for Δv and using lemma 3 the above expression cancels out and we are left with $\frac{\partial \Delta q}{\partial T} = 0$. We are then left with $\frac{\partial^2 W}{\partial T^2} = -\phi''(T)$ which is negative for all T and therefore the solution in Proposition 4 is unique. $\square$

C. Cobb Douglass Solution - For Online Publication

Consider a firm that makes an investment in capital and chooses variable inputs to produce an output. The firm produces according to a production function $q(x, v)$ where the quantity produced q is increasing in both the capital stock x and the variable input v. Output is sold in a competitive market with price normalized to one and variable inputs and capital are purchased in competitive factor markets with prices c and m respectively.

$$\pi = T\left(x^a v_1^b(1+\tau^o) - mv_1\right) + (1-T)\left(x^a v_2^b - mv_2\right) - (c-\tau^i)x$$

Firm First Order conditions:

$$\begin{aligned}
\frac{\partial \pi}{\partial x} &: \frac{a}{x^{1-a}}\left(Tv_1^b(1+\tau^o) + (1-T)v_2^b\right) = c - \tau^i) \\
\frac{\partial \pi}{\partial v_1} &: \frac{b}{v_1^{1-b}}\left(x^a(1+\tau^o)\right) = m \\
\frac{\partial \pi}{\partial v_2} &: \frac{b}{v_2^{1-b}}x^a = m
\end{aligned}$$

We use these FOC to solve for the choice variable as functions of primitives and policy:

$$\begin{aligned}
x^* &= \left[\frac{a}{c-\tau^i}\left(\frac{b}{m}\right)^{\frac{b}{1-b}}\left(T(1+\tau^o)^{\frac{1}{1-b}} + (1-T)\right)\right]^{\frac{1-b}{1-a-b}} \\
v_1^* &= \left(\left(\frac{b}{m}\right)^{1-a}\left[\frac{a}{c-\tau^i}\left(T(1+\tau^o)^{\frac{1}{1-b}} + (1-T)\right)\right]^a\right)^{\frac{1}{1-a-b}}(1+\tau^o)^{\frac{1}{1-b}} \\
v_2^* &= \left(\left(\frac{b}{m}\right)^{1-a}\left[\frac{a}{c-\tau^i}\left(T(1+\tau^o)^{\frac{1}{1-b}} + (1-T)\right)\right]^a\right)^{\frac{1}{1-a-b}}
\end{aligned}$$

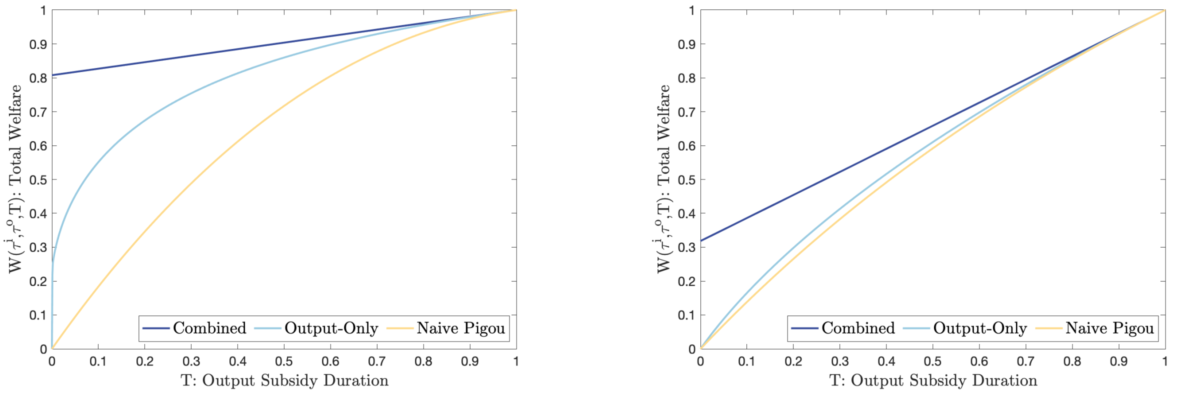
Letting $\mathcal{W} = \pi + \gamma\left[T\left(x^a v_1^b\right) + (1-T)\left(x^a v_2^b\right)\right] - \lambda(\tau^i x + \tau^o T x^a v_1^b) - \phi(T)$; plugging in x, v_1, and v_2; differentiating; and combining FOC yields

$$\begin{aligned}
\tau^{o} &= \gamma \\
\tau^{i} &= \gamma(1-T)\frac{c}{(1+\gamma-b)(1-T)+(1-b)T(1+\gamma)^{\frac{1}{1-b}}} \\
\phi'(T) &= (1+\gamma)\,\frac{(1+\gamma)^{\frac{b}{1-b}}-1}{(1+\gamma)^{\frac{1}{1-b}}-1}-b
\end{aligned}$$

Noting that this solution is unapproximated and not exactly equal to $\gamma\Delta q$ as second order terms lead to slight differences from Proposition 4.

D. Appendix Tables and Figures - For Online Publication

Figure D.1: Welfare Losses from Sub-Optimal Policies - Lower Returns to Scale



(a) Fixed-Input Intensive Production

(b) Variable-Input Intensive Production

Note: This figure shows what percent of total welfare is lost from suboptimal policy. The allocation under first-best, Pigouvian policy is normalized to one and the competitive (unsubsidized) allocation is normalized to zero. Three policies are plotted: (1) a (second-best) combined subsidy that chooses τ^i and τ^o given T, (2) an output-only subsidy that chooses τ^o optimally given T and $\tau^i = 0$, and (3) a naive Pigouvian policy that chooses $\tau^o = \gamma$ and $\tau^i = 0$ for every value of T. Results from a Cobb-Douglas calibration $q_t = x^a v^b$. Calibrated values: $(a, b) \in \{(0.3, 0.1), (0.1, 0.3)\}$, $c = 0.5$, $m = 0.2$, and $\gamma = 0.5$.

Table D.1: Estimates of Changes in Production after the Subsidy Period

Panel A: Main Effects	Capacity Factor	Net Generation (MWh)	Exit: $\mathbb{1}$(Net Generation = 0)
Overall Effect	-2.32	-1072	0.00
	(0.67)	(388)	(0.01)
Short-Term (Years 11-12)	-1.45	-733	0.00
	(0.54)	(352)	(0.00)
Long-Term (Years 13-15)	-3.16	-1405	0.00
	(0.87)	(492)	(0.01)
Average in Year 10	31.3	16,858	0.02

Panel B: Heterogeneity by Vintage	2002-2006	2007-2008	2009-2001
Short-Term (Years 11-12)	-1.63	-0.54	-1.20
	(1.12)	(0.61)	(0.63)
Average in Year 10	32.4	32.0	29.1

Panel C: Effect Heterogeneity	1603 Firms (Placebo)	Low Price	High Price
Overall Effect	-	-2.37	-2.32
		(1.03)	(0.51)
Short-Term (Years 11-12)	-0.33	-1.97	-1.09
	(0.44)	(0.87)	(0.40)
Long-Term (Years 13-15)	-	-2.73	-3.65
		(1.23)	(0.77)
Average in Year 10	28.2	32.0	30.7

Note: This table reports estimates from event study analyses of the end of PTC eligibility after the ten-year time limit. All estimates are weighted averages of event-coefficients relative to the 120th month of production. Panel A reports the main results across three different measures of production, the capacity factor, net generation, and an indicator for whether there was zero production in a given month (a measure of exit). Panel B reports the differences in short-term effects between older and newer facilities (began production in 2002-2006 versus 20017-2008 versus 2009-2011). Panel C reports placebo and heterogeneity tests, including wind firms that elected to receive the 1603 investment grant and were therefore not eligible for a PTC, and separately by firms who receive lower and higher average wholesale prices. For all regressions standard errors are two-way cluster corrected for arbitrary variance-covariance structure at the facility level and month-of-year level. All regressions control for facility and state-by-month-by-year fixed effects.
$^{+}p < 0.10$, $*p < 0.05$, $**p < 0.01$.