Learning-by-Doing and Green Subsidies

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Overview

Learning-by-doing is often used to justify green subsidies.[1] However, the theoretical relationship between learning-by-doing and optimal green subsidy design has not been formally characterized. This paper seeks to fill that gap.

Arrow (1962) established the theoretical importance of learning-by-doing (LBD) for economic growth. Subsequent work by Spence (1981) and Fudenberg and Tirole (1983) examined the relationship between LBD and market structure, and Petrakis et al. (1997) demonstrated that under perfect competition and sensible marginal cost functional forms, the existence of *proprietary* LBD does not warrant government intervention. Ghemawat and Spence (1985) showed that if learning spills over across product market rivals, the market may underinvest in production early on, with the potential for the government to increase welfare with targeted subsidies.

In this paper, we extend this IO theory literature to incorporate unpriced product market externalities. Our motivating example is the green energy sector, where the social marginal benefit of production exceeds the private marginal benefit due to unpriced environmental externalities from dirty energy production.[2] Using a two-period model, we characterize the optimal green subsidy in the presence of learning-by-doing, and relate it to a "Pigouvian" subsidy equal to the marginal external benefit of consumption. We then show how that subsidy level varies with market structure, the rate of learning, and the presence of spillovers.

Having characterized the optimal green subsidy based on these primitives, we then discuss the implications of these findings for important green industries. A burgeoning empirical literature has estimated the magnitude of learning-by-doing and spillovers in the solar industry (Bradt, 2025; Bollinger and Gillingham, 2026), EV batteries (Barwick et al., 2025), and wind turbines (Covert and Sweeney, 2026). We discuss the magnitudes estimated and counterfactual results in that work, and place them in the context of our theoretical framework. We also summarize the market structure and subsidy levels in these and other important green industries, such as geothermal and green hydrogen.

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[1] Examples include the Inflation Reduction Act and the California Solar Initiative (Council of Economic Advisers, 2024; California Public Utilities Commission, 2006).

[2] Subsidies for green substitutes can never achieve the first best, which would be a Pigouvian tax on dirty energy. See Sallee (2025) for a thorough discussion. In this paper, we abstract from this complication and assume a known constant marginal external benefit from consuming the green good.

Preliminary results

We adopt the two-period, subgame perfect equilibrium framework of Fudenberg and Tirole (1983). Symmetric firms face linear inverse demand curve $P(Q) = a - bQ$ in each period and compete simultaneously in quantities. Consumption generates a constant marginal external benefit e in both periods. The government sets per-unit output subsidies s_1 and s_2 to maximize discounted welfare, with discount factor $\beta < 1$. We consider two notions of market structure. Under free entry, firms observe the subsidy levels, pay a fixed entry cost F prior to period 1, and enter until discounted profits equal F. Under fixed entry, the number of firms is fixed exogenously prior to the announcement of the subsidy levels. Firm i's cost of producing q in period 1 is $cq + \frac{\kappa}{2}q^2$. The convex term ($\kappa > 0$) reflects capacity constraints and keeps learning from driving the industry to monopoly (Petrakis et al., 1997). Learning-by-doing lowers the intercept of marginal cost in period 2:

$$c_{i2} = c - \alpha q_{i1} - \gamma \sum_{j \neq i} q_{j1},$$

where α is the rate at which a firm learns from its own production and γ is the rate at which it learns from its rivals' production.[3]

We begin under the assumption that learning is proprietary ($\gamma = 0$), so a firm captures the full value of its own experience. Petrakis et al. (1997) show that price-taking firms fully internalize this value. With an externality, the optimal subsidy for price-taking firms is therefore exactly Pigouvian ($s_1 = s_2 = e$). Cournot competition adds two distortions, markups and strategic investment in experience (Fudenberg and Tirole, 1983). Under free entry, however, an output subsidy cannot correct them. A subsidy above e raises per-firm profits, which attracts entry until profits are back to F, and Cournot markets with fixed costs already attract too many firms (Mankiw and Whinston, 1986). To show this, we vary market structure by changing the entry cost F.[4] Figure 1A shows that under free entry (blue lines), even with a substantial rate of learning ($\alpha = 0.3$), the optimal subsidy is essentially Pigouvian at every level of competition. Thus, under free entry proprietary learning-by-doing does not provide a rationale for subsidies above e.

We then introduce spillovers. Each unit a firm produces lowers its rivals' future costs. This creates an appropriability problem (Ghemawat and Spence, 1985). Figure 1B plots the optimal subsidies against market structure for a substantial spillover rate ($\gamma = 0.2$). Under free entry the mature subsidy stays at Pigou, while the early subsidy rises well above it: from $1.5e$ with two laissez-faire firms to $1.8e$ with 10 and $1.9e$ with 50. The premium grows with competition because the more firms there are, the larger the share of each firm's cost reduction that comes from rivals' experience. Decomposing the optimal subsidy shows that the premium is mostly the technological spillover $\beta(n-1)\gamma q_2$, the value of a firm's early output in lowering its rivals' future costs (81% of the premium with two laissez-faire firms and 95% with 10). As without spillovers, entry offsets the markup correction almost one

[3]The results below use $a = b = 1$, $c = 0.7$, $\kappa = 1$, $\beta = 0.9$ and $e = 0.1$, so the external benefit is about 14% of marginal cost, and report subsidies as multiples of Pigou, s_t/e. The learning premium described below does not scale with e, so these multiples are larger when the externality is small relative to costs.

[4]In the free entry case, scenarios are indexed by the "laissez-faire number of firms" – the number of firms that would be in the market without any subsidy (which falls as F rises).

for one. As the entry cost vanishes, the early subsidy converges to the competitive spillover subsidy $e + \beta\gamma Q_2$, where Q_2 is mature-period industry output.

If instead the number of firms is fixed (for example because subsidies are announced after firms have already entered), the optimal subsidy must also correct the Cournot market-power distortion. With n firms the optimal subsidies are

$$s_2^* = e + bq_2, \qquad s_1^* = e + bq_1 + \beta q_2\big[(n-1)\gamma + \sigma\gamma - \theta\alpha\big],$$

evaluated at the target outputs q_t. Here bq_t offsets the Cournot markup, and $\sigma, \theta > 0$ are small strategic terms: firms underinvest in experience that helps their rivals and overinvest in their own experience to commit to lower costs. With few firms the markup correction dominates. With two firms the optimal subsidies are $2.9e$ and $2.6e$, and even with proprietary learning they are 2.4–2.5e (Figure 1). Under fixed entry the subsidy therefore falls with competition, the opposite of the free-entry pattern, and the two regimes converge as the number of firms grows (an early subsidy of $1.97e$ versus $1.87e$ with 50 firms).

Figure 2 shows how the optimal subsidies vary with the spillover rate and with the overall rate of learning in markets with 2, 10 and 50 laissez-faire firms. In the left column we raise the spillover rate from proprietary learning ($\gamma = 0$) to complete diffusion ($\gamma = \alpha$), holding own learning at $\alpha = 0.3$. In the right column we raise the learning rate α while holding fixed the share of learning that spills over ($\gamma = 2\alpha/3$). Under free entry (top row), the mature subsidy stays within 10% of Pigou throughout, and all of the variation is in the early subsidy. The early subsidy rises steeply with the spillover rate. With 10 firms it is $0.99e$ with proprietary learning, $1.34e$ at $\gamma = 0.1$, $1.77e$ at $\gamma = 0.2$ and $2.31e$ at complete diffusion, and it is higher in more competitive markets. It rises in the same way with the learning rate, from exactly Pigou with no learning to $1.8e$ at the baseline and $3.0e$ when the learning rate doubles (with 10 firms, unit costs then fall by 13% and 32%). The extent that the overall learning rate matters is driven by the spillover channel. Raising own learning from 0.3 to 0.45 with γ held at 0.3 leaves the early subsidy unchanged, at $2.31e$. Under fixed entry (bottom row), the same spillover premium comes on top of the market-power correction, which raises both subsidies and is largest with few firms.

Taken together, these results suggest that the existence of learning-by-doing alone does not justify green subsidies exceeding the Pigouvian level. Additional subsidies are only justified by knowledge spillovers, or by standard market-power considerations in the case of fixed entry.

Planned extensions

Future work will extend the model to consider curved demand, growing demand, exogenous technological change, differentiated products and exponential learning. We will also eschew the two-period framework and model competition as a multi-period dynamic game, which will allow for more realistic learning dynamics and the possibility of exit (Besanko et al., 2010, 2014).

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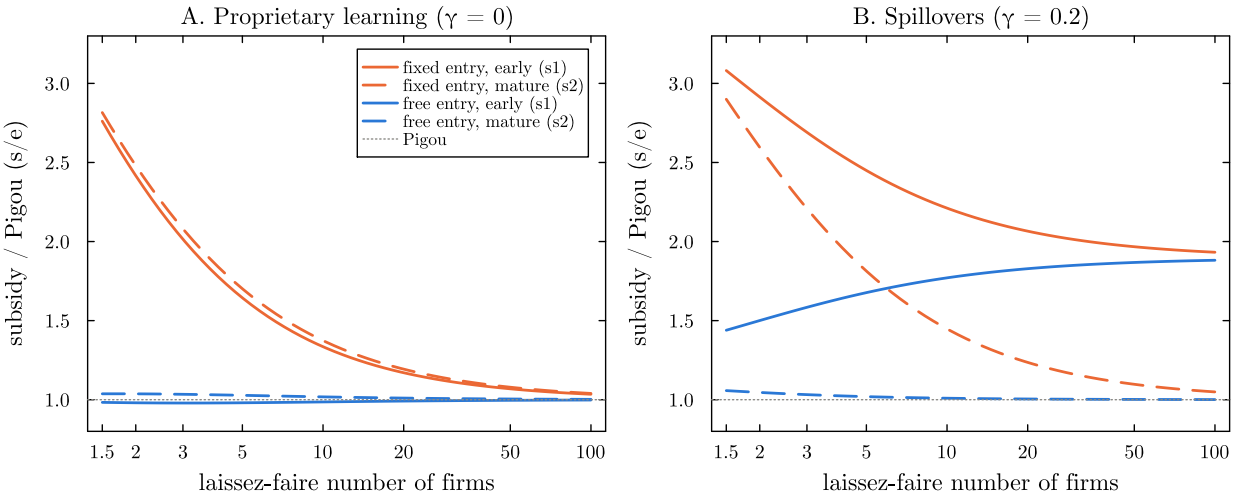


Figure 1: Optimal subsidies relative to e versus market structure. The horizontal axis is the number of firms that would be in the market without any subsidy. Under free entry, firms anticipate the subsidy and the number of competitors in the market adjusts.

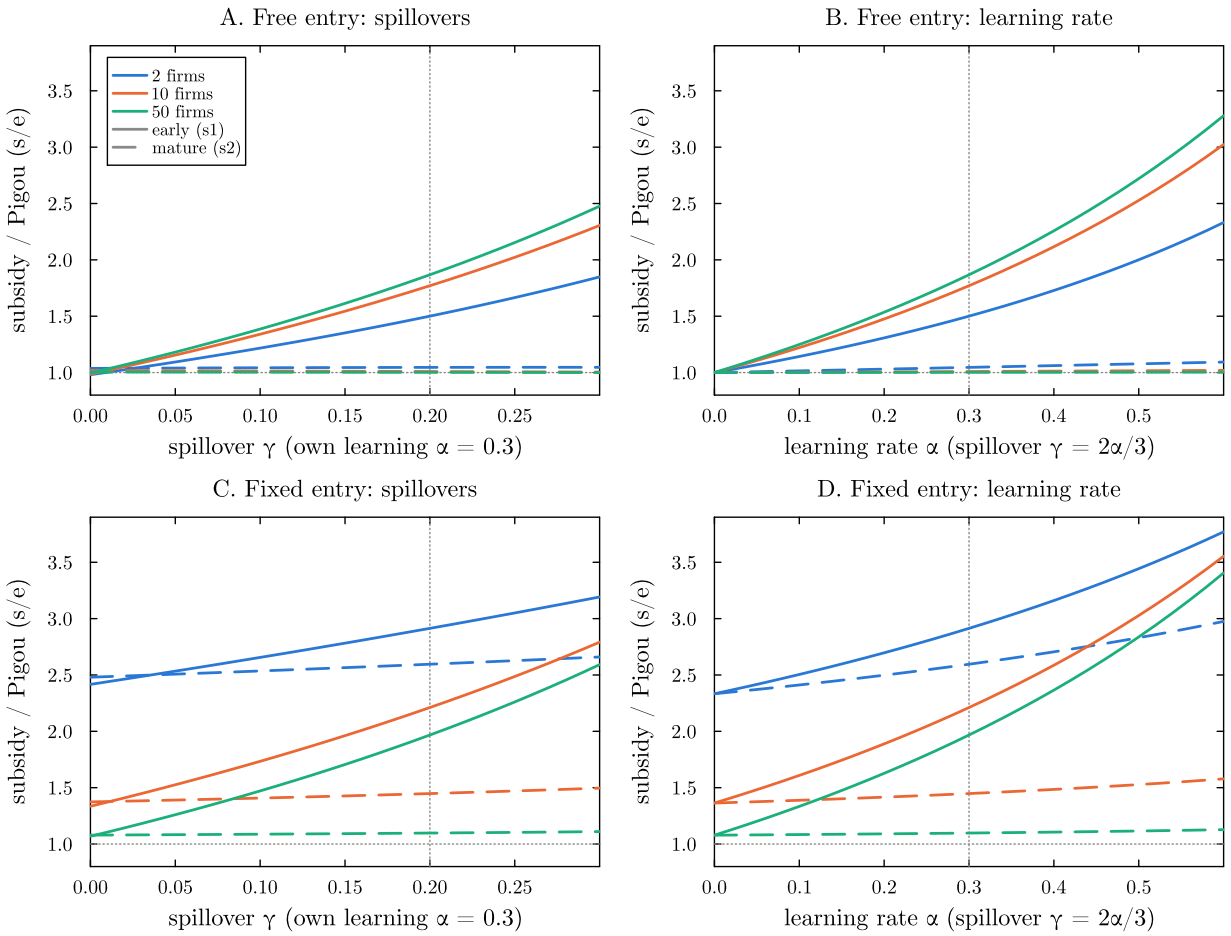


Figure 2: Optimal early (solid) and mature (dashed) subsidies relative to e in markets with 2, 10 and 50 firms. Left: spillover rate γ from proprietary learning to complete diffusion ($\gamma = \alpha$), with $\alpha = 0.3$. Right: learning rate α with a fixed spillover share, $\gamma = 2\alpha/3$. Dotted vertical lines mark the baseline ($\alpha = 0.3$, $\gamma = 0.2$).