FUELING ENERGY TRANSITION: CAPITAL DYNAMICS FROM ENERGY SUPPLY TO MANUFACTURING SECTORS

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Abstract. This paper examines how the interaction between manufacturing firms and electricity producers shapes the cost and incidence of decarbonization. We develop a two-sector framework in which manufacturers choose between purchased electricity and on-site clean generation, while the electricity sector produces power using clean and dirty capital. This make-or-buy margin allows climate policy to reallocate clean investment across sectors. The results show that the value of self-generation depends on the electricity market structure. Under perfect competition, self-generation lowers welfare in the calibrated economy, but reduces dirty electricity capital by about 12 percent, corresponding to roughly 79 million tonnes of CO_2 under a proportional emissions mapping. Under monopoly, it improves welfare by giving manufacturers an outside option against high electricity prices and limiting price pass-through. Carbon taxes reduce dirty capital and induce anticipatory investment, while clean-capital subsidies expand clean capacity but require household financing. The analysis highlights electricity sourcing as a key margin through which climate policy affects prices, investment, and welfare. **JEL:** Q41, Q58, D24, O33.

Keywords: Carbon taxation, electricity market, self-generation, capital reallocation, general equilibrium.

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1. Introduction

The decarbonization of energy systems is among the defining economic challenges of the twenty-first century. Besides innovation in clean technologies, the transition is fundamentally a problem of capital reallocation: fossil-based ("dirty") capital must be retired and replaced by clean capital, a process that is costly, slow, and exposed to policy risk. A large literature studies how this reallocation, the substitution between dirty and clean energy, and the resulting stranded-asset dynamics shape the transition path and the associated policy trade-offs (Campiglio et al., 2022; Jo, 2025; Jo and Miftakhova, 2024; van der Ploeg and Rezai, 2020; Van der Ploeg and Rezai, 2020, among others). Yet most of this work is cast in a single-sector, two-technology framework, in which capital shifts from dirty to clean technologies within one representative producer.

This aggregation conflates two activities that decarbonize very differently: the production of electricity and its use in manufacturing. The electricity sector holds a large stock of long-lived fossil capital and decarbonizes by reallocating investment from dirty to clean generation; under carbon pricing it is the natural locus of capital inertia and stranded-asset risk. Manufacturers, by contrast, decarbonize partly by changing how they source energy, and are exposed to climate policy through the pass-through of policy into electricity prices and supply conditions. Collapsing the two sectors into a single producer therefore obscures both the channel through which policy reaches industrial firms—the price of electricity—and the margins along which those firms respond.

One of these margins has become increasingly important: rather than purchasing all of their electricity from the grid, manufacturers can generate part of it on site, effectively facing a *make-or-buy* decision for clean power. This is no longer a theoretical possibility. Industrial self-generation in Europe rose from roughly 8.6 to 12.3 percent of industrial electricity use between 2012 and 2021, and a growing literature documents the spread of on-site renewable generation in energy-intensive industries such as chemicals, cement, and metals (Kiessling et al., 2024; Walmsley et al., 2023). A related body of work studies behind-the-meter generation in the residential sector and shows that private incentives depend heavily on tariffs, tax incentives, and rebates (Borenstein, 2017); we shift the focus to manufacturing, where firms differ from households in scale, electricity intensity, investment behavior, and exposure to climate policy. The make-or-buy margin matters for the macroeconomics of the transition because it reallocates part of the clean-investment decision from centralized electricity producers to industrial balance sheets.

Standard transition models, by treating manufacturing as a passive electricity demander, abstract from this channel entirely.

This motivates the central question of the paper: how does the manufacturing make-or-buy decision for electricity affect the pace, cost, and incidence of decarbonization? We address it with a two-sector general-equilibrium framework that builds directly on the electricity-sector technology in Papageorgiou et al. (2017). As in their electricity-generating sector, grid electricity is produced from a CES aggregate of clean and dirty electricity capital. We then embed this block in a theoretical general-equilibrium model of manufacturing and allow manufacturers to either buy grid power or self-generate clean electricity on site. A representative manufacturer produces the final good by combining neutral capital and labor with power, where power is a CES composite of grid electricity and clean self-generation. The two sectors are linked through the equilibrium electricity price: climate policy that targets dirty electricity capital raises the price of purchased power, shifts manufacturers' make-or-buy choice toward self-generation, and feeds back into electricity-sector investment and pricing. We solve the model under perfect competition and monopoly, which bracket the degree of market power in electricity supply and isolate how decentralized generation interacts with electricity-sector pricing.

Second, we distinguish four types of capital—neutral manufacturing capital, clean manufacturing capital (e.g., on-site solar PV), dirty electricity capital (e.g., coal and gas plants), and clean electricity capital (e.g., wind and solar farms). This disaggregation lets climate policy reshape the economy's capital composition both within the electricity sector and across the boundary between the two sectors, and it makes the cross-sector incidence of policy—who installs clean capital, and where—an explicit equilibrium object rather than an aggregate residual. On the household side, agents are forward looking and face policy risk: before a carbon tax is implemented they assign positive probability to its future introduction, so anticipation alters savings and investment before any tax is actually paid. We use this structure to study three policy experiments: a carbon tax on dirty electricity capital, distinguishing a stochastic pre-tax anticipation regime from a post-tax regime; and clean-capital subsidies targeted at the electricity sector, at manufacturing, or at both. The model is calibrated to European manufacturing and electricity data, drawing on Eurostat and IRENA, with substitution and technology parameters disciplined by the macro-energy literature; the baseline competitive economy reproduces manufacturing electricity use, output, and wholesale electricity prices of the same order of magnitude as the data, even though these moments are not targeted directly.

Three findings stand out. First, climate policy triggers a joint adjustment of both sectors rather than a within-electricity reallocation alone. A carbon tax on dirty electricity capital reallocates electricity investment toward clean generation and raises the price of purchased electricity; manufacturers respond endogenously by adjusting clean self-generation, which feeds back into electricity demand, prices, and investment incentives. The make-or-buy margin is active both before and after tax implementation: in the anticipation phase, it limits dirty-capital accumulation relative to the no-make-or-buy counterfactual, while in the post-tax steady state it provides an additional adjustment margin. The size and incidence of this response depend on substitution possibilities in generation and in manufacturing energy sourcing. The generation-side elasticity mainly affects reallocation within the electricity sector, whereas the power-aggregation elasticity governs the strength of the cross-sector make-or-buy channel.

Second, the welfare value of the make-or-buy margin depends on the market regime. Under perfect competition, self-generation can be privately optimal but socially costly: because the centralized electricity sector is the more efficient producer, decentralized generation shifts part of production toward a less productive technology and lowers welfare by about two percent in consumption-equivalent terms. It nonetheless reduces reliance on dirty electricity capital—shutting down the margin would raise dirty electricity capital by roughly twelve percent—which, under a proportional mapping to EU power-sector emissions, corresponds to avoided emissions on the order of 79 million tonnes of CO_2. Under monopoly the welfare ranking reverses: self-generation gives manufacturers an outside option against high electricity prices, disciplines the monopolist, raises electricity use, output, and consumption, and substantially reduces the welfare loss from market power. Make-or-buy is therefore neither intrinsically welfare-improving nor welfare-reducing; its value depends on whether it mainly duplicates efficient centralized production or instead relaxes an existing distortion.

Third, taxes and subsidies operate through different margins, and their relative attractiveness depends on the regime and on the policy criterion. The carbon tax reduces dirty capital directly and preserves more steady-state consumption in the competitive economy, whereas clean-capital subsidies expand clean capacity and can raise output by lowering electricity prices, but require a larger investment effort and fiscal resources from households. The sectoral targeting of subsidies also shapes incidence: a subsidy to clean electricity-sector capital mainly expands centralized clean generation, a subsidy to clean manufacturing capital shifts investment toward decentralized self-generation, and a joint subsidy raises total clean capacity but reallocates part of it away from the electricity sector toward manufacturing. The two subsidies are thus complements in expanding clean capacity but partial substitutes in determining where it is installed. Under monopoly, subsidies are particularly effective along the output and electricity-price dimensions because they reduce dirty-capital reliance and relax monopoly under-provision. However, they remain costly in consumption-equivalent welfare terms, so the ranking of instruments depends on whether the objective is dirty-capital reduction, output, consumption, or welfare.

Taken together, these results show that industrial decarbonization cannot be assessed by analyzing the electricity sector in isolation. Manufacturing self-generation is not a residual feature but a general-equilibrium margin that reallocates part of the transition burden from centralized producers to industrial firms, with implications for the pace of decarbonization, the path of electricity prices, and the distribution of transition costs across sectors.

The remainder of the paper is organized as follows. Section 2 reviews the related literature. Section 3 presents the empirical motivation. Section 4 develops the model and Section 5 describes the data and parametrization. Section 6 reports the quantitative results—the baseline steady state, the comparison of market regimes, the role of make-or-buy, the effects of carbon taxation, the clean-capital subsidy experiments, and the sensitivity analysis. Section 7 concludes.

2. Related literature

Our paper sits at the intersection of three broad literatures. The first studies the macroeconomics of climate policy and transition risk, including stranded assets and the valuation of carbon risk. The second analyzes energy as an input in production, the substitution possibilities between clean and dirty energy, and the institutional features of electricity markets that shape firms' energy choices. The third concerns industrial electrification, distributed generation, and self-generation incentives, emphasizing both the technical potential of decentralized clean electricity and the wedges between private and social incentives for behind-the-meter generation.

A first strand concerns optimal policy and transition dynamics in climate-economy models. Classic general-equilibrium analyses characterize how carbon taxes correct the externality and how the burden of the tax propagates through production and consumption, providing a benchmark for welfare and policy comparisons (Golosov et al., 2014). In integrated assessment models, a key challenge is that climate damages and policy interact with macro risks, which matters for welfare-based carbon pricing and the social cost of carbon (Cai and Lontzek, 2019; Carleton et al., 2022; Nordhaus, 2017). Recent contributions emphasize that the transition itself is not frictionless: capital becomes obsolete, reallocation is costly, and policy can generate large transitional dynamics even when long-run allocations are well understood (Campiglio et al., 2022; Fried et al., 2022). Our contribution to this strand is to study transition dynamics in a setting where decarbonization is shaped by sectoral interdependence: climate policy affects electricity producers first but transmits to manufacturers through electricity prices, and manufacturers respond endogenously. By explicitly modeling the make-or-buy margin (self-generation versus procurement) within a two-sector equilibrium framework, we show how manufacturing adjustment feeds back into electricity-sector investment incentives, prices, and the overall pace and cost of the transition.

A second set of papers concerns energy as an input in production and substitution between clean and dirty energy. Macro evidence on substitution elasticities and nested CES structures motivates modelling energy inputs as imperfect substitutes with capital and other factors (Arrow et al., 1961; Kemfert, 1998; Papageorgiou et al., 2017). Recent work emphasizes that the elasticity of substitution between clean and dirty energy may itself be endogenous or non-constant, interacting with directed technical change and policy (Acemoglu et al., 2012; Jo, 2025; Jo and Miftakhova, 2024). This line of research informs our modelling choice to distinguish clean and dirty electricity production technologies and to represent manufacturing power input as an aggregator over purchased electricity and on-site clean capacity. Our contribution is to embed these substitution and sourcing margins in a two-sector equilibrium environment where relative prices are endogenous and policy-induced changes in electricity-sector composition feed back into manufacturers' technology choices. In doing so, we connect micro-level energy substitution and procurement decisions to macro-level transition dynamics and sectoral risk allocation.

Third, our work relates to the literature on industrial electrification, distributed generation, and self-generation incentives. Studies of power-to-heat and the direct electrification potential of industrial heat highlight large technical abatement opportunities but also substantial investment and system-integration needs (Azevedo et al., 2021; Bouckaert et al., 2021; D'Aprile et al., 2020; Madeddu et al., 2020). This engineering and policy literature motivates why the manufacturing sector is a natural place to look for economically significant transition dynamics. At the same time, a related literature on distributed generation and prosumers emphasizes that behind-the-meter generation decisions are shaped by electricity tariffs, net-metering rules, tax incentives, rebates, and the allocation of fixed network costs. In a canonical contribution, Borenstein (2017) shows that the private profitability of residential solar PV depends strongly on retail tariff design and policy incentives, and that private incentives for self-generation need not coincide with social value. More recent work extends this insight to settings with storage, changing rate structures, and broader prosumer adoption. Boampong and Brown (2020) study behind-the-meter rooftop solar and battery storage and show that retail rate design is central for investment incentives, avoided utility costs, and cost-shifting concerns, including for commercial and industrial consumers. Kim et al. (2023) analyzes cross-subsidy effects from residential PV diffusion under net-metering arrangements, while Kerby and Tarekegne (2024) show how state net-metering policies and utility tariff structures shape the economics of residential rooftop solar and storage. More broadly, recent reviews document the expansion of prosumer models and the increasing relevance of decentralized renewable generation in the energy transition (Leal Filho et al., 2024).

Our contribution to this third strand is to shift the focus from residential prosumers and engineering pathways to manufacturing self-generation in general equilibrium. This distinction is important because manufacturing firms are large electricity users, face substantial exposure to electricity prices and reliability constraints, and make capital-intensive investment decisions. The make-or-buy margin in manufacturing is therefore not only a question of private electricity-bill savings. It also affects the allocation of clean and dirty capital, electricity-sector investment incentives, carbon-tax incidence, welfare, and emissions. By embedding self-generation in a two-sector macroeconomic model, we provide an economic-equilibrium counterpart to industrial electrification studies and connect the prosumer literature's private-versus-social incentive wedge to the macroeconomic incidence of decarbonization policy.

3. Empirical Motivation

The paper studies the transition toward net-zero emissions in an economy in which manufacturing firms and electricity producers are distinct yet interdependent. This distinction is empirically important because climate policy affects the electricity sector directly, while manufacturing firms are exposed indirectly through electricity prices, supply conditions, and their own investment choices. The empirical motivation for the model is organized around three modeling choices: the market structure of the electricity sector, including the reduced-form treatment of fixed costs and limited entry; the possibility for manufacturers to self-generate electricity; and the restriction to production processes that can already operate using electricity.

Electricity markets differ in their degree of competitiveness. Some institutional settings remain concentrated and regulated, while others have moved toward competitive generation and retail supply. We therefore study monopoly and perfect competition as two benchmark cases that bound the extent of market power in the electricity supply market. Manufacturing firms are not only passive electricity consumers: they may purchase electricity from the grid or produce it on-site, a decision we refer to as the make-or-buy decision. Finally, the model focuses on low-energy-intensive production processes that can already operate using electricity, allowing us to isolate the electricity-sourcing decision while abstracting from hard-to-abate industrial processes.

3.1. **The Competitiveness Friction in the Electricity Market.**

The degree of competition in electricity supply affects manufacturers' incentives to buy electricity from the grid or produce it on-site. Market power changes the price of purchased electricity and, therefore, the value of self-generation as an outside option. We therefore use cross-market institutional variation to discipline the two benchmark environments studied in the model.

The U.S. electricity sector provides a useful reference point for the monopoly benchmark. Historically, vertically integrated utilities supplied generation, transmission, distribution, and retail service within regulated service territories. Although generation and retail supply have been liberalized in several regions, important parts of the sector remain regulated and concentrated. In particular, transmission and distribution retain natural-monopoly characteristics, while vertically integrated utilities continue to operate in many traditionally regulated regions (Cleary and Palmer, 2022).

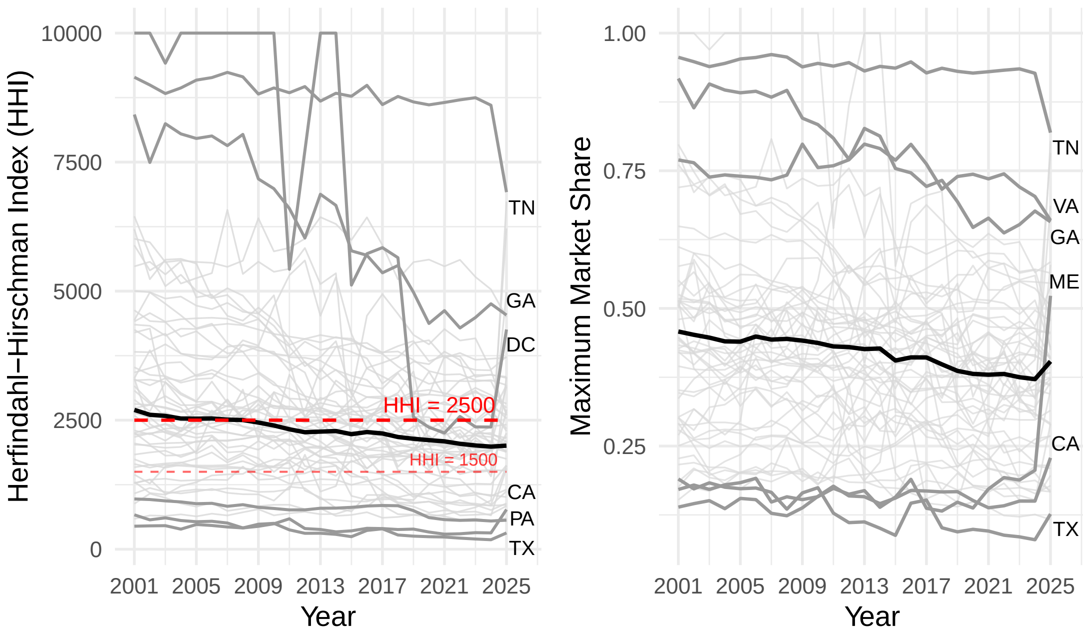

FIGURE 3.1. Competitiveness in the Electricity Generation Market in the United States

Notes: The figure reports two indicators of concentration in U.S. state-level electricity generation markets. The left panel shows the Herfindahl–Hirschman Index (HHI), computed as $HHI_{s,t} = \sum_i q_{i,s,t}^2 \times 10{,}000$, where $q_{i,s,t}$ is operator i's share of net electricity generation in state s and year t. The right panel shows the market share of the largest electricity producer. Grey lines represent individual states, while labeled lines indicate the three highest and three lowest states by their average over the sample period. The black line reports the generation-weighted U.S. average. The dashed red lines indicate the standard HHI thresholds for moderately concentrated markets, $HHI = 1{,}500$, and highly concentrated markets, $HHI = 2{,}500$. Data are from the U.S. Energy Information Administration, Form EIA-923.

Figure 3.1 complements this institutional evidence by documenting concentration in state-level electricity generation markets. The left panel reports the Herfindahl–Hirschman Index computed from operators' shares of net generation, while the right panel reports the market share of the largest producer. The figure shows that many state-level markets remain highly concentrated, with HHI values often above standard concentration thresholds and large dominant-producer shares. We therefore interpret monopoly not as a literal description of the entire U.S. electricity sector, but as a relevant benchmark for concentrated and regulated electricity markets.

The model does not explicitly introduce fixed costs or endogenous entry in electricity generation. Instead, the monopoly benchmark should be interpreted as a reduced-form representation of electricity markets in which high fixed costs, regulatory constraints, and limited entry confer market power on incumbent electricity producers. This interpretation applies to the electricity sector, where generation assets are large-scale and grid access is regulated. By contrast, on-site generation by manufacturers is modeled as a firm-level clean-capital investment margin. Although on-site investments may also be lumpy in practice, they are more modular than utility-scale electricity generation and can be deployed at smaller scales. The make-or-buy margin should therefore be interpreted as manufacturers' ability to partially substitute away from purchased electricity, rather than as entry into the electricity market.

The European electricity market serves as the primary empirical reference for our analysis. Like the United States, Europe combines regulated network infrastructure with potentially competitive generation and retail activities. However, while the U.S. remains institutionally heterogeneous, with many regions retaining vertically integrated utilities and concentrated state-level generation markets, European policy has explicitly pursued an integrated internal electricity market through market opening, third-party access, unbundling, and cross-border integration (European Commission, 2026). This contrast motivates our use of monopoly and perfect competition as benchmark cases, while the paper's European focus leads us to interpret the competitive benchmark as the more relevant long-run reference point.

Consistent with this institutional direction, Figure 3.2 shows that concentration in European electricity generation has declined over time in many countries: the number of firms required to account for 95 percent of generation has increased, while the market share of the largest producer has fallen. This tendency is not uniform: Western European countries generally display lower concentration and a larger number of active producers, whereas several Eastern European countries remain more concentrated. The European market is therefore not perfectly competitive in a literal sense, but the combination of policy design and declining concentration suggests a gradual movement toward a more competitive benchmark.

3.2. **The Manufacturer as an Autoproducer.** Manufacturing firms are not only passive electricity consumers. Figure 3.3 shows that electricity production by autoproducers in the European Union has increased over time and that autoproduction accounts for a rising share of industrial electricity use. This margin remains quantitatively smaller than grid procurement, but it is economically relevant because it changes the allocation of investment, risk, and policy exposure between the electricity sector and manufacturing firms. When firms self-generate, part of the clean-capital investment decision moves from the electricity sector to the manufacturing sector.

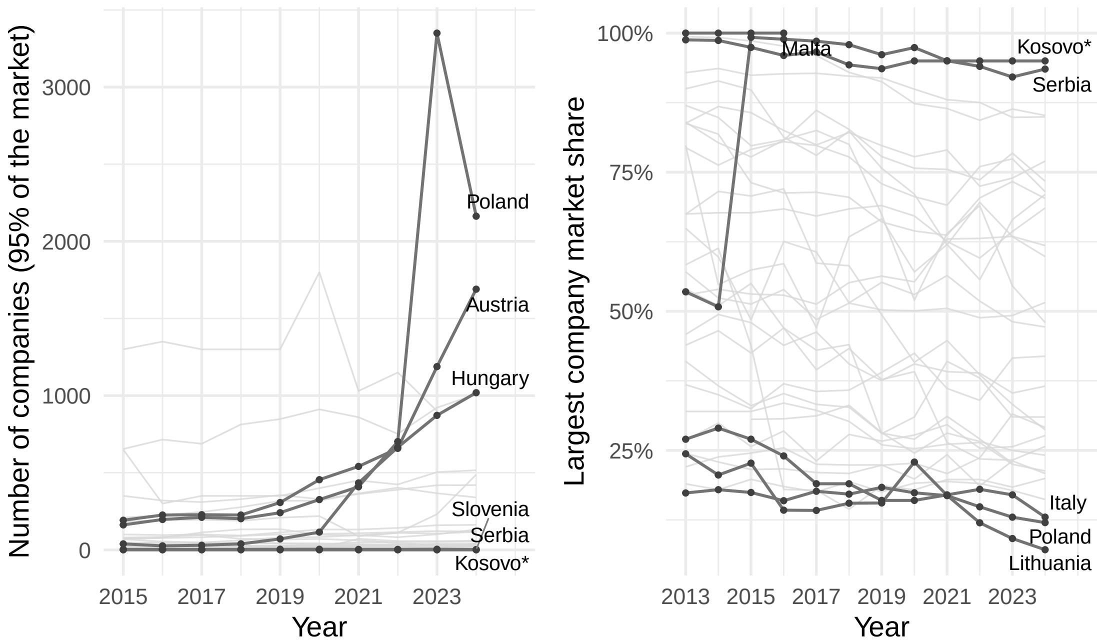

FIGURE 3.2. Competitiveness in the Electricity Generation Market in Europe

Notes: The figure reports two indicators of concentration in the electricity generation market. The left panel shows the number of companies required to account for 95 percent of national electricity generation. The right panel shows the market share of the largest electricity producer. Grey lines represent individual countries, while labeled lines identify the three highest and three lowest countries in the latest available year for each indicator. Data series `nrg_ind_market`. Source: Eurostat, authors' calculations.

This observation motivates the make-or-buy margin in the model. Firms can either buy electricity from the grid or make electricity on-site using decentralized clean technologies. This margin has become increasingly relevant as the costs of distributed generation decline and storage improves, thereby strengthening the substitutability between centralized (i.e., buy) and decentralized (i.e., make) electricity supply. The goal is not to argue that autoproduction is the dominant aggregate channel of industrial decarbonization. Rather, we evaluate whether a rising but still limited self-generation margin changes the incidence of climate policy, the demand for grid electricity, and the incentives for clean investment.

The make-or-buy margin also has a direct interpretation in terms of abatement costs. If manufacturers can only purchase electricity from the grid, emissions reductions must come mainly from changes in the electricity sector's mix of clean and dirty capital. By contrast, on-site clean generation gives manufacturers an additional margin of adjustment: they can reduce their reliance on grid electricity by investing directly in clean capital. This expands the set of available abatement technologies and can flatten the

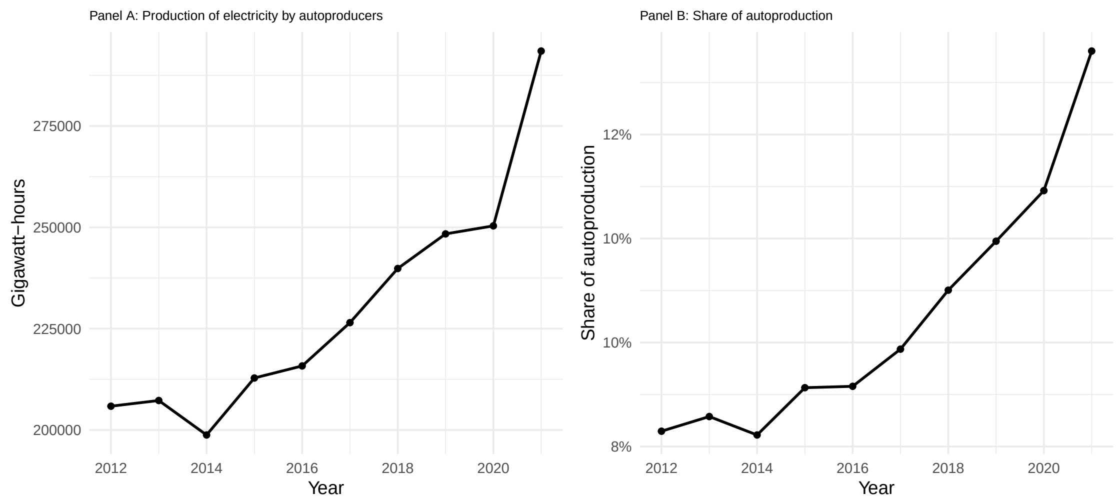

FIGURE 3.3. Electricity Autoproduction in the European Union
Notes: Panel A reports electricity production by autoproducers in the European Union, measured in gigawatt-hours. Panel B reports the share of autoproduction, computed as autoproducers' electricity production divided by final energy consumption in the industrial sector. Data series `nrg_ind_pehap`. Source: Eurostat, authors' calculations.

economy's effective marginal abatement cost curve. We return to this mechanism in the quantitative results, where we compare the tax response with and without make-or-buy.

3.3. **Electrifiable Manufacturing Processes.** Energy use in production is highly heterogeneous across processes, implying markedly different decarbonization pathways across sectors. A large body of work on net-zero energy systems emphasizes that deep decarbonization cannot rely on a single technological margin, but instead requires a combination of electrification, fuel substitution, and carbon management strategies that vary across activities (Davis et al., 2018). In this context, the literature increasingly distinguishes between emissions that are "hard to abate"—for which no cost-effective or energy-efficient alternative to fossil-based production is readily available—and those that can be mitigated through existing technologies. A recent contribution formalizes this distinction by defining hard-to-abate emissions as those for which available abatement options are more costly or more energy-intensive than carbon dioxide removal, implying the persistence of residual emissions even in net-zero scenarios (Dufour-Décieux et al., 2025).

This conceptual distinction is closely related to technological heterogeneity in energy use. Sectoral evidence indicates that direct electrification can already substitute for fossil fuels in a wide range of applications, particularly for low- and medium-temperature processes and modular production activities. By contrast, many industrial processes—such as those that rely on high-temperature heat or involve process emissions—require complementary solutions, including hydrogen, synthetic fuels, or carbon capture (International Renewable Energy Agency, 2024). At a more granular level, this asymmetry reflects the limited substitutability between different types of energy services: while a subset of production tasks can be powered almost exclusively by electricity, others remain structurally dependent on non-electric energy carriers or specific chemical inputs (D'Aprile et al., 2020).

Motivated by this heterogeneity, we restrict attention to low-energy-intensive production processes that can operate entirely with electricity. This restriction abstracts from hard-to-abate activities for which electrification is technologically limited or requires complementary inputs such as hydrogen, synthetic fuels, or carbon capture. It therefore allows the model to isolate the interaction between manufacturing and the electricity sector in settings where clean electricity is already a feasible production input, rather than modeling the broader technological constraints that characterize hard-to-abate industrial decarbonization.

4. Model

We formalize the environment described above in a two-sector vertical economy with a representative household and two production sectors: manufacturing and electricity. The household supplies labor inelastically and rents capital to both sectors. The model is presented in discrete time and has an annual time step t.

4.1. Manufacturing Sector.

The manufacturing sector represents the subset of production activities discussed in Section 3: low-energy-intensive processes that can operate entirely using electricity. The model, therefore, does not describe hard-to-abate industrial activities directly. Instead, it isolates the interaction between manufacturing firms and the electricity sector in settings where electricity is already a feasible production input.

The manufacturing sector produces the final good Y_t using labor N_t, neutral capital $K_t^{n,M}$, and power Pow_t according to

$$Y_t = (A_t N_t)^{1-\nu-\kappa} (K_t^{n,M})^{\nu} Pow_t^{\kappa}. \tag{1}$$

We consider two specifications for the power input.

Make-or-buy. Power is a CES aggregate of purchased electricity E_t and internally produced electricity using clean capital $K_t^{c,M}$:

$$Pow_t = \left[\omega_P (A_t^{c,M} K_t^{c,M})^{\psi_P} + (1-\omega_P) E_t^{\psi_P}\right]^{1/\psi_P}, \tag{2}$$

where the parameter $\omega_P \in (0,1)$ governs the relative importance of internally produced versus purchased electricity. The parameter ψ_P governs substitutability between the two sources of power; with this CES specification, the elasticity of substitution is $\sigma_P = 1/(1-\psi_P)$. The term $A_t^{c,M}$ captures the productivity of clean capital used for on-site electricity generation.

No make-or-buy. Electricity is directly used in production, i.e. $Pow_t = E_t$.

Profit maximization implies that the demand for purchased electricity satisfies

$$P_t^E = \kappa(1-\omega_P)\frac{Y_t}{E_t}\left(\frac{E_t}{Pow_t}\right)^{\psi_P} \tag{3}$$

in the make-or-buy case, and

$$P_t^E = \kappa \frac{Y_t}{E_t}, \tag{4}$$

otherwise. These expressions highlight that the elasticity of substitution between internal and external electricity determines the responsiveness of electricity demand to prices.

4.2. **Electricity Sector.** The electricity sector produces electricity using clean and dirty capital:

$$E_t = \left[\omega_E (A_t^{c,E} K_t^{c,E})^{\psi_E} + (1-\omega_E)(A_t^{d,E} K_t^{d,E})^{\psi_E}\right]^{1/\psi_E}, \tag{5}$$

where the parameter $\omega_E \in (0,1)$ governs the relative contribution of clean and dirty electricity capital. The parameter ψ_E governs substitutability between the two technologies; with this CES specification, the elasticity of substitution is $\sigma_E = 1/(1-\psi_E)$. The terms $A_t^{c,E}$ and $A_t^{d,E}$ capture the productivity of clean and dirty electricity capital, respectively.

We consider two market structures.

Perfect competition. Firms take prices as given, and input choices satisfy standard marginal productivity conditions.

Monopoly. The electricity producer sets the electricity price, taking as given the demand schedule of the manufacturing sector. Let Λ_t denote the marginal cost of producing electricity and let ε_t^E denote the absolute value of the price elasticity of electricity demand. The optimal monopoly price satisfies

$$P_t^E = \mu_t \Lambda_t, \qquad \mu_t = \frac{\varepsilon_t^E}{\varepsilon_t^E - 1}, \tag{6}$$

whenever $\varepsilon_t^E > 1$. The markup is therefore decreasing in the elasticity of electricity demand. The make-or-buy margin affects monopoly pricing because self-generation makes demand for purchased electricity more elastic, limiting the monopolist's ability to raise prices. In the absence of self-generation, demand is less elastic, and the implied markup is higher.

4.3. **Households.** The representative household owns the aggregate capital stock, supplies labor inelastically, and chooses consumption and next-period capital to maximize expected lifetime utility. Let r_t^K denote the rental rate of capital, W_t the wage, Π_t^M and Π_t^E profits from the manufacturing and electricity sectors, and T_t lump-sum transfers of tax revenues. The household budget constraint can be written as

$$C_t + K_{t+1} = W_t + (1 - \delta + r_t^K)K_t + \Pi_t^M + \Pi_t^E + T_t. \tag{7}$$

Households initially live in an economy without a carbon tax, but they know that dirty capital will eventually be taxed. The timing of the tax is uncertain, whereas the tax itself is permanent once implemented.

This uncertainty generates two regimes. Before implementation, the economy is in the pre-tax regime. In this regime, households know that the carbon tax may be introduced next period with probability p^τ and that the economy remains untaxed with probability $1-p^\tau$. They therefore choose consumption and savings while internalizing the possibility of a future transition to the taxed economy. After implementation, the economy enters the post-tax regime and remains there forever.

The household's pre-tax continuation value is therefore an expectation over two possible next-period states. With probability p^τ, the economy moves to the post-tax regime; with probability $1 - p^\tau$, it remains in the pre-tax regime. The household solves

$$V(K) = \max_{\{C,K'\}} \left\{ U(C) + \beta \left[p^\tau V^\tau(K') + (1 - p^\tau)V(K') \right] \right\}, \tag{8}$$

subject to the pre-tax budget constraint.

This forward-looking policy risk modifies the Euler equation because an additional unit of savings has different marginal value depending on whether the tax is implemented next period. The pre-tax Euler equation is

$$U_C(C) = \beta \left[p^\tau U_C(C^{\tau\prime})(1 - \delta + r^{K,\tau\prime}) + (1 - p^\tau) U_C(C')(1 - \delta + r^{K\prime}) \right]. \tag{9}$$

The first term captures the marginal value of savings if the tax is implemented next period, while the second term captures the marginal value of savings if the economy remains untaxed. Thus, the pre-tax allocation is not the same as the no-tax steady state: households adjust current savings in anticipation of a possible future policy change.

Once the tax is implemented, the economy enters the post-tax regime permanently. The household then solves a standard deterministic savings problem,

$$V^\tau(K) = \max_{\{C,K'\}} \{U(C) + \beta V^\tau(K')\}, \tag{10}$$

subject to the post-tax budget constraint. The corresponding Euler equation is

$$U_C(C^\tau) = \beta U_C(C^{\tau\prime})(1 - \delta + r^{K,\tau\prime}). \tag{11}$$

In steady state, this implies

$$1 = \beta(1 - \delta + r^{K,\tau}). \tag{12}$$

The post-tax steady state is therefore identical to the steady state obtained under an unanticipated permanent tax. In both cases, once the tax is in place, the household faces the same post-tax prices, transfers, and continuation problem. The difference between an anticipated and an unanticipated tax lies only in the pre-tax allocation. Under an unanticipated tax, households do not incorporate the future tax into their lifetime optimization prior to its implementation. Under stochastic anticipation, instead, households adjust their pre-tax choices because the post-tax regime enters their expected continuation value with probability p^τ.

4.4. **Market Clearing.** Equilibrium requires that factor markets clear:

$$K_t = K_t^{n,M} + K_t^{c,M} + K_t^{c,E} + K_t^{d,E}, \tag{13}$$

$$N_t = 1. \tag{14}$$

Final-good feasibility requires

$$Y_t = C_t + I_t, \tag{15}$$

where aggregate capital evolves according to

$$K_{t+1} = (1-\delta)K_t + I_t. \tag{16}$$

Equivalently, this can be written as

$$C_t + K_{t+1} = Y_t + (1-\delta)K_t. \tag{17}$$

The carbon tax is modeled as a reduced-form tax on dirty electricity capital. This captures a policy wedge that raises the user cost of fossil-based generation capacity. Tax revenues are rebated in a lump sum to the representative household and are given by

$$T_t = \tau K_t^{d,E}. \tag{18}$$

Full derivations of the firms' and households' optimization problems are provided in Appendix A.1 and Appendix A.2.

5. Data and parametrization

This section describes the model's parametrization. We use two complementary strategies. Some parameters are taken directly from the literature, while others are derived using data. The empirical moments used in the calibration are constructed from Eurostat and IRENA data for the period 2012–2022. Eurostat provides information on electricity generation by source, electricity use, and autoproduction in industry, manufacturing output, and capital stocks. IRENA provides a levelized cost of electricity series, which we use to proxy relative technology-specific electricity prices.

5.1. Electricity sector.

Electricity is produced with clean and dirty electricity capital according to the CES aggregator

$$E_t = \left[\omega_E (A^{c,E} K_t^{c,E})^{\psi_E} + (1-\omega_E)(A^{d,E} K_t^{d,E})^{\psi_E}\right]^{1/\psi_E}. \tag{19}$$

The parametrization of this block follows the macro-energy literature, in particular Papageorgiou et al. (2017), Fried et al. (2022), and Golosov et al. (2014). We set the technology parameters for clean and dirty electricity capital to

$$A^{c,E} = 2.43, \qquad A^{d,E} = 4.72, \tag{20}$$

following Fried et al. (2022). These values imply that, absent policy intervention, dirty electricity capital is more productive than clean electricity capital. This asymmetry captures the idea that fossil-based generation remains relatively efficient in private production terms, even though it generates emissions externalities.

We set the CES share parameter and substitution parameter to

$$\omega_E = 0.4146, \qquad \psi_E = 0.46. \tag{21}$$

The substitution parameter lies within the range reported by Papageorgiou et al. (2017). The implied elasticity of substitution is $1/(1-\psi_E)$, so $\psi_E = 0.46$ corresponds to imperfect but economically meaningful substitution between clean and dirty electricity technologies.

To discipline the share parameter of the electricity CES aggregator, we additionally use the approach in Golosov et al. (2014). The first-order condition for the relative use of dirty and clean electricity inputs implies

$$\frac{p_t^d}{p_t^c} = \frac{1-\omega_E}{\omega_E}\left(\frac{E_t^d}{E_t^c}\right)^{\psi_E - 1}, \tag{22}$$

where p_t^d/p_t^c denotes the relative price of fossil-fuel-based electricity to renewable electricity, and E_t^d/E_t^c denotes the corresponding relative quantities. We proxy technology-specific electricity prices using levelized cost of electricity (LCOE) measures from IRENA. We measure fossil-fuel-based and renewable electricity generation using Eurostat data, and use average values over the calibration period to construct the empirical counterpart of equation (22). This procedure provides a data-based check on the electricity share parameter used in the quantitative model.

5.2. **Manufacturing sector.** The manufacturing sector combines purchased electricity with clean self-generated electricity. Power used in manufacturing is given by

$$Pow_t = \left[\omega_P (A^{c,M} K_t^{c,M})^{\psi_P} + (1-\omega_P)(E_t^{\text{ind}})^{\psi_P}\right]^{1/\psi_P}, \tag{23}$$

where $K_t^{c,M}$ denotes clean manufacturing capital used for on-site electricity generation and E_t^{ind} denotes electricity purchased from the electricity sector.

This specification separates three conceptually distinct objects. The parameter $A^{c,M}$ captures the technical productivity of clean capital used by manufacturers for on-site generation. The share parameter ω_P captures the average empirical importance of self-generation in manufacturing power use. The substitution parameter ψ_P captures how easily manufacturers can substitute self-generated electricity for purchased electricity at the margin. This distinction is useful because the limited role of autoproduction in the data may reflect many firm-level frictions—including installation costs, site constraints, intermittency, financing constraints, contract structures, and the need for reliable grid supply—that are difficult to model separately. We therefore discipline the scale and flexibility of the self-generation margin through ω_P and ψ_P, rather than through a sector-specific productivity penalty.

We set the productivity of clean manufacturing capital equal to the productivity of clean electricity capital,

$$A^{c,M} = A^{c,E}.$$

This assumption isolates the make-or-buy mechanism from differences in the technical efficiency of clean generation technologies. We therefore do not assume that clean capital used by manufacturers for on-site generation is intrinsically more or less productive than clean capital used by the electricity sector. Instead, differences between grid purchases and on-site generation are captured by the CES share parameter ω_P, the substitution parameter ψ_P, and the fact that $K^{c,M}$ enters as a firm-level self-generation choice rather than as electricity-sector capacity.

We calibrate the share parameter ω_P using the same logic as in the electricity sector. In particular, we use the relative first-order condition in equation (22), replacing clean and dirty electricity generation with self-generated and purchased electricity. The empirical ratio of self-generated to purchased electricity is constructed from Eurostat data on industrial autoproduction and industrial electricity use. Since technology-specific prices for self-generated industrial electricity are difficult to observe consistently, we assume that the effective price of self-generated electricity equals the price of purchased electricity. This assumption should be interpreted as a normalization used to discipline the average self-generation share, not as a claim that firm-level costs are identical across electricity-sourcing strategies. Under this normalization, the observed self-generation share implies

$$\omega_P = 0.15.$$

The low value of ω_P reflects the fact that autoproduction remains small relative to grid purchases in the data. In reduced form, it also captures the limited adoption of self-generation induced by installation costs, site constraints, financing constraints, tariffs, and contractual arrangements.

We set the substitution parameter in the manufacturing power aggregator to

$$\psi_P = 0.3.$$

This value implies a lower elasticity of substitution between self-generated and purchased electricity than between clean and dirty technologies in the electricity sector. The assumption captures the idea that manufacturers cannot costlessly replace grid electricity with on-site generation. Self-generation is constrained by available space, intermittency, scale, storage needs, financing, and the match between production schedules and electricity generation. The parameter ψ_P therefore governs the marginal flexibility of the make-or-buy margin: when purchased electricity becomes more expensive, firms can substitute toward self-generation, but only imperfectly. In the results section, we provide sensitivity analysis with respect to both substitution parameters, ψ_E and ψ_P.

Total manufacturing output is produced according to

$$Y_t = (AN_t)^{1-\nu-\kappa}(K_t^{n,M})^{\nu} Pow_t^{\kappa}, \qquad \nu = 0.3, \quad \kappa = 0.04, \quad N_t = 1. \tag{24}$$

We take the capital elasticity ν and the power elasticity κ from the literature, as reported in Table 5.1. Labor is normalized to one. The aggregate manufacturing TFP parameter A is pinned down using Eurostat data on manufacturing output, manufacturing capital, and electricity use in manufacturing. This procedure yields

$$A = 1.3693.$$

The full set of calibrated parameters is reported in Table 5.1.

Calibrated parameter	Symbol	Value	Source
Capital elasticity	ν	0.3	Nordhaus (2017)
Energy elasticity	κ	0.04	Golosov et al. (2014)
IES	γ	1.5	Cai and Lontzek (2019)
Discount factor	β	0.985	Cai and Lontzek (2019)
Depreciation rate	δ	0.1	Cai and Lontzek (2019)
CES coefficient electricity	w_E	0.41	Papageorgiou et al. (2017)
			+ authors' calculation based on Golosov et al. (2014)
CES substitution parameter electricity	ψ_E	0.46	Papageorgiou et al. (2017)
CES coefficient energy	w_P	0.15	authors' calculation based on Golosov et al. (2014)
CES substitution parameter power	ψ_P	0.3	authors' calculation
Global TFP	A	1.37	authors' calculation
TFP dirty capital - electricity	$A^{d,E}$	4.72	Fried et al. (2022)
TFP clean capital - electricity	$A^{c,E}$	2.43	Fried et al. (2022)
TFP clean capital - manufacturer	$A^{c,M}$	2.43	Fried et al. (2022)

TABLE 5.1. Economic parameters

Section 6 reports sensitivity analysis with respect to the substitution parameters in both the electricity sector and the manufacturing power aggregator.

6. Results

The quantitative analysis begins by comparing welfare across the four baseline environments: perfect competition versus monopoly, with and without the make-or-buy margin. This comparison directly measures the welfare cost of electricity-market power and the welfare value of allowing manufacturers to self-generate electricity. We then study how these welfare effects interact with climate policy. In particular, we introduce a tax on dirty electricity capital and interpret the response through the lens of marginal abatement costs. The make-or-buy margin provides an additional abatement channel, as manufacturers can reduce their reliance on grid electricity by investing in clean on-site generation. This channel is especially important under monopoly, where self-generation also serves as an outside option that limits increases in electricity prices. We next compare the carbon tax with clean-capital subsidies targeted either to electricity-sector clean capital, manufacturing self-generation capital, or both. Finally, we conduct a sensitivity analysis with respect to the substitution parameter ψ_P, which governs the ease with which manufacturers substitute self-generated electricity for purchased electricity. Full steady-state tables and additional robustness results are reported in Appendix B.

6.1. **Baseline steady state.** We begin with the baseline steady state: the perfectly competitive economy with the make-or-buy margin and no tax. This is the main empirical benchmark, since European manufacturers both purchase electricity from the grid and, to a lesser but growing extent, produce electricity on-site.

Table 6.1 reports the main allocations. The model implies EUR 5.28 trillion of neutral manufacturing capital and EUR 0.06 trillion of clean manufacturing capital. In the electricity sector, clean capital equals EUR 0.14 trillion, while dirty capital equals EUR 0.50 trillion. Manufacturing purchases 1.30 PWh of electricity from the grid, produces EUR 2.03 trillion of output, and faces an electricity price of EUR 0.06/kWh.

The baseline allocation is broadly consistent with the empirical scale of European manufacturing and electricity markets. Eurostat reports EU industrial electricity consumption of about 0.815 PWh in 2023, while the model implies 1.30 PWh. Eurostat manufacturing value added is approximately EUR 2.5 trillion, compared with EUR 2.03 trillion in the model. The model electricity price of EUR 0.06/kWh, or EUR 60/MWh,

TABLE 6.1. Baseline Steady State: Perfect Competition with Make-or-Buy

Variable	Description	Baseline value
$K^{n,M}$	Neutral manufacturing capital, trillion EUR	5.28
$K^{c,M}$	Clean manufacturing capital, trillion EUR	0.06
$K^{c,E}$	Clean electricity capital, trillion EUR	0.14
$K^{d,E}$	Dirty electricity capital, trillion EUR	0.50
E	Electricity purchased by manufacturing, PWh	1.30
Y	Manufacturing output, trillion EUR	2.03
P^E	Electricity price, EUR/kWh	0.06

is below the 2023 EU day-ahead average of roughly EUR 93/MWh but close to the post-crisis wholesale range, with average day-ahead prices around EUR 75/MWh in 2024.

Overall, the baseline reproduces the relevant order of magnitude for electricity use, manufacturing output, and wholesale electricity prices. It also captures the central capital pattern of the model: a large stock of neutral manufacturing capital, a small but positive stock of clean self-generation capital, and an electricity sector that remains more intensive in dirty than in clean capital. This provides the benchmark against which we evaluate taxes, subsidies, and alternative market structures.

6.2. **Market power and the make-or-buy margin.** We first isolate the roles of electricity-market structure and manufacturing self-generation before introducing climate policy. This comparison is useful because the make-or-buy margin has different effects depending on whether purchased electricity is competitively priced or distorted by market power. Under perfect competition, purchased electricity is already supplied at marginal cost. Under monopoly, purchased electricity is expensive and scarce, so self-generation provides manufacturers with an outside option against high electricity prices.

Table 6.2 reports the corresponding no-tax steady states. Welfare is expressed as a consumption-equivalent change relative to the competitive no-tax economy without make-or-buy.[1] Monopoly is costly in both cases: relative to the competitive benchmark, welfare falls by 13.83 percent without make-or-buy and by 10.45 percent with make-or-buy. The make-or-buy margin therefore mitigates, but does not eliminate, the welfare cost of market power. By contrast, under perfect competition, make-or-buy lowers welfare by 2.03 percent relative to the no-make-or-buy benchmark.

[1]Appendix C.1 describes the welfare levels and the consumption-equivalent transformation used in the quantitative analysis.

TABLE 6.2. No-Tax Steady States with and without Make-or-Buy

	Perfect competition		Monopoly	
Variable	No MoB	MoB	No MoB	MoB
$K^{n,M}$	5.39	5.28	4.44	4.66
$K^{c,M}$	–	0.06	–	0.13
$K^{c,E}$	0.16	0.14	0.01	0.01
$K^{d,E}$	0.56	0.50	0.02	0.04
E	1.45	1.30	0.05	0.09
Y	2.07	2.03	1.70	1.79
C	1.46	1.43	1.26	1.31
P^E	0.06	0.06	1.43	0.62
Welfare change	0.00%	-2.03%	-13.83%	-10.45%

Notes: MoB denotes the economy with the make-or-buy margin. No MoB denotes the counterfactual economy in which manufacturing firms cannot produce electricity in-house. Welfare changes are consumption-equivalent changes relative to the competitive no-tax economy without make-or-buy. Capital and output are measured in trillion EUR, electricity in PWh, and electricity prices in EUR/kWh.

The negative welfare effect under perfect competition should be interpreted with care. The make-or-buy economy is not simply the no-make-or-buy economy plus a costless option. In the no-make-or-buy economy, manufacturing power is identical to purchased electricity, $Pow_t = E_t$. In the make-or-buy economy, power is a CES composite of purchased electricity and on-site clean generation. The CES structure makes self-generation valuable at the margin, so firms optimally choose a positive stock of clean manufacturing capital, $K^{c,M} = 0.06$. However, because purchased electricity is already competitively priced, self-generation does not address a major electricity price distortion. It instead reallocates aggregate capital away from other uses, including neutral manufacturing capital and electricity-sector capital. In the calibrated competitive economy, this reallocation lowers output from 2.07 to 2.03 and consumption from 1.46 to 1.43, generating the small welfare loss reported in the table.

The mechanism changes under a monopoly. Without make-or-buy, the electricity producer charges a high price, $P^E = 1.43$, and manufacturing firms purchase only $E = 0.05$ units of electricity. When make-or-buy is available, manufacturers partially substitute away from purchased electricity by investing in clean self-generation capital. This outside option reduces the residual demand the monopolist faces and lowers the electricity price to $P^E = 0.62$. Electricity purchases increase to $E = 0.09$, output rises from 1.70 to 1.79, and consumption rises from 1.26 to 1.31. The make-or-buy margin is therefore welfare-improving under monopoly because it mitigates a pre-existing market-power distortion.

The same comparison also clarifies the abatement-cost role of make-or-buy. Even under perfect competition, where make-or-buy lowers welfare, it reduces dirty electricity capital from $K^{d,E} = 0.56$ to $K^{d,E} = 0.50$. This occurs because manufacturers can meet part of their power demand through clean on-site generation rather than through the electricity sector's mix of clean and dirty capital. The make-or-buy margin, therefore, adds an abatement channel: dirty capital can fall not only because the electricity sector substitutes clean for dirty capital, but also because manufacturing reduces its reliance on grid electricity.

This additional channel can be interpreted as a flattening of the economy's effective marginal abatement cost curve. Without make-or-buy, reducing dirty electricity capital requires adjustment primarily inside the electricity sector. With make-or-buy, manufacturers have a second margin of adjustment through clean self-generation. The effect is quantitatively modest under perfect competition because the electricity price is already close to marginal cost. It is much stronger under a monopoly, where self-generation both substitutes for dirty grid electricity and reduces monopoly price pass-through. Thus, make-or-buy has two distinct effects: it reallocates clean investment toward manufacturing, and, when electricity supply is distorted by market power, it lowers the effective cost of reducing dirty electricity use.

To put the environmental effect in perspective, we translate the reduction in dirty electricity capital into an emissions equivalent. In the competitive make-or-buy benchmark, dirty electricity capital equals $K^{d,E} = 0.50$. Without make-or-buy, it rises to $K^{d,E} = 0.56$, an increase of about 12 percent. If dirty electricity capital is assumed to scale one-for-one with electricity-sector emissions, and if the competitive make-or-buy benchmark is mapped to EU power-sector emissions of 657 million tonnes of CO_2 in 2023, the no-make-or-buy counterfactual would imply emissions of approximately 736 million tonnes of CO_2. The make-or-buy margin therefore avoids roughly 79 million tonnes of CO_2 relative to the no-make-or-buy counterfactual.

This calculation is only an accounting exercise. It assumes that dirty electricity capital is proportional to emissions and that the benchmark dirty capital stock maps into observed EU power-sector emissions. Nevertheless, it illustrates that the environmental effect of make-or-buy is quantitatively meaningful. In the competitive economy, make-or-buy lowers consumption-equivalent welfare by about 2 percent, but it also reduces dirty electricity capital by 12 percent, corresponding to roughly 79 million tonnes of CO_2 avoided under the proportional mapping.

Overall, the value of the make-or-buy margin depends on the underlying market distortion: it is costly in the calibrated competitive economy, but valuable when electricity prices include a monopoly wedge. At the same time, its environmental value can be positive even when its welfare effect is negative, because it reduces reliance on dirty electricity capital.

6.3. **Tax Anticipation and Implementation.** We now introduce a tax on dirty electricity capital. In the baseline policy experiment, the tax rate is set to 10 percent. To interpret its magnitude, consider the competitive make-or-buy benchmark, where dirty electricity capital equals $K^{d,E} = 0.50$ trillion EUR. A 10 percent tax therefore implies a tax burden of EUR 50 billion. If dirty electricity capital is interpreted as the capital stock responsible for EU electricity-sector emissions, and if EU power-sector emissions are taken to be 657 million tonnes of CO_2 in 2023, this corresponds to an implicit carbon price of approximately EUR 76/tCO_2. The policy shock is therefore of the same order of magnitude as recent European carbon prices.

We distinguish between two tax regimes. The first is the stochastic pre-tax regime, in which agents anticipate that the tax may be implemented in the future with probability $p^{\tau} = 0.40$ each period. The second is the post-tax regime, in which the tax is permanently in place. This distinction matters because anticipation changes investment before the tax is actually implemented: firms adjust capital stocks in response to expected future policy even though current tax payments have not yet materialized.

The stochastic pre-tax regime generates a strong anticipation effect. Since capital is freely reallocatable across uses, agents respond to the expected future tax before it is implemented. In the pre-tax state, dirty electricity capital is not yet taxed, but households and firms know that it may become more costly in the next period. This creates an incentive to adjust capital while the economy is still untaxed. The result is a temporary expansion in neutral manufacturing capital, electricity demand, and output. This response can be interpreted as a policy-risk-induced precautionary investment motive: agents front-load investment and production before the tax raises the user cost of dirty electricity capital. Because the current model does not account for adjustment costs or irreversibility, the anticipatory response is large. With capital adjustment frictions, the same mechanism would remain, but the pre-tax boom would likely be smoother and quantitatively smaller.

Tables 6.3 and 6.4 report the no-tax, stochastic pre-tax, and post-tax allocations under perfect competition and monopoly. The anticipation effect is visible in both market regimes. Under perfect competition without make-or-buy, neutral manufacturing capital rises from 5.39 in the no-tax steady state to 7.12 in the pre-tax regime, while electricity purchases increase from 1.45 to 1.92 and output rises from 2.07 to 2.28. With make-or-buy, the same pattern appears: neutral capital rises from 5.28 to 6.89, clean manufacturing capital increases from 0.06 to 0.08, and output rises from 2.03 to 2.22. The monopoly economy displays an even stronger expansion of neutral manufacturing capital in the pre-tax regime. These increases do not reflect a permanent improvement in productivity. They reflect the fact that agents front-load investment and production before the dirty-capital tax is realized.

TABLE 6.3. Tax Anticipation and Tax Implementation under Perfect Competition

	No make-or-buy			Make-or-buy		
Variable	No tax	Pre-tax	Post-tax	No tax	Pre-tax	Post-tax
$K^{n,M}$	5.39	7.12	5.25	5.28	6.89	5.15
$K^{c,M}$	–	–	–	0.06	0.08	0.07
$K^{c,E}$	0.16	0.21	0.23	0.14	0.19	0.20
$K^{d,E}$	0.56	0.74	0.25	0.50	0.65	0.22
E	1.45	1.92	0.90	1.30	1.70	0.79
Y	2.07	2.28	2.02	2.03	2.22	1.98
C	1.46	1.47	1.44	1.43	1.44	1.41
P^E	0.06	0.05	0.09	0.06	0.05	0.09
Welfare change	0.00%	-1.15%	-1.22%	-2.03%	-3.06%	-3.13%

Notes: Welfare changes are consumption-equivalent changes relative to the competitive no-tax economy without make-or-buy. Capital and output are measured in trillion EUR, electricity in PWh, and electricity prices in EUR/kWh.

Under perfect competition, the welfare ranking is unchanged relative to the no-tax comparison. The make-or-buy economy has lower consumption-equivalent welfare than the no-make-or-buy economy, both before and after the implementation of the tax. In the post-tax steady state, welfare losses are 1.22 percent without make-or-buy and 3.13 percent with make-or-buy. This reflects the same force as in the no-tax economy: when electricity is competitively priced, self-generation reallocates capital toward an additional power-sourcing margin without correcting a major market-power distortion.

TABLE 6.4. Tax Anticipation and Tax Implementation under Monopoly

	No make-or-buy			Make-or-buy		
Variable	No tax	Pre-tax	Post-tax	No tax	Pre-tax	Post-tax
$K^{n,M}$	4.44	8.43	4.32	4.66	7.76	4.58
$K^{c,M}$	–	–	–	0.13	0.21	0.14
$K^{c,E}$	0.01	0.01	0.01	0.01	0.02	0.02
$K^{d,E}$	0.02	0.03	0.01	0.04	0.06	0.02
E	0.05	0.09	0.03	0.09	0.15	0.06
Y	1.70	2.12	1.66	1.79	2.13	1.76
C	1.26	1.27	1.22	1.31	1.33	1.28
P^E	1.43	0.93	2.24	0.62	0.44	0.90
Welfare change	-13.83%	-16.00%	-16.12%	-10.45%	-11.97%	-12.07%

Notes: Welfare changes are consumption-equivalent changes relative to the competitive no-tax economy without make-or-buy. Capital and output are measured in trillion EUR, electricity in PWh, and electricity prices in EUR/kWh.

Because perfect competition is our primary empirical benchmark for the European setting, we focus on the environmental ranking under this regime. Under perfect competition, the make-or-buy economy consistently uses less dirty electricity capital. In the pre-tax regime, dirty electricity capital is 0.65 with make-or-buy, compared with 0.74 without make-or-buy. After implementation, it falls to 0.22 with make-or-buy and 0.25 without make-or-buy. Thus, even when make-or-buy is welfare-reducing in the competitive economy, it lowers the dirty-capital intensity of electricity production. This reinforces the interpretation of self-generation as an additional abatement margin.

Under monopoly, the make-or-buy margin remains welfare-improving in all tax regimes. In the post-tax steady state, welfare losses are 16.12 percent without make-or-buy and 12.07 percent with make-or-buy. The reason is the electricity-price channel. Without make-or-buy, the post-tax monopoly electricity price rises to $P^E = 2.24$. With make-or-buy, the corresponding price is only $P^E = 0.90$. Self-generation gives manufacturers an outside option, makes residual electricity demand more elastic, and limits monopoly price pass-through. This raises electricity use, output, and consumption relative to the monopoly economy without make-or-buy.

Figure 6.1 extends the comparison across tax rates. In all four model variants, a higher tax reduces dirty electricity capital. Under perfect competition, the effect of make-or-buy on electricity prices is small because electricity is already priced close to its marginal cost. Its main role is to shift part of the adjustment toward clean manufacturing capital and away from dirty electricity capital. Under monopoly, the price response is much larger.

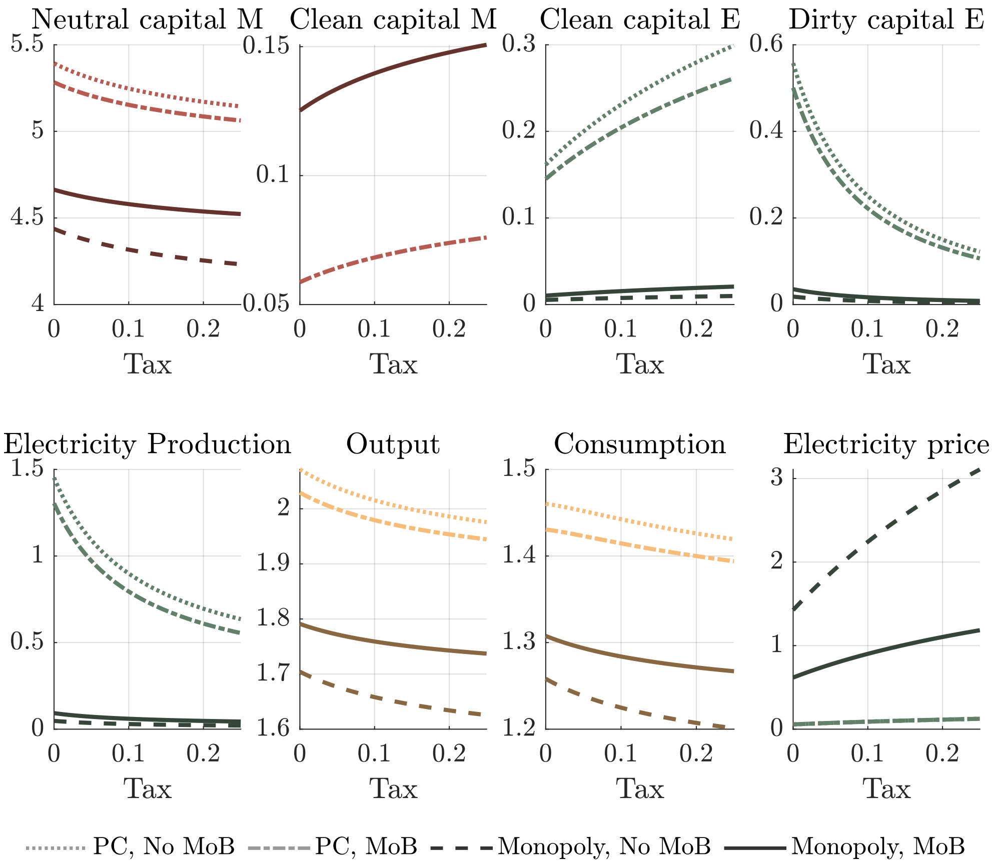

FIGURE 6.1. Post-Tax Steady States across Market Regimes and Make-or-Buy Specifications

Notes: The figure reports post-tax steady-state allocations for alternative tax rates on dirty electricity capital. Each panel plots one equilibrium object as a function of the tax rate. The four lines correspond to perfect competition without make-or-buy, perfect competition with make-or-buy, monopoly without make-or-buy, and monopoly with make-or-buy. The make-or-buy specifications allow manufacturers to substitute purchased electricity with self-generated clean electricity.

Without make-or-buy, the electricity price increases sharply with the tax. With make-or-buy, the increase is substantially muted because manufacturers can substitute toward on-site clean generation. This muted price response reinforces the marginal-abatement-cost interpretation: self-generation provides an additional adjustment margin and limits the price increase required to reduce dirty electricity capital.

Overall, the tax experiment shows that make-or-buy changes both the incidence and the cost of decarbonization. Under perfect competition, self-generation reduces dirty electricity capital but lowers welfare in the calibrated economy. Under monopoly, it reduces the welfare cost of market power and limits the increase in electricity prices induced by the tax. The same make-or-buy margin can therefore lower aggregate welfare in a competitive environment, while becoming valuable when electricity supply is distorted by market power.

6.4. **Clean-Capital Subsidies.** We now consider subsidies to clean capital. The subsidy experiment is implemented symmetrically to the carbon-tax experiment, but with the opposite sign. Whereas the carbon tax raises the user cost of dirty electricity capital, a clean-capital subsidy lowers the user cost of clean capital. A subsidy to clean electricity-sector capital enters the electricity producer's problem as a negative tax on $K^{c,E}$, while a subsidy to clean manufacturing capital enters the manufacturer's problem as a negative tax on $K^{c,M}$. The fiscal side also changes sign: the carbon tax generates revenues that are rebated lump-sum to the household, whereas the subsidy is financed by a lump-sum tax on the representative household. Subsidies can therefore expand clean capital and lower electricity prices, but they also absorb household resources through their fiscal cost.

The timing of the subsidy experiment differs from the tax experiment. The carbon tax is studied both before and after implementation because agents anticipate the future tax with probability p^τ. By contrast, the subsidy experiments are unanticipated steady-state counterfactuals. We therefore compare the subsidy allocations directly to the no-subsidy and post-tax allocations, rather than introducing a stochastic pre-subsidy regime. This distinction is important for interpretation: the subsidy tables isolate the long-run allocation induced by each policy instrument, not an anticipatory transition.

Tables 6.5 and 6.6 report subsidies under perfect competition and monopoly. We consider three instruments: a subsidy for clean manufacturing capital, a subsidy for clean electricity-sector capital, and a joint subsidy for both. In the no-make-or-buy economy, a subsidy to clean manufacturing capital is irrelevant because $K^{c,M}$ is not available; hence, only the electricity-sector subsidy is reported in that case.

Under perfect competition, the location of the subsidy determines where clean capital is installed. A subsidy to clean electricity-sector capital expands clean capacity in the electricity sector and reduces dirty electricity capital sharply: in the make-or-buy economy, $K^{c,E}$ rises to 3.25 and $K^{d,E}$ falls to 0.26. A subsidy to clean manufacturing capital instead shifts investment toward self-generation: $K^{c,M}$ rises to 0.96, while dirty electricity capital falls only to 0.46. Thus, subsidizing the electricity sector is more effective at changing the clean-dirty mix of electricity production, whereas subsidizing clean capital in manufacturing mainly reduces firms' reliance on purchased electricity.

The welfare effects reflect the output–consumption trade-off created by subsidies. Under perfect competition, subsidies raise output by expanding clean capacity and lowering electricity prices, but they require fiscal resources from households and entail substantial investment. In the make-or-buy economy, the subsidy to clean manufacturing capital yields the lowest welfare among the subsidy cases, with a welfare loss of 8.28 percent. The joint subsidy performs better, with a welfare loss of 2.79 percent, because it expands clean capacity in both sectors and lowers dirty electricity capital to 0.25.

TABLE 6.5. Clean-Capital Subsidies under Perfect Competition

	No make-or-buy		Make-or-buy		
Variable	No Sub.	Sub. to Elec.	Sub. to Man.	Subsidy to Elec	Joint subsidy
$K^{n,M}$	5.39	5.67	5.37	5.54	5.60
$K^{c,M}$	–	–	0.96	0.04	0.74
$K^{c,E}$	0.16	3.54	0.13	3.25	3.04
$K^{d,E}$	0.56	0.29	0.46	0.26	0.25
E	1.45	3.52	1.19	3.23	3.02
Pow	–	–	1.33	2.31	2.81
Y	2.07	2.18	2.06	2.13	2.15
C	1.46	1.23	1.37	1.22	1.19
P^E	0.06	0.02	0.06	0.02	0.02
W	1.37	1.44	1.36	1.40	1.42
Welfare change	-6.37%	-1.52%	-8.28%	-3.87%	-2.79%

Notes: The joint subsidy denotes a subsidy to both clean manufacturing capital and clean electricity-sector capital. In the no-make-or-buy economy, clean manufacturing capital is not available; therefore, a subsidy to clean manufacturing capital is identical to the no-subsidy allocation, and the joint subsidy is identical to a subsidy to clean electricity-sector capital. These redundant columns are omitted. Welfare changes are consumption-equivalent changes, in percent, relative to the competitive no-tax economy without make-or-buy and without subsidies. Capital and output variables are measured in trillion EUR, electricity quantities in PWh, and electricity prices in EUR/kWh.

This distinction also matters for the comparison with the carbon tax. In the competitive make-or-buy economy, the post-tax allocation reduces dirty electricity capital to 0.22, while the electricity-sector subsidy reduces it to 0.26 and the joint subsidy to 0.25. The tax is therefore slightly more effective at reducing dirty capital in the competitive benchmark and preserves more consumption. Subsidies, however, raise output by expanding clean capacity and lowering electricity prices. The trade-off is that this expansion requires a larger investment effort and is financed by the household, which depresses consumption.

Under monopoly, subsidies have an additional role because they mitigate the quantity restriction generated by market power. A subsidy to clean electricity-sector capital lowers the electricity price, expands electricity use, and raises output and consumption relative to the monopoly no-subsidy allocation. With make-or-buy, the electricity-sector subsidy reduces dirty capital to 0.02, raises output to 1.85, and raises consumption to 1.34. The

Table 6.6. Clean-Capital Subsidies under Monopoly

	No make-or-buy		Make-or-buy		
Variable	No Sub.	Sub. to Elec.	Sub. to Man.	Subsidy to Elec	Joint subsidy
$K^{n,M}$	4.44	4.67	4.89	4.83	5.04
$K^{c,M}$	–	–	1.69	0.10	1.41
$K^{c,E}$	0.01	0.12	0.01	0.21	0.25
$K^{d,E}$	0.02	0.01	0.04	0.02	0.02
E	0.05	0.12	0.11	0.20	0.25
Pow	–	–	0.26	0.21	0.44
Y	1.70	1.79	1.88	1.85	1.93
C	1.26	1.31	1.22	1.34	1.26
P^E	1.43	0.62	0.44	0.31	0.22
W	1.12	1.18	1.24	1.22	1.28
Welfare change	-22.97%	-18.98%	-19.05%	-16.17%	-12.58%

Notes: The joint subsidy denotes a subsidy to both clean manufacturing capital and clean electricity-sector capital. In the no-make-or-buy economy, clean manufacturing capital is not available; therefore, a subsidy to clean manufacturing capital is identical to the no-subsidy allocation, and the joint subsidy is identical to a subsidy to clean electricity-sector capital. These redundant columns are omitted. Welfare changes are consumption-equivalent changes, in percent, relative to the competitive no-tax economy without make-or-buy and without subsidies. Capital and output variables are measured in trillion EUR, electricity quantities in PWh, and electricity prices in EUR/kWh.

welfare loss falls to 16.17 percent, compared with 19.05 percent under the manufacturing subsidy.

A subsidy to clean manufacturing capital operates through the outside-option channel. It raises clean manufacturing capital to 1.69, lowers the electricity price to 0.44, and increases output to 1.88. However, consumption is lower than under the electricity-sector subsidy because the policy induces a large reallocation of resources toward manufacturing self-generation. The joint subsidy generates the lowest electricity price and the highest output, and it also delivers the highest welfare among the monopoly subsidy cases, with a welfare loss of 12.58 percent.

Overall, clean-capital subsidies and dirty-capital taxes operate through different margins. Taxes directly penalize dirty capital. Subsidies expand clean energy capacity and lower electricity prices, but they require fiscal resources from households. Under perfect competition, the tax reduces dirty capital with a smaller consumption loss than the subsidy policies. Under monopoly, clean subsidies reduce dirty capital and relax monopoly-induced electricity scarcity, but they remain costly in welfare terms because they require household financing. They are therefore attractive along the output and electricity-price dimensions, but not necessarily in consumption-equivalent welfare. The ranking of instruments depends on the policy criterion and on whether the subsidy targets clean capital in the electricity sector, manufacturing self-generation, or both.

6.5. **Sensitivity to Substitution Elasticities.** Finally, we examine how the post-tax steady state depends on the two substitution elasticities that govern adjustment across sectors. Figure 6.2 reports the long-run allocation after a tax on dirty capital in the electricity sector. Equivalently, the exercise can be interpreted as the steady-state response to an unanticipated tax. The parameter ψ_E governs substitution between clean and dirty capital within electricity production, while ψ_P governs substitution between purchased electricity and clean on-site generation in the manufacturing power aggregate. The central result is that these two elasticities operate through different margins: ψ_E mainly affects within-sector reallocation in electricity, whereas ψ_P governs the cross-sector make-or-buy channel.

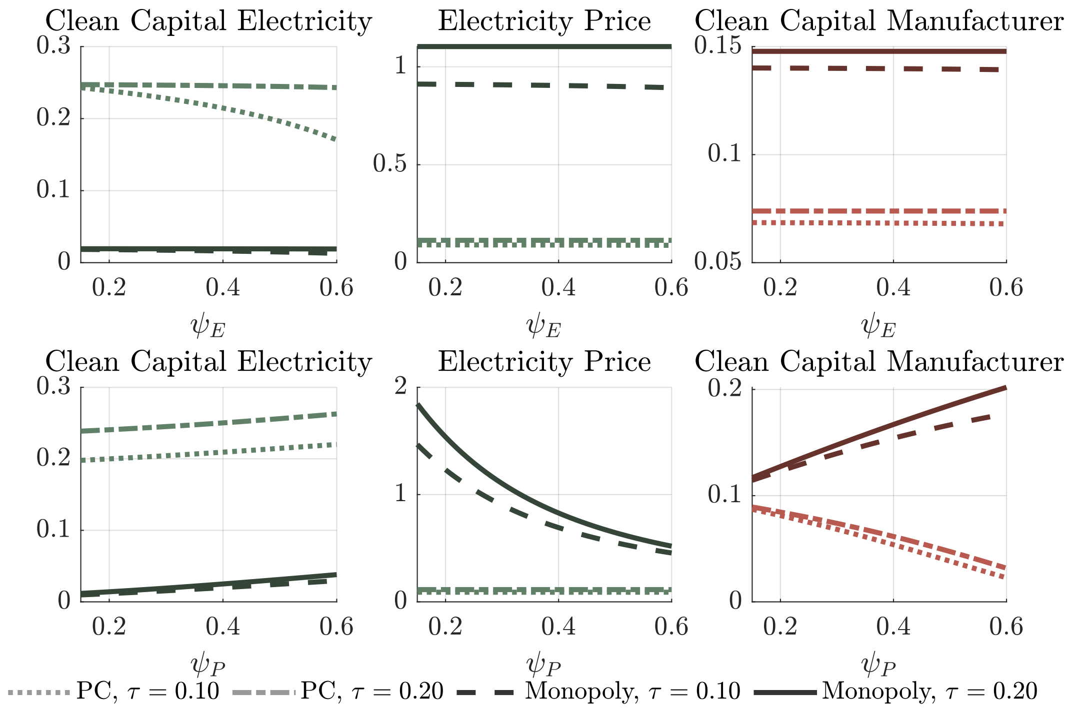

FIGURE 6.2. Steady-State Responses to CES Substitution Parameters in Electricity Production and Power Aggregation

Note: The figure reports steady-state outcomes for alternative values of the CES substitution parameters ψ_E and ψ_P. The top row varies ψ_E, which governs substitutability between clean and dirty capital in electricity production, while holding ψ_P fixed at its baseline value. The bottom row varies ψ_P, which governs substitutability between internally produced clean electricity and purchased electricity in the power aggregate, while holding ψ_E fixed at its baseline value. Columns report, respectively, clean capital in the electricity sector, the electricity price, and clean capital used for on-site generation in manufacturing. Each panel compares perfect competition and monopoly at two electricity tax rates, $\tau = 0.10$ and $\tau = 0.20$. Electricity-sector variables are shown in green and manufacturing variables in red. Darker shades correspond to monopoly cases, while line styles distinguish the two tax rates within each market structure.

The first margin is the generation-side substitution elasticity. Increasing ψ_E changes the ease with which electricity producers substitute clean for dirty capital. In the competitive case, clean electricity capital is more sensitive to this parameter, whereas the response is muted under monopoly. The electricity price is nearly flat in ψ_E within each market structure, although its level remains substantially higher under monopoly. Clean manufacturing capital is also almost invariant to ψ_E. Thus, the generation-side elasticity mainly affects the composition of electricity-sector capital rather than manufacturers' sourcing decisions.

The second margin is the power-aggregation elasticity. The parameter ψ_P directly governs how easily manufacturers substitute purchased electricity with clean on-site generation, and is therefore the key parameter for the make-or-buy channel. As ψ_P increases, clean manufacturing capital falls under perfect competition but rises under monopoly. Under perfect competition, electricity remains relatively cheap, so greater substitutability weakens the incentive to self-generate. Under monopoly, electricity is more expensive, so greater substitutability makes clean self-generation a more valuable outside option. This response is amplified when the electricity tax increases from $\tau = 0.10$ to $\tau = 0.20$.

The cross-sector feedback is asymmetric. The manufacturing sector is only weakly affected by ψ_E: changes in the electricity-sector production elasticity pass through to manufacturing mostly through small changes in equilibrium electricity prices. By contrast, the electricity sector is more strongly affected by ψ_P, because manufacturers' ability to self-generate changes their demand for purchased electricity. This feedback is especially visible under monopoly, where a higher ψ_P lowers the electricity price by disciplining monopoly pricing power. The magnitude of this effect depends on the tax rate, with stronger feedback at higher taxes.

Overall, the post-tax sensitivity analysis shows that policy incidence depends not only on the tax rate but also on the substitution margin through which firms adjust. The generation-side elasticity ψ_E governs how clean capital reallocates within electricity production. The power-aggregation elasticity ψ_P governs the transmission of electricity-sector conditions to manufacturing investment. This makes ψ_P particularly important for policy evaluation: when manufacturers can more easily substitute toward self-generation, an electricity tax induces stronger cross-sector reallocation and weakens the pass-through of monopoly pricing power.[2]

[2]Appendix C.2 reports the sensitivity of equilibrium outcomes to ψ_P and ψ_E over the tax schedule.

6.6. **Discussion.** The quantitative results can be summarized in four points. First, the competitive make-or-buy economy provides a natural benchmark: it matches the order of magnitude of key electricity and manufacturing variables, even though these moments are not directly targeted. Second, the make-or-buy margin has different welfare implications across market structures. Under perfect competition, self-generation slightly lowers welfare because the electricity sector is already an efficient supplier; under monopoly, it raises welfare by giving manufacturers an outside option against high electricity prices. Third, the same margin has environmental effects in both regimes: allowing manufacturers to self-generate clean electricity reduces dirty capital from the electricity sector. Fourth, taxes and subsidies operate through different channels. Taxes directly penalize dirty electricity capital, while clean subsidies expand clean capacity but differ in whether they target centralized electricity production or decentralized manufacturing self-generation.

Overall, the results show that industrial decarbonization cannot be understood by studying the electricity sector in isolation. The make-or-buy margin links electricity prices, manufacturing investment, and the composition of electricity-sector capital. Policies that affect electricity production costs also alter manufacturers' incentives to self-generate electricity. Conversely, manufacturers' ability to self-generate changes the demand faced by electricity producers and feeds back into electricity prices, capital allocation, output, consumption, and welfare. The model, therefore, highlights the importance of treating manufacturing firms not only as passive electricity users but also as potential producers of clean electricity.

The analysis has two main limitations. First, the model abstracts from adjustment costs and capital irreversibility. Capital can be reallocated across uses through the aggregate capital constraint, so the model captures long-run comparative statics rather than gradual transition dynamics. In reality, electricity plants, industrial equipment, and on-site generation assets are long-lived and only imperfectly reversible. Introducing adjustment costs, vintage capital, or irreversible investment would make it possible to distinguish short-run utilization responses from long-run capital replacement. It would also allow the model to study stranded dirty electricity assets, capital lock-in, and the timing of clean investment.

Second, the model abstracts from heterogeneity across manufacturing firms. Manufacturing is represented by a single aggregate firm, although firms differ substantially in electricity intensity, access to space for self-generation, exposure to electricity prices, contracting possibilities, and technical ability to substitute between purchased electricity and on-site generation. Introducing heterogeneous firms would make it possible to study which firms adopt self-generation, how policy incidence varies across industries, and whether clean subsidies mainly benefit firms with low adjustment costs or also induce adoption among constrained firms. This extension would connect the make-or-buy mechanism more directly to observed industrial behavior and allow the model to study the distributional incidence of electricity market power and climate policy within manufacturing.

These limitations point to a natural next step. Adding adjustment frictions and firm heterogeneity would strengthen the framework's quantitative interpretation while preserving its central mechanism. The current model shows how the make-or-buy margin reshapes aggregate policy incidence; a richer version could study how this adjustment unfolds over time and how its costs and benefits are distributed across firms.

7. Conclusion

This paper studies decarbonization when electricity producers and manufacturing firms adjust jointly and interact through a make-or-buy margin. We develop a two-sector framework in which electricity is produced using clean and dirty capital, while manufacturing firms combine neutral capital with power that can either be purchased from the electricity sector or produced in-house using clean self-generation capital. The model features four types of capital—neutral manufacturing capital, clean manufacturing capital, dirty electricity capital, and clean electricity capital—which allows us to study how climate policy reallocates investment both within the electricity sector and across the boundary between electricity producers and manufacturing firms.

The objective of the paper is primarily positive rather than normative. We do not ask whether manufacturing self-generation should necessarily be promoted as an optimal policy instrument. Instead, we quantify a mechanism that is already present in the data: manufacturing firms increasingly have the option to produce part of their electricity on site. The central question is how this make-or-buy decision affects the pace, costs, and incidence of decarbonization.

We first show that the baseline competitive economy with make-or-buy generates aggregate magnitudes that are broadly consistent with the scale observed in the data.

Although the calibration does not directly target electricity consumption, manufacturing output, or electricity prices, the model produces values in the empirical range for European manufacturing and wholesale electricity markets. This makes the competitive make-or-buy economy a useful benchmark for the policy experiments.

The results highlight that the make-or-buy margin has different implications depending on the electricity-market regime. Under perfect competition, allowing manufacturers to self-generate clean electricity slightly lowers welfare. The reason is that centralized electricity producers are relatively efficient suppliers of electricity, so self-generation can shift part of production toward a less productive decentralized technology. In this case, make-or-buy is privately optimal for firms but not necessarily socially cost-minimizing. However, the same margin reduces dirty electricity capital. In the competitive benchmark, shutting down make-or-buy increases dirty electricity capital by about 12 percent. Under a proportional mapping to EU electricity-sector emissions, this corresponds to avoided emissions of roughly 79 million tonnes of CO_2. Thus, even when make-or-buy lowers welfare in the competitive allocation, it can generate a quantitatively meaningful environmental benefit.

Under monopoly, the make-or-buy margin becomes welfare-improving. Monopoly power raises electricity prices and restricts electricity supply. In this environment, manufacturing self-generation provides an outside option against the monopolistic electricity supplier. It lowers firms' dependence on purchased electricity, increases effective power availability, raises output and consumption, and reduces welfare losses relative to the monopoly economy without make-or-buy. The monopoly case should not be interpreted as a literal quantitative description of European electricity markets, since the model abstracts from regulation. Rather, it illustrates how decentralized generation can mitigate electricity-market distortions and change the incidence of market power.

The taxation experiments show that carbon policy cannot be understood as a within-electricity reallocation alone. A tax on dirty electricity capital directly reduces the attractiveness of dirty electricity production and shifts investment toward clean electricity capital. At the same time, the tax changes electricity prices and therefore affects manufacturers' make-or-buy decisions. In the stochastic pre-tax regime, firms adjust investment before the tax is implemented, reflecting expected future policy. In the post-tax steady state, dirty electricity capital falls sharply in both market regimes. Under perfect competition, make-or-buy remains welfare-reducing, but it consistently reduces dirty capital relative to the no-make-or-buy counterfactual. Under monopoly, make-or-buy improves welfare because it mitigates the high electricity prices generated by market power.

We also study clean-capital subsidies. The subsidy experiments show that policy targeting matters. A subsidy to clean electricity-sector capital mainly expands centralized clean electricity production and is highly effective at reducing dirty electricity capital. A subsidy to clean manufacturing capital works through a different channel: it shifts investment toward decentralized self-generation and reduces manufacturers' reliance on purchased electricity. A joint subsidy expands clean capital in both sectors, but the two subsidies are not simply additive. They are complements in raising total clean capacity, but partial substitutes in determining where clean capital is installed.

The comparison between taxes and subsidies reveals an important policy trade-off. In the competitive economy, the tax reduces dirty capital more directly and preserves more steady-state consumption than broad clean-capital subsidies. Subsidies, by contrast, expand clean capacity and can raise output by lowering electricity prices, but they require a larger investment effort and absorb household resources through their fiscal cost. In the monopoly economy, subsidies are more attractive along the output and electricity-price dimensions because they address two distortions at once: they reduce dirty capital and relax monopoly under-provision by lowering electricity prices and expanding electricity use. However, they remain costly in consumption-equivalent welfare terms, so the ranking of instruments depends on whether the policy objective emphasizes dirty-capital reduction, output, consumption, or welfare.

The sensitivity analysis shows that the strength and incidence of these mechanisms depend on substitution elasticities. The generation-side elasticity ψ_E mainly governs the reallocation of clean capital within electricity production. By contrast, the power-aggregation elasticity ψ_P governs the make-or-buy margin and therefore the interdependence between electricity producers and manufacturing firms. This parameter is especially important under monopoly: when manufacturers can more easily substitute toward self-generation, their outside option weakens electricity-market power, lowers the electricity price, and changes the allocation of clean investment across sectors.

Overall, the results show that industrial decarbonization cannot be assessed by analyzing the electricity sector in isolation. Manufacturing firms are not only electricity demanders; they can also become producers of clean electricity. This make-or-buy margin changes the elasticity and composition of electricity demand, feeds back into electricity-sector investment incentives, affects electricity prices, and reallocates the burden of decarbonization across sectors. Policies that affect the cost of dirty or clean electricity production therefore also affect where clean capital is installed and who bears the associated transition costs.

The analysis has two main limitations that point to important directions for future research. First, capital is perfectly reallocatable across periods through the aggregate capital constraint. The four capital stocks sum to total capital, and the model does not yet include irreversible investment, vintage structure, or adjustment costs. This simplifies the analysis but abstracts from the fact that coal plants, gas plants, renewable generation assets, industrial machinery, and on-site generation equipment are long-lived and only imperfectly reversible. Introducing irreversible investment and adjustment costs would allow the model to distinguish short-run utilization changes from long-run capital replacement and to study stranded assets explicitly. Dirty electricity capital could then become economically obsolete before the end of its physical lifetime, while clean self-generation capital could create new transition exposure for manufacturing firms.

Second, manufacturing is represented by a single aggregate firm. In reality, manufacturing firms differ substantially in electricity intensity, access to land or rooftop space, financing constraints, reliability needs, exposure to electricity prices, and ability to substitute between purchased electricity and self-generation. Introducing firm heterogeneity would make it possible to study which firms adopt self-generation, how policy affects different parts of the manufacturing sector, and how the costs and benefits of decarbonization are distributed across firms. It would also allow the model to speak more directly to observed differences between energy-intensive sectors such as chemicals, metals, cement, and paper and less electricity-intensive manufacturing industries.

These extensions would strengthen the empirical and policy relevance of the framework while preserving the paper's core message: industrial decarbonization is a joint equilibrium outcome shaped by electricity supply, manufacturing make-or-buy choices, and the way climate policy shifts investment, costs, and risks across sectors.

References

Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The environment and directed technical change. *American Economic Review*, 102(1):131–166.

Arrow, K. J., Chenery, H. B., Minhas, B. S., and Solow, R. M. (1961). Capital-labor substitution and economic efficiency. *The Review of Economics and Statistics*, 43(3):225–250.

Azevedo, I., Bataille, C., Bistline, J., Clarke, L., and Davis, S. (2021). Net-Zero Emissions Energy Systems: What We Know and Do Not Know. *Energy and Climate Change*, 2:100049.

Boampong, R. and Brown, D. P. (2020). On the benefits of behind-the-meter rooftop solar and energy storage: The importance of retail rate design. *Energy economics*, 86:104682.

Borenstein, S. (2017). The private net benefits of residential solar pv: The role of electricity tariffs, tax incentives, and rebates. *Journal of the Association of Environmental and Resource Economists*, 4(S1):S85–S122.

Bouckaert, S., Pales, A. F., McGlade, C., Remme, U., Wanner, B., Varro, L., D'Ambrosio, D., and Spencer, T. (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector.

Cai, Y. and Lontzek, T. S. (2019). The Social Cost of Carbon with Economic and Climate Risks. *Journal of Political Economy*, 127(6):2684–2734.

Campiglio, E., Dietz, S., and Venmans, F. (2022). Optimal Climate Policy as if the Transition matters. Technical report, London School of Economics and Political Science.

Carleton, T., Jina, A., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., Hultgren, A., Kopp, R. E., McCusker, K. E., Nath, I., et al. (2022). Valuing the Global Mortality Consequences of Climate Change accounting for Adaptation Costs and Benefits. *The Quarterly Journal of Economics*, 137(4):2037–2105.

Cleary, K. and Palmer, K. (2022). US Electricity Markets 101. Resources for the Future Explainer. Originally published March 3, 2020; updated March 17, 2022. Accessed: 2026-05-31.

D'Aprile, P., Engel, H., van Gendt, G., Helmcke, S., Hieronimus, S., Nauclér, T., Pinner, D., Walter, D., and Witteveen, M. (2020). Net-Zero Europe: Decarbonization Pathways and Socioeconomic Implications. Technical report, McKinsey & Company.

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y.-M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B.-M., Hoffert, M. I., Ingersoll, E., Jaramillo, P., Lackner, K. S., Mach, K. J., Mastrandrea, M., Ogden, J., Peterson, P. F., Sanchez, D. L., Sperling, D., Stagner, J., Trancik, J. E., Yang, C.-J., and Caldeira, K. (2018). Net-Zero Emissions Energy Systems. *Science*, 360(6396):eaas9793.

Dufour-Décieux, V., Sievert, K., Steffen, B., Bardow, A., and Schmidt, T. S. (2025). (How to) Avoid the Inflationary Labeling of Emissions as "Hard to Abate". *Joule*, 9(7).

European Commission (2026). Electricity Market Design. https://energy.ec.europa.eu/topics/markets-and-consumers/electricity-market-design_en. Accessed: 2026-05-31.

Fried, S., Novan, K., and Peterman, W. B. (2022). Climate Policy Transition Risk and the Macroeconomy. *European Economic Review*, 147:104174.

Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal Taxes on Fossil Fuel in General Equilibrium. *Econometrica*, 82(1):41–88.

International Renewable Energy Agency (2024). Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7.

Jo, A. (2025). Substitution between clean and dirty energy with biased technical change. *International Economic Review*, 66(2):883–902.

Jo, A. and Miftakhova, A. (2024). How constant is constant elasticity of substitution? endogenous substitution between clean and dirty energy. *Journal of Environmental Economics and Management*, 125:102982.

Kemfert, C. (1998). Estimated Substitution Elasticities of a Nested CES Production Function Approach for Germany. *Energy Economics*, 20(3):249–264.

Kerby, J. and Tarekegne, B. (2024). A guide to residential energy storage and rooftop solar: State net metering policies and utility rate tariff structures. *Renewable Energy Focus*, 49:100566.

Kiessling, S., Gohari Darabkhani, H., and Soliman, A.-H. (2024). Greater energy independence with sustainable steel production. *Sustainability*, 16(3):1174.

Kim, J., Baek, K., Lee, E., and Kim, J. (2023). Analysis of net-metering and cross-subsidy effects in south korea: Economic impact across residential customer groups by electricity consumption level. *Energies*, 16(2):717.

Leal Filho, W., Trevisan, L. V., Salvia, A. L., Mazutti, J., Dibbern, T., de Maya, S. R., Bernal, E. F., Eustachio, J. H. P. P., Sharifi, A., Alarcón-del Amo, M.-d.-C., et al. (2024). Prosumers and sustainable development: An international assessment in the field of renewable energy. *Sustainable Futures*, 7:100158.

Madeddu, S., Ueckerdt, F., Pehl, M., Peterseim, J., Lord, M., Kumar, K. A., Krüger, C., and Luderer, G. (2020). The CO2 Reduction Potential for the European Industry via Direct Electrification of Heat Supply (Power-to-Heat). *Environmental Research Letters*, 15(12).

Nordhaus, W. D. (2017). Revisiting the Social Cost of Carbon. *Proceedings of the National Academy of Sciences*, 114(7):1518–1523.

Papageorgiou, C., Saam, M., and Schulte, P. (2017). Substitution between Clean and Dirty Energy Inputs: A Macroeconomic Perspective. *Review of Economics and Statistics*, 99(2):281–290.

van der Ploeg, F. and Rezai, A. (2020). The risk of policy tipping and stranded carbon assets. *Journal of Environmental Economics and Management*, 100:102258.

Van der Ploeg, F. and Rezai, A. (2020). Stranded assets in the transition to a carbon-free economy. *Annual review of resource economics*, 12(1):281–298.

Walmsley, T. G., Philipp, M., Picón-Núñez, M., Meschede, H., Taylor, M. T., Schlosser, F., and Atkins, M. J. (2023). Hybrid renewable energy utility systems for industrial sites: A review. *Renewable and Sustainable Energy Reviews*, 188:113802.

Appendix A. Model

A.1. **First-Order Conditions in the Deterministic Model.** This appendix provides detailed derivations of the first-order conditions (FOCs) for each sector in the deterministic version of the model. We distinguish between two dimensions: the organization of the manufacturing sector, with or without a make-or-buy (MoB) decision, and the structure of the electricity sector, competitive or monopolistic.

In all cases, firms take prices as given under perfect competition, while the electricity sector internalizes demand when acting as a monopolist. All variables and parameters are described in Section 4.

A.1.1. *Manufacturing Sector.* The manufacturing sector produces the final good using capital, labor, and electricity. Electricity is either directly used (no MoB case) or combined with internally produced energy through a composite input (MoB case).

With Make-or-Buy (MoB).. In this case, the firm can produce electricity internally using clean capital $K_t^{c,M}$ or purchase electricity from the electricity sector. These two inputs are aggregated through a CES function Pow_t. The firm solves:

$$\max \Pi_t^M = \max_{K_t^{c,M}, K_t^{n,M}, E_t, N_t} Y_t - r_t^K (K_t^{c,M} + K_t^{n,M}) - W_t N_t - P_t^E E_t, \tag{25}$$

$$\text{s.t.} \quad Y_t = (A_t N_t)^{1-\nu-\kappa} \left(K_t^{n,M}\right)^{\nu} Pow_t^{\kappa}, \tag{26}$$

$$Pow_t = \left[\omega_P \left(A_t^{c,M} K_t^{c,M}\right)^{\psi_P} + (1-\omega_P) E_t^{\psi_P}\right]^{\frac{1}{\psi_P}}, \tag{27}$$

where FOCs are given by

$$\frac{\partial \Pi_t^M}{\partial K_t^{c,M}} = 0 \quad \Leftrightarrow r_t^K = \kappa \omega_P \frac{Y_t}{K_t^{c,M}} \left(\frac{A_t^{c,M} K_t^{c,M}}{Pow_t}\right)^{\psi_P} \tag{28}$$

$$\frac{\partial \Pi_t^M}{\partial K_t^{n,M}} = 0 \quad \Leftrightarrow r_t^K = \nu \frac{Y_t}{K_t^{n,M}} \tag{29}$$

$$\frac{\partial \Pi_t^M}{\partial N_t} = 0 \quad \Leftrightarrow w_t = (1-\nu-\kappa) \frac{Y_t}{N_t} \tag{30}$$

$$\frac{\partial \Pi_t^M}{\partial E_t} = 0 \quad \Leftrightarrow P_t^E = \kappa (1-\omega_P) \frac{Y_t}{E_t} \left(\frac{E_t}{Pow_t}\right)^{\psi_P}. \tag{31}$$

Without Make-or-Buy. In the absence of a make-or-buy decision, electricity is directly used in production. The problem simplifies to:

$$\max \Pi_t^M = \max_{K_t^{n,M}, E_t, N_t} Y_t - r_t^K K_t^{n,M} - W_t N_t - P_t^E E_t, \tag{32}$$

$$\text{s.t.} \quad Y_t = (A_t N_t)^{1-\nu-\kappa} \left(K_t^{n,M}\right)^{\nu} E_t^{\kappa}, \tag{33}$$

where FOCs become

$$\frac{\partial \Pi_t^M}{\partial K_t^{n,M}} = 0 \quad \Leftrightarrow r_t^K = \nu \frac{Y_t}{K_t^{n,M}} \tag{34}$$

$$\frac{\partial \Pi_t^M}{\partial N_t} = 0 \quad \Leftrightarrow w_t = (1-\nu-\kappa) \frac{Y_t}{N_t} \tag{35}$$

$$\frac{\partial \Pi_t^M}{\partial E_t} = 0 \quad \Leftrightarrow P_t^E = \kappa \frac{Y_t}{E_t} \tag{36}$$

A.1.2. *Electricity Sector.* The electricity sector combines clean and dirty capital through a CES technology

$$E_t = \left[\omega_E \left(A_t^{c,E} K_t^{c,E}\right)^{\psi_E} + (1-\omega_E) \left(A_t^{d,E} K_t^{d,E}\right)^{\psi_E}\right]^{\frac{1}{\psi_E}}. \tag{37}$$

Competitive Electricity Sector. Under perfect competition, firms take prices as given and choose capital inputs to maximize profits.

The electricity sector maximizes its profit subject to its production function, controlling the level of inputs $K_t^{d,E}$ and $K_t^{c,E}$, and taking prices r_t^K as given, such that

$$\max \Pi_t^E = \max_{K_t^{c,E}, K_t^{d,E}} P_t^E E_t - r_t^K (K_t^{c,E} + K_t^{d,E}),$$

s.t. Equation 37.

Deriving the FOCs, we have:

$$\frac{\partial \Pi_t^E}{\partial K_t^{c,E}} = 0 \quad \Leftrightarrow \frac{r_t^K}{P_t^E} = \omega_E A_t^{c,E} \left(\frac{E_t}{A_t^{c,E} K_t^{c,E}}\right)^{1-\psi_E} \tag{38}$$

$$\frac{\partial \Pi_t^E}{\partial K_t^{d,E}} = 0 \quad \Leftrightarrow \frac{r_t^K}{P_t^E} = (1-\omega_E) A_t^{d,E} \left(\frac{E_t}{A_t^{d,E} K_t^{d,E}}\right)^{1-\psi_E} \tag{39}$$

Monopolistic Electricity Sector. Under a monopoly, the problem is solved in two stages.

Stage 1: Cost minimization.

The electricity firm minimizes the cost of producing a given level of output E_t, taking input prices as given. This corresponds to a standard expenditure minimization problem under CES technology. In the general CES case, we write the EMP as

$$\begin{aligned} e(p_i, \bar{Y}) &= \min_{x_i} \sum_i x_i p_i, \\ \text{s.t.} \quad \bar{Y} &= \left(\sum_i w_i x_i^{\psi} \right)^{\frac{1}{\psi}}, \end{aligned} \tag{40}$$

where the goal is to find the minimal amount of inputs x_i needed to produce $\bar{Y}$, given prices p_i.

Implementing a Lagrangian with a multiplier λ, we find with the FOCs that

$$x_i = \frac{(w_i/p_i)^{\frac{1}{1-\psi}}}{\left(\sum_j \left(w_j / p_j^{\psi} \right)^{\frac{1}{1-\psi}} \right)^{\frac{1}{\psi}}} \bar{Y}, \tag{41}$$

$$\lambda = \frac{1}{\left(\sum_j \left(w_j / p_j^{\psi} \right)^{\frac{1}{1-\psi}} \right)^{\frac{1-\psi}{\psi}}}. \tag{42}$$

In our setup, $x_i \in \left\{ K_t^{c,E}, K_t^{d,E} \right\}$, $w_i \in \left\{ \omega_E \left(A_t^{c,E} \right)^{\psi_E}, (1-\omega_E) \left(A_t^{d,E} \right)^{\psi_E} \right\}$. Therefore, the resulting input demand functions and marginal cost Λ_t are:

$$K_t^{c,E} = \frac{\left(\omega_E \frac{\left(A_t^{c,E} \right)^{\psi_E}}{r_t^K} \right)^{\frac{1}{1-\psi_E}}}{\left\{ \left(\omega_E \left(\frac{A_t^{c,E}}{r_t^K} \right)^{\psi_E} \right)^{\frac{1}{1-\psi_E}} + \left((1-\omega_E) \left(\frac{A_t^{d,E}}{r_t^K + \tau} \right)^{\psi_E} \right)^{\frac{1}{1-\psi_E}} \right\}^{\frac{1}{\psi_E}}} E_t, \tag{43}$$

$$K_t^{d,E} = \frac{\left((1-\omega_E) \frac{\left(A_t^{d,E} \right)^{\psi_E}}{r_t^K + \tau} \right)^{\frac{1}{1-\psi_E}}}{\left\{ \left(\omega_E \left(\frac{A_t^{c,E}}{r_t^K} \right)^{\psi_E} \right)^{\frac{1}{1-\psi_E}} + \left((1-\omega_E) \left(\frac{A_t^{d,E}}{r_t^K + \tau} \right)^{\psi_E} \right)^{\frac{1}{1-\psi_E}} \right\}^{\frac{1}{\psi_E}}} E_t, \tag{44}$$

$$\Lambda_t = \frac{1}{\left\{ \left(\omega_E \left(\frac{A_t^{c,E}}{r_t^K} \right)^{\psi_E} \right)^{\frac{1}{1-\psi_E}} + \left((1-\omega_E) \left(\frac{A_t^{d,E}}{r_t^K + \tau} \right)^{\psi_E} \right)^{\frac{1}{1-\psi_E}} \right\}^{\frac{1-\psi_E}{\psi_E}}}. \tag{45}$$

Stage 2: Price setting.

The monopolist chooses the electricity supply, taking into account the demand from the manufacturing sector. The structure of demand differs across the two manufacturing setups.

$$\max \Pi_t^E = \max_{E_t} \left[P_t^E(E_t) - \Lambda_t \right] E_t,$$
$$\text{s.t.} \quad \begin{cases} \text{Eq.31}, & \text{for MoB case.} \\ \text{Eq.36}, & \text{for no MoB case.} \end{cases} \tag{46}$$

The FOCs for each case are:

$$\begin{cases} \Lambda_t = \left\{ \psi_P + (\kappa - \psi_P)(1-\omega_P)\left(\frac{E_t}{Pow_t}\right)^{\psi_P} \right\}, & \text{for MoB case.} \\ \Lambda_t = \kappa P_t^E, & \text{for no MoB case.} \end{cases} \tag{47}$$

A.1.3. *The Representative Household.* The representativee household solves the dynamic optimization problem

$$\begin{aligned} V(K) &= \max_{C,K'} U(C) + \beta V(K') \\ \text{s.t.} \quad & C + K' = (1-\delta+r^K)K + W + \Pi^M + \Pi^E + T, \\ & K_0 \geq 0, \\ & \lim_{T\to\infty} \beta^T V_K(K_T)K_T = 0, \end{aligned} \tag{48}$$

The FOC and envelope theorem lead to the unique Euler equation

$$\left(\frac{C'}{C}\right)^{\gamma} = \beta(1+r'). \tag{49}$$

A.2. **First-Order Conditions in the Stochastic Model.** The only modification from the deterministic case lies in the representative household optimization problem. All else stays equal.

A.2.1. *The Representative Household.* The representative household solves two optimization problems, depending on whether the economy is in the pre-tax or post-tax regime.

Post-tax regime. Once the tax is implemented, the economy remains in the post-tax regime. The household problem is

$$V^\tau(K) = \max_{\{C,K'\}} \{U(C) + \beta V^\tau(K')\} \tag{50}$$

subject to

$$C + K' = (1-\delta+r^{K,\tau})K + W^\tau + \Pi^{M,\tau} + \Pi^{E,\tau} + T^\tau, \tag{51}$$

where

$$T^\tau = \tau K^{d,E}. \tag{52}$$

The first-order condition is

$$U_C(C^\tau) = \beta V_K^\tau(K'). \tag{53}$$

The envelope condition is

$$V_K^\tau(K) = U_C(C^\tau)(1 - \delta + r^{K,\tau}). \tag{54}$$

Combining both gives the post-tax Euler equation:

$$U_C(C^\tau) = \beta U_C(C^{\tau\prime})(1 - \delta + r^{K,\tau\prime}). \tag{55}$$

In steady state:

$$1 = \beta(1 - \delta + r^{K,\tau}), \tag{56}$$

so that

$$r^{K,\tau} = \frac{1}{\beta} - (1 - \delta). \tag{57}$$

Pre-tax regime. Before the tax is implemented, the household takes into account that the economy moves to the post-tax regime with probability p^τ in the following period. The pre-tax household problem is

$$V(K) = \max_{\{C,K'\}} \{U(C) + \beta [p^\tau V^\tau(K') + (1 - p^\tau)V(K')]\} \tag{58}$$

subject to

$$C + K' = (1 - \delta + r^K)K + W + \Pi^M + \Pi^E. \tag{59}$$

The first-order condition is

$$U_C(C) = \beta [p^\tau V_K^\tau(K') + (1 - p^\tau)V_K(K')]. \tag{60}$$

The envelope condition in the pre-tax regime is

$$V_K(K) = U_C(C)(1 - \delta + r^K). \tag{61}$$

Using the post-tax and pre-tax envelope conditions, the pre-tax Euler equation is

$$U_C(C) = \beta \left[p^\tau U_C(C^{\tau\prime})(1 - \delta + r^{K,\tau\prime}) + (1 - p^\tau)U_C(C')(1 - \delta + r^{K\prime})\right]. \tag{62}$$

In steady state, this becomes

$$U_C(C) = \beta \left[p^\tau U_C(C^\tau)(1 - \delta + r^{K,\tau}) + (1 - p^\tau)U_C(C)(1 - \delta + r^K)\right]. \tag{63}$$

Using the post-tax steady-state condition

$$1 - \delta + r^{K,\tau} = \frac{1}{\beta}, \tag{64}$$

we obtain

$$1 = p^\tau \frac{U_C(C^\tau)}{U_C(C)} + \beta(1 - p^\tau)(1 - \delta + r^K). \tag{65}$$

Therefore,

$$r^K = \frac{1 - p^\tau \frac{U_C(C^\tau)}{U_C(C)}}{\beta(1 - p^\tau)} - (1 - \delta). \tag{66}$$

With CRRA preferences,

$$U(C) = \frac{C^{1-\gamma}}{1-\gamma}, \qquad U_C(C) = C^{-\gamma}, \tag{67}$$

so that

$$r^K = \frac{1 - p^\tau \left(\frac{C^\tau}{C}\right)^{-\gamma}}{\beta(1-p^\tau)} - (1-\delta). \tag{68}$$

Appendix B. Steady State Values

The tables B.1 and B.2 show the steady state values for the four model variants presented in A.

Table B.1. Steady-state values under perfect competition with tax

(a) No make-or-buy

	No tax	Pre tax	Post tax
$K^{n,M}$	5.39	7.12	5.25
$K^{c,M}$	–	–	–
$K^{c,E}$	0.16	0.21	0.23
$K^{d,E}$	0.56	0.74	0.25
E	1.45	1.92	0.90
Pow	–	–	–
Y	2.07	2.28	2.02
C	1.46	1.47	1.44
P^E	0.06	0.05	0.09
W	1.37	1.50	1.33

(b) Make-or-buy

	No tax	Pre tax	Post tax
$K^{n,M}$	5.28	6.89	5.15
$K^{c,M}$	0.06	0.08	0.07
$K^{c,E}$	0.14	0.19	0.20
$K^{d,E}$	0.50	0.65	0.22
E	1.30	1.70	0.79
Pow	1.01	1.32	0.66
Y	2.03	2.22	1.98
C	1.43	1.44	1.41
P^E	0.06	0.05	0.09
W	1.34	1.47	1.31

Table B.2. Steady-state values under monopoly with tax

(a) No make-or-buy

	No tax	Pre tax	Post tax
$K^{n,M}$	4.44	8.43	4.32
$K^{c,M}$	–	–	–
$K^{c,E}$	0.01	0.01	0.01
$K^{d,E}$	0.02	0.03	0.01
E	0.05	0.09	0.03
Pow	–	–	–
Y	1.70	2.12	1.66
C	1.26	1.27	1.22
P^E	1.43	0.93	2.24
W	1.12	1.40	1.09
Λ	0.06	0.04	0.09
π^E	0.07	0.08	0.06

(b) Make-or-buy

	No tax	Pre tax	Post tax
$K^{n,M}$	4.66	7.76	4.58
$K^{c,M}$	0.13	0.21	0.14
$K^{c,E}$	0.01	0.02	0.02
$K^{d,E}$	0.04	0.06	0.02
E	0.09	0.15	0.06
Pow	0.11	0.19	0.08
Y	1.79	2.13	1.76
C	1.31	1.33	1.28
P^E	0.62	0.44	0.90
W	1.18	1.41	1.16
Λ	0.06	0.04	0.09
π^E	0.05	0.06	0.05

The subsidy experiments are implemented symmetrically to the carbon-tax experiment. Whereas the tax raises the user cost of dirty electricity capital, a subsidy lowers the user cost of clean capital. Formally, a subsidy to clean electricity-sector capital enters the electricity producer's problem as a negative tax on $K^{c,E}$, while a subsidy to clean manufacturing capital enters the manufacturer's problem as a negative tax on $K^{c,M}$. The economic mechanism is therefore the mirror image of the carbon tax: instead of penalizing dirty capital, the policy makes clean capital cheaper and induces firms to expand clean investment.

The fiscal side also changes sign relative to the tax experiment. The carbon tax raises public revenue that is rebated in a lump sum to the household. By contrast, clean-capital subsidies require fiscal resources and are financed by a lump-sum tax on the representative household. Thus, subsidies can increase clean capital, lower electricity prices, and raise output, but they also reduce household resources through the tax needed to finance the subsidy. This distinction is important for interpreting the output–consumption trade-off in the subsidy results.

The tables B.3 and B.4 show the steady state values for the four model variants in the subsidy case.

TABLE B.3. Steady-state values under perfect competition with subsidies

(A) No make-or-buy

	No subsidy	Subsidy E
$K^{n,M}$	5.39	5.67
$K^{c,E}$	0.16	3.54
$K^{d,E}$	0.56	0.29
E	1.45	3.52
Y	2.07	2.18
C	1.46	1.23
P^E	0.06	0.02
W	1.37	1.44
$K^{c,M}$	–	–
Pow	–	–

(B) Make-or-buy

	No subsidy	Subsidy E	Subsidy M	Subsidy E+M
$K^{n,M}$	5.28	5.54	5.37	5.60
$K^{c,E}$	0.14	3.25	0.13	3.04
$K^{d,E}$	0.50	0.26	0.46	0.25
E	1.30	3.23	1.19	3.02
Y	2.03	2.13	2.06	2.15
C	1.43	1.22	1.37	1.19
P^E	0.06	0.02	0.06	0.02
W	1.34	1.40	1.36	1.42
$K^{c,M}$	0.06	0.04	0.96	0.74
Pow	1.01	2.31	1.33	2.81

APPENDIX C. ADDITIONAL QUANTITATIVE RESULTS

C.1. **Welfare Levels and Consumption-Equivalent Changes.** This appendix describes the welfare measures reported in the quantitative analysis. We report two objects. The first is the level of lifetime welfare implied by the representative household's value function. The second is the consumption-equivalent welfare change relative to the benchmark economy with perfect competition, no make-or-buy margin, and no tax.

Preferences are CRRA:

$$U(C) = \frac{C^{1-\gamma} - 1}{1-\gamma}, \qquad \gamma \neq 1. \tag{69}$$

For a deterministic steady state with constant consumption C, lifetime welfare is

$$V(C) = \sum_{t=0}^{\infty} \beta^t U(C) = \frac{U(C)}{1-\beta}. \tag{70}$$

TABLE B.4. Steady-state values under monopoly with subsidies

(A) No make-or-buy

	No subsidy	Subsidy E
$K^{n,M}$	4.44	4.67
$K^{c,E}$	0.01	0.12
$K^{d,E}$	0.02	0.01
E	0.05	0.12
Y	1.70	1.79
C	1.26	1.31
P^E	1.43	0.62
W	1.12	1.18
Λ	0.06	0.02
π^E	0.07	0.07
$K^{c,M}$	–	–
Pow	–	–

(B) Make-or-buy

	No subsidy	Subsidy E	Subsidy M	Subsidy E+M
$K^{n,M}$	4.66	4.83	4.89	5.04
$K^{c,E}$	0.01	0.21	0.01	0.25
$K^{d,E}$	0.04	0.02	0.04	0.02
E	0.09	0.20	0.11	0.25
Y	1.79	1.85	1.88	1.93
C	1.31	1.34	1.22	1.26
P^E	0.62	0.31	0.44	0.22
W	1.18	1.22	1.24	1.28
Λ	0.06	0.02	0.06	0.02
π^E	0.05	0.06	0.04	0.05
$K^{c,M}$	0.13	0.10	1.69	1.41
Pow	0.11	0.21	0.26	0.44

We use this expression to compute welfare in the no-tax and post-tax steady states:

$$V_j^{no} = \frac{U(C_j^{no})}{1-\beta}, \qquad V_j^{post} = \frac{U(C_j^{post})}{1-\beta}, \tag{71}$$

where j indexes the market structure and make-or-buy regime.

In the stochastic pre-tax regime, agents consume C_j^{pre} today and anticipate a transition to the post-tax regime with probability p^τ each period. The pre-tax value therefore satisfies

$$V_j^{pre} = U(C_j^{pre}) + \beta \left[p^\tau V_j^{post} + (1-p^\tau) V_j^{pre} \right]. \tag{72}$$

Solving for V_j^{pre} gives

$$V_j^{pre} = \frac{U(C_j^{pre}) + \beta p^\tau V_j^{post}}{1-\beta(1-p^\tau)}. \tag{73}$$

These values are reported in the welfare-level table.

		No-tax	Stochastic pre-tax	Post-tax
Perfect competition	No MoB	22.995	22.356	22.318
	MoB	21.856	21.265	21.228
Monopoly	No MoB	14.467	12.943	12.860
	MoB	16.736	15.731	15.663

TABLE C.1. Lifetime welfare across market structures and tax regimes

Notes: Entries report lifetime utility values under CRRA preferences. The stochastic pre-tax regime corresponds to the economy before tax implementation, when agents anticipate a future transition to the taxed regime with probability p^τ each period.

To make welfare differences easier to interpret, we also compute consumption-equivalent welfare changes. Let V^b denote welfare in the benchmark economy, defined as the no-tax steady state under perfect competition without make-or-buy. For any alternative economy j, the consumption-equivalent change λ_j is defined as the permanent proportional change in benchmark consumption that makes the representative household indifferent between the benchmark and economy j:

$$\sum_{t=0}^{\infty} \beta^t U\left((1+\lambda_j)C^b\right) = V_j. \tag{74}$$

Using CRRA preferences, this implies

$$\lambda_j = \left[\frac{(1-\gamma)(1-\beta)V_j + 1}{(1-\gamma)(1-\beta)V^b + 1}\right]^{\frac{1}{1-\gamma}} - 1. \tag{75}$$

We report $100 \times \lambda_j$ in percent. Negative values indicate welfare losses relative to the competitive no-tax economy without make-or-buy.

		No MoB	MoB
Perfect competition	No tax	0.00%	-2.03%
	Stochastic pre-tax	-1.15%	-3.06%
	Post-tax	-1.22%	-3.13%
Monopoly	No tax	-13.83%	-10.45%
	Stochastic pre-tax	-16.00%	-11.97%
	Post-tax	-16.12%	-12.07%

Table C.2. Consumption-equivalent welfare changes relative to the competitive no-tax economy without make-or-buy

Notes: Entries report consumption-equivalent welfare changes, in percent, relative to the benchmark economy with perfect competition, no make-or-buy margin, and no tax. Negative values indicate welfare losses relative to the benchmark. The stochastic pre-tax regime corresponds to the economy before tax implementation, when agents anticipate a future transition to the taxed regime with probability p^τ each period.

C.2. **Post-Tax Sensitivity to Substitution Elasticities.** This appendix reports the full tax-sweep counterpart of the sensitivity exercise discussed in Section 6. The figure plots post-tax steady states as the tax on dirty electricity capital varies, for alternative values of the CES substitution parameters ψ_E and ψ_P. This exercise isolates how the long-run allocation after the tax depends on the ease of substitution within electricity production and within the manufacturing power aggregate.

The left column varies ψ_E, which governs substitution between clean and dirty capital in electricity production. A higher ψ_E increases the responsiveness of clean electricity capital to the tax, especially under perfect competition. Its effect on clean manufacturing capital is much smaller, indicating that the generation-side substitution margin mainly affects reallocation within the electricity sector.

The middle column varies ψ_P, which governs substitution between purchased electricity and clean on-site generation. This margin has a stronger cross-sector effect. When

ψ_P changes, both clean manufacturing capital and clean electricity capital respond, because manufacturers' sourcing decisions affect demand for purchased electricity. The effect is particularly relevant under monopoly, where the electricity price is higher and self-generation becomes a more valuable outside option.

The bottom-right panel shows that the electricity price is much higher under monopoly than under perfect competition, while its response to ψ_E is limited. Overall, the figure confirms that ψ_E mainly governs within-sector technological substitution in electricity production, whereas ψ_P governs the interdependence between the electricity and manufacturing sectors.

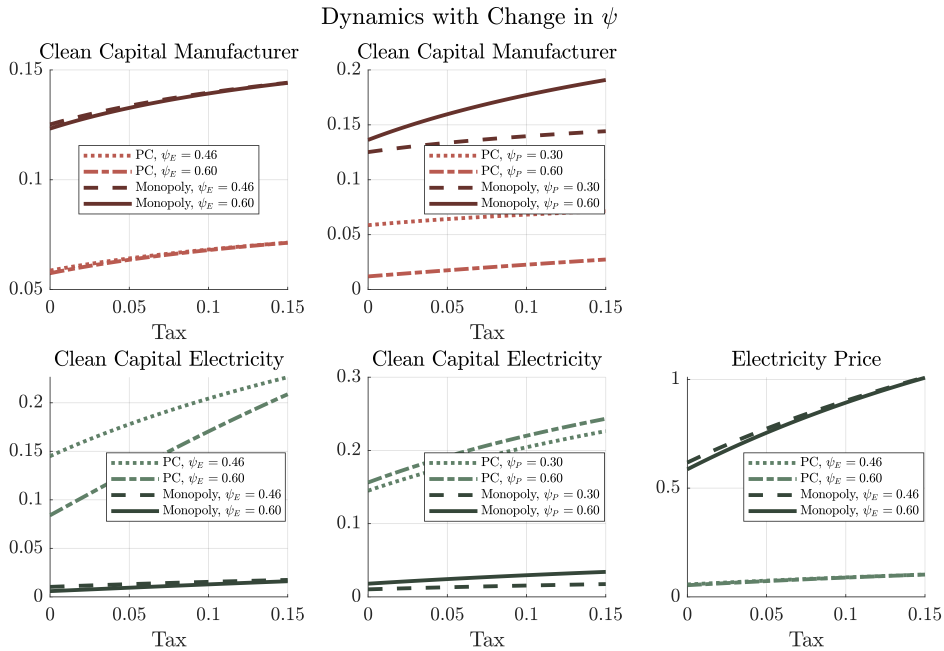

FIGURE C.1. Post-tax Steady-State Responses to Substitution Elasticities

Note: The figure reports post-tax steady states for alternative values of the CES substitution parameters. The horizontal axis is the tax on dirty electricity capital. Panels in the first column vary ψ_E, which governs substitutability between clean and dirty capital in electricity production, while holding ψ_P fixed at its baseline value. Panels in the second column vary ψ_P, which governs substitutability between purchased electricity and clean on-site generation in the manufacturing power aggregate, while holding ψ_E fixed at its baseline value. The bottom-right panel reports the electricity price for the ψ_E comparison. Each panel compares perfect competition and monopoly. Manufacturing variables are shown in red and electricity-sector variables in green; darker shades correspond to monopoly cases. Line styles distinguish the market structure and the value of the substitution parameter varied in that panel.