Research Statement

Koichiro Ito, University of Chicago
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ito@uchicago.edu
http://home.uchicago.edu/ito

I gained my research interest in environmental and energy economics relatively early in life. As a high school student, I wondered why the economic system of our society did not seem to have well-designed solutions to environmental problems, such as pollution and climate change. This question motivated me to study environmental economics in college.

Economics textbooks gave me a simple answer to this question—in an ideal world with perfectly competitive firms and well-informed and rational consumers, society can address environmental problems simply by internalizing negative externalities through a Pigouvian tax, as described by Pigou (1924). However, the real world is not that simple. Consumers, firms, and even governments might not be as perfectly informed or rational as standard economic theory assumes. Markets may have imperfection such as the existence of market power or incomplete property rights. Governments might have limited ability to implement corrective policies because of political constraints or imperfect governance.

The core of my research is to investigate the behaviors of consumers, firms, and governments in environmental and energy markets, and explore market and policy design that accommodates these behaviors in the real economy. To do this, I develop theoretical predictions based on microeconomics models, collect data, econometrically test if theoretical predictions are consistent or inconsistent with data, and provide policy implications. Below, I describe three distinct but closely related themes of my research program.

Theme	Key Paper
1. Consumer behavior in energy markets	"Do Consumers Respond to Marginal or Average Price? Evidence from Nonlinear Electricity Pricing," *American Economic Review*, 104 (2): 537-63, 2014.
2. Firm behavior in energy markets	"Sequential Markets, Market Power and Arbitrage" (with Mar Reguant), *American Economic Review*, 106 (7): 1921-57, 2016.
3. Environmental and energy markets in developing countries	"Willingness to Pay for Clean Air: Evidence from Air Purifier Markets in China" (with Shuang Zhang), conditionally accepted, *Journal of Political Economy*.

1 Consumer Behavior in Energy Markets

In conventional models of consumer behavior in electricity markets, consumers are assumed to have perfect information and understanding of their electricity price schedules. This assumption has played a key role in theoretical and empirical studies in economics as well as demand forecasts in utility businesses.

In my paper, "**Do Consumers Respond to Marginal or Average Price? Evidence from Nonlinear Electricity Pricing**" (*American Economic Review*, 2014), I investigate if this common assumption is substantiated by real-world data. Many residential electricity customers in the United States have "increasing-block pricing," in which the unit price of electricity increases as a customer's monthly consumption increases. Economic theory provides at least three possibilities about the form of the consumer's perceived price of nonlinear price schedules. The standard model of nonlinear budget sets predicts that consumers with perfect information and understanding of price schedules respond to *marginal price*. With uncertainty about consumption, rational consumers might respond to *expected marginal price*. Alternatively, consumers might use *average price* as an approximation of marginal price if the cognitive cost of understanding complex pricing is substantial. I develop three econometric tests to uncover the form of perceived price. I then apply these tests to household-level administrative data on monthly electricity usage in California from 1999 to 2007.

Results from the three empirical strategies show strong evidence that consumers respond to average price rather than marginal or expected marginal price. This sub-optimizing behavior changes the policy implications of nonlinear pricing. First, the suboptimal response makes nonlinear pricing unsuccessful in achieving its policy goal of energy conservation. Second, the sub-optimal response changes the efficiency cost of nonlinear pricing. It reduces the efficiency cost for a reasonable range of the private marginal costs of electricity. However, it increases the efficiency cost when the social marginal cost of electricity is substantially high due to negative environmental externalities caused by electricity generation.

This paper influenced subsequent academic research (Kahn and Wolak, 2013; Copeland and Garratt, 2015; McRae and Meeks, 2016) as well as policy ruling and utility businesses outside academia. For example, the California Public Utilities Commission (CPUC) ordered electric utilities to simplify residential electricity tariffs in 2015, citing empirical evidence presented in this paper as a ground for the reform (California Public Utility Commission, 2015). Electric utilities, including BC Hydro in British Columbia, Canada, have incorporated consumers' responses to "average price" rather than marginal price in their demand forecasting models and found improvements in demand forecasts.

In addition to electricity pricing, regulators frequently use various forms of "rebate programs" to incentivize energy conservation and adaptation of energy-efficient products. While such rebate programs are ubiquitous, evidence on its causal impact is quite limited. Many existing studies are based on observational data on electricity usage "before and after" a policy intervention, and therefore, are likely to be confounded by omitted variable bias.

My paper, "**Asymmetric Incentives in Subsidies: Evidence from a Large-Scale Electricity Rebate Program**" (*American Economic Journal: Economic Policy*, 2015), shows why commonly-used estimation is likely to produce misleading conclusions about the effect of electricity rebate programs, taking California's "20/20 electricity rebate program" as an application. This program provided almost all California residents a 20 percent discount on their summer electricity bills if a household reduced its summer electricity usage by 20 percent of the previous summer's electricity consumption. Many residents indeed received this rebate, and regulators praised the success of this program based on the fact that a large number of customers received the rebate. This program eventually encouraged other states and countries to adopt similar programs.

In this study, I show that many customers (and in certain areas, almost all of these customers) received their rebates for reasons unrelated to their conservation efforts. Data on household-level electricity usage reveal that a customer's electricity consumption fluctuates substantially on a year-to-year basis. This fluctuation naturally makes a large number of consumers use less electricity in a given year compared to their usage in other years. To isolate these fluctuations from the causal impact of the program, I develop a regression discontinuity design that exploits a discrete threshold of the program eligibility rule. I find that the rebate incentive produced precisely-estimated zero treatment effects on energy conservation in coastal areas. In contrast, it induced short-run and long-run reductions in electricity usage in inland areas. Income, climate, and air conditioner saturation significantly drive the heterogeneity. With these findings, I examine how the policy design can be improved to increase its cost-effectiveness.

An important recent technological development in electricity markets is the widespread adoption of an advanced metering infrastructure (AMI). Such "smart meters" are able to record real-time electricity usage data, and therefore, allow dynamic pricing. In collaboration with the Japanese central and local governments, electric utilities, and manufacturers, I conducted field experiments to study how policymakers can take advantage of this technology to improve market efficiency and address electricity crises.

In "**Moral Suasion and Economic Incentives: Field Experimental Evidence from Energy Demand**" (*American Economic Journal: Economic Policy*, 2018), co-authored with Takanori Ida at Kyoto University and Makoto Tanaka at GRIPS, we designed a field experiment to study two policy interventions that are commonly used by regulators in many countries. The first intervention is "moral suasion" (a message from a government to encourage energy conservation when the supply of electricity is limited), by which policymakers attempt to influence intrinsic motivation to generate pro-social behavior on energy conservation. The second intervention is economic incentives—policymakers use dynamic electricity pricing to affect extrinsic motivation based on standard demand theory.

Using a randomized controlled trial (RCT) for households in the Kyoto prefecture in Japan, we find notable differences between the effects of the two policy interventions. First, moral suasion induced short-run reductions in electricity usage, but the effects diminished quickly over repeated interventions, indicating strong *habituation* (Thompson and Spencer, 1966). Second, economic incentives created much larger and persistent effects. Moreover, the effect was much more persistent over repeated interventions, suggesting relatively little habituation compared to the case with moral suasion. Third, we examine *dishabituation*—whether habituated responses can be restored back to their original levels (Rankin and Carew, 1988). The habituated response to moral suasion was "reset" (i.e., recovered back to the original level) when we restarted our intervention a few months after the initial intervention period. Fourth, economic incentives resulted in *habit formation* (Becker and Murphy, 1988) as energy conservation persisted even after the intervention period. Such persistence was not observed for moral suasion. These findings suggest that moral suasion is an effective policy for short-run but unlikely to provide persistent impacts, whereas economic incentives are likely to produce larger and more persistent impacts.

While we find the effectiveness of dynamic electricity pricing in this field experiment, utility companies in many countries offer dynamic pricing as an optional price schedule to customers instead of a mandate. This voluntary take-up policy induces self-selection and therefore, it is important to study who self-selects into dynamic pricing and ask whether the self-selected customers are the ones that improve

the social welfare or not. With this motivation, we conducted another field experiment in Yokohama, Japan, and are currently working on two papers, "**Information Frictions, Inertia, and Selection on Elasticity: A Field Experiment on Electricity Tariff Choice**" (work in progress) and "**Policy Design with Advantageous Selection: Experimental Evidence from Electricity Plan Choice**" (work in progress). With a randomized controlled trial with 2,000 households, we empirically find two key self-selection mechanisms. First, consumers who would save money from dynamic pricing without changing their electricity usage—called "structural winners"—self-select into dynamic pricing, as long as they are informed about such gains. Second, consumers who have price-elastic demand are more likely to self-select in anticipation of their behavioral responses to price changes. We use these findings to compare the welfare impacts of different policy designs, including 1) a voluntary take-up policy, 2) a voluntary take-up with a targeted financial incentive, and 3) a complete mandate.

2 Firm Behavior in Energy Markets

Energy markets such as electricity, natural gas, oil, and automobile markets, are among the most important markets for the economy. However, it is also challenging to study these markets due to their complexity and continuous changes in market structures and relevant regulations. In this scheme of my research agenda, I study firm behavior and its interaction with regulation. In particular, my studies aim to investigate how to design markets to address two primary market failures—the existence of market power and negative environmental externalities.

In "**Sequential Markets, Market Power and Arbitrage**" (*American Economic Review*, 2016), co-authored with Mar Reguant at Northwestern University, we study how arbitrage between forward and spot wholesale electricity markets interact with the market power of electricity producers. We start by noting a frequent observation that prices do not converge between forward and spot wholesale electricity markets. That is, there is a systematic difference in prices across these sequential markets that is not arbitraged away. The most frequent explanations are risk aversion and asymmetric shocks, but they do not adequately explain the observed data. We offer market power as an alternative explanation. We present a new theoretical framework to examine how the existence of market power can interact with constraints to arbitrage, and prevent full price convergence in sequential markets. In a wholesale electricity market, demand is inelastic and allocated in full in the forward market, and financial arbitrage is constrained by regulation. In this setting, a firm that has market power has an incentive to act as a price-discriminating dynamic monopolist in the two markets. The optimal strategy for the dynamic monopolist is to withhold some production in the forward market in order to increase profit. This strategic behavior theoretically creates higher equilibrium prices for forward markets than a spot market.

We test this prediction by collecting micro-data from the Spanish electricity market. We find that the price declines across sequential markets in this sector are consistent with our theoretical prediction. We also quantify that the degree of market power positively influences the size of the forward price premiums. In addition, we find evidence that some wind farms exploit these arbitrage opportunities in ways that are not available to other market participants. Consistent with a prediction from the model, wind farms

owned by dominant firms (i.e. firms that have market power) do not engage in arbitrage, and only fringe wind farms perform arbitrage in the market.

The final prediction of the theoretical model is that arbitrage almost always improves welfare in a simple model with perfect competition, but such implications can change once the existence of market power is taken into account. To quantify the welfare effects of sequential markets, market power, and arbitrage, we build a structural Cournot model with a forward and spot market. Using the structural estimates, we show that 1) the existence of forward markets reduces market power and enhances market efficiency, consistent with a prediction from Allaz and Vila (1993), 2) price convergence in sequential markets should not be readily taken as evidence that the market is efficient, and 3) in the presence of market power, full arbitrage is not necessarily welfare-enhancing, since it reduces consumer costs but increases deadweight loss.

For environmental and energy policies, another important energy sector is transportation. For example, the transportation sector accounts for 70 percent of U.S. oil consumption and 30 percent of U.S. greenhouse gas emissions (Knittel, 2012). Economists have long argued that a tax on emissions is the first best policy to address environmental externalities in the transportation sector. However, in most countries (including the United States), such a tax is usually politically infeasible. For this reason, policymakers have designed a myriad of the second best policies in a politically constrained environment. My studies show that such second best policies often ignore strategic behavior by firms and result in unintended consequences that could run counter to goals.

In "**The Economics of Attribute-Based Regulation: Theory and Evidence from Fuel-Economy Standards**" (*Review of Economics and Statistics*, 2018), co-authored with James Sallee at University of California at Berkeley, we study the welfare consequences of "attribute-based regulations." An attribute-based regulation (ABR) aims to change one characteristic or behavior of a product, firm, or individual (the "targeted characteristic"), but it takes some other characteristic or behavior (the "secondary attribute") into consideration when determining compliance. For example, Corporate Average Fuel Economy (CAFE) standards in the United States are designed to increase the fuel economy of cars (targeted characteristic), but they take the size of each car (secondary attribute) into consideration. Firms making larger cars are allowed to have lower average fuel economy. Fuel-economy regulations are attribute-based in the world's four largest car markets: China, Europe, Japan and the United States, and therefore it is important to understand the welfare consequences of such regulation.

We develop a theoretical model to identify potential benefits and costs of ABR. First, we show that ABR distorts the choice of the secondary attribute by creating an implicit unnecessary subsidy for that attribute. The size of this distortion depends on the elasticity of the secondary attribute with respect to the implicit subsidy created by ABR. In the context of fuel-economy regulation, this prediction implies that size-based fuel economy standards—where the secondary attribute is the size of each car—incentivize firms to upsize their cars to meet the environmental regulation. It makes their sizes deviate from the efficient levels and weakens the incentive to improve fuel economy. Second, we show that "compliance trading schemes" provides the full efficiency benefits of ABR without incurring the distortion described above. ABR is an imperfect substitute for compliance trading, and it is justified only if there is some constraint that prevents trading. Instead, we suspect that many ABRs are motivated by distributional

considerations. In this case, the distortions induced by ABR represent the cost of achieving desired redistribution.

To test these theoretical predictions, we collect data from the Japanese car markets, which enforced attribute-based fuel economy regulation since the 1970's. We use bunching analysis based on quasi-experimental variation in the policy to quantify that the regulatory incentive induced approximately a 10 percent increase in vehicle weight for the cars affected by the policy. This distortion resulted in an increase in safety risk, the cost of which is around $1 billion per year in the Japanese car market. We then develop an empirical model that enables us to simulate three counterfactual policies: 1) attribute-based fuel-economy standards, 2) a flat standard without compliance trading, and 3) a flat standard with compliance trading. We show that attribute-based standards improve efficiency compared to a flat standard with no compliance trading, but this benefit is partially offset by distortions in the attributes. However, attribute-based standards are an imperfect substitute for compliance trading because marginal compliance costs are not perfectly correlated with the attribute, which results in only partial equalization of the marginal compliance costs. In our case, the ABR recovers only about half of the welfare gain that would be achieved by a flat standard with compliance trading. These findings provide important policy implications for fuel-economy regulation in the United States as the government is in the process of updating the policy design.

In an ongoing research project, "**International Spillovers of Policy Impacts Through Multinational Firms: Evidence from Global Automobile Markets**" (work in progress), James Sallee and I are investigating if the distortions documented in our previous paper could have a spillover effect to other countries through production and trade by multinational firms. In most economic studies, the primary focus of empirical research is to investigate the effect of one country's domestic policy on its own country's economy and welfare. However, when a regulation affects products manufactured and traded by multinational firms, one country's policy might have a key impact far beyond its borders. If this mechanism exists, a country's domestic policy can have larger (positive or negative) impacts on the global economy than what economic analysis currently predicts. In this project, we examine if the introduction of attribute-based fuel economy regulations in the United States in 2012 influenced the automobile fleets in the U.S. and abroad through production and sales by multinational automakers.

3 Environmental and Energy Markets in Developing Countries

In the third scheme of my research agenda, I study environmental and energy markets in developing countries. Until recently, the majority of research in environmental and energy economics has focused on problems in developed countries, such as the United States. Nowadays, China and India together emit around 30 percent of the global emissions, while 15 percent of the global emission comes from the United States. Moreover, air and water pollution levels are much more severe in the developing world, which are causing large negative impacts on various economic outcomes, including infant mortality, life expectancy, and labor supply. For these reasons, it is important to study environmental and energy problems not only in the developed nations but also in developing countries

In "**Willingness to Pay for Clean Air: Evidence from Air Purifier Markets in China**" (conditionally accepted, *Journal of Political Economy*), co-authored with Shuang Zhang at University of Colorado Boulder, we ask how much people in developing countries are willing to pay for air quality improvements. Despite the importance of this parameter, evidence has been scarce because of limited availability of data and a lack of readily available exogenous variation in air quality for empirical analysis. In this paper, we address these challenges and provide among the first revealed preference estimates of willingness to pay (WTP) for clean air in developing countries.

Our approach is based on the idea that demand for home-use air purifiers, a main defensive investment for reducing indoor air pollution, provides valuable information for the estimation of WTP for air quality improvements. We begin by developing a random utility model in which consumers purchase air purifiers to reduce indoor air pollution. A key advantage of analyzing air purifier markets is that one of the product attributes—high-efficiency particulate arrestance (HEPA)—informs both consumers and econometricians of the purifier's effectiveness to reduce indoor particulate matter. The extent to which consumers value this attribute, along with the price elasticity of demand, reveals their WTP for indoor air quality improvement.

We apply this framework to scanner data on market transactions in air purifier markets in Chinese cities. The dataset provides comprehensive transaction records of 690 air purifier products for some of the most polluted cities in the world. Our estimation reveals that households are willing to pay $1.34 per year to remove 1 $\mu g/m^3$ of PM_{10}. We also find that substantial heterogeneity in WTP is explained by household income and exposures to media coverage on air pollution. Using these estimates, we examine welfare implications of existing and counterfactual environmental policies in China.

The substantial willingness to pay we found in this paper motivated us to ask the next question—"What policy can be an effective way to improve air pollution in China?" In "**Setting the Price Right: Evidence from Heating Price Reform in China**" (working paper), co-authored with Shuang Zhang, we provide the first empirical evidence on ongoing reform in energy pricing in China. Inefficient energy pricing and the lack of incentives to conserve energy are common problems in developing countries and result in substantial allocative inefficiency. We evaluate a recent major reform in the residential heating system in China that replaced a non-metered fixed payment system with a two-part tariff, called consumption-based billing. We develop an event-study research design that exploits quasi-experimental variation in the staggered rollouts of the reform over ten years.

Using administrative data on household-level daily heating usage before and after the reform, we find that the reform induced a substantial 37 percent reduction in heating usage in four years. We also find evidence of learning. Households reduced heating usage gradually over time, with larger reduction in warmer days (i.e. days when the value of heating was relatively low) in later years. We then use plant-level emission data to examine environmental benefits of the reform. The reduced heating usage was associated with a 35 percent reduction in SO_2 emission concentration. We use these results to calculate the reduction in deadweight loss that was produced by the policy. Our findings provide important implications for energy policy because a growing number of developing countries are in the process of implementing consumption-based energy billing in lieu of pre-existing inefficient fixed-charge billing.

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