Energy Storage Investment and Operation in Efficient Electric Power Systems

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This essay grew out of our work on the MIT Energy Initiative's ongoing *Future of Storage* project, which is concerned with the roles of different energy storage technologies in future decarbonized electric power systems. Our work has focused on simulating optimal investment in and operation of regional electric power systems with tight limits on carbon emissions circa 2050.

In this essay we explore the general properties of cost-efficient electric power systems in which storage performs energy arbitrage to balance supply and demand. We start from an investment planning model descended from the work of Boiteux and Turvey. We assume constant returns to scale in storage as well as in generation, and neglect startup costs of thermal generators. We assume perfect foresight but do not restrict the evolution of demand or of renewable generation. Time periods are linked by use of storage and of ramping constraints on thermal generators.

Using Karush-Kuhn-Tucker analysis we are able to obtain a number of general results regarding investment in and operation of storage facilities under perfect competition and that serve to unify and extend the prior literature. First, we show explicitly that the problem of maximizing overall social welfare in that model can be decomposed into the problems faced by profit-maximizing, perfectly competitive suppliers of each available technology. Second, we show that classic merit-order dispatch for thermal generators is not generally optimal when ramping constraints are binding. Third, our analysis reveals the greater complexity of efficient investment in and operation of storage facilities than for generation. In general, even under constant returns to scale, storage technologies are described by the values of seven parameters. We show that all deployed storage technologies break even at equilibrium under constant returns to scale.

We show analytically that if it is optimal to employ multiple storage technologies, the ones with the lowest capital cost of energy storage capacity are generally the best suited to providing long-term storage. Finally, we employ a numerical case study to illustrate the complexity of operating patterns of storage in systems with multiple storage technologies. Storage technologies optimally play multiple roles, providing charge-discharge cycles of various durations. This exercise supports the insights developed analytically, shows that general analytical results of the "merit-order" variety are not available for storage, and demonstrates the value of frequency domain analysis to characterize the cost-efficient operating regimes of multiple storage technologies.

We see three important directions for future work. First, if the market price of energy is capped below the value of lost load, as is often the case in practice, there will likely be under-investment in storage. It seems plausible, but unproven, that the second-best response involves subsidies to investment in storage. Moreover, even if such subsidies are second-best optimal, they surely vary with the characteristics of storage technologies in ways that are not yet understood.

Second, our use of frequency domain analysis here to describe the optimal operation of storage systems seems to us likely to have merely scratched the surface of what that approach

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can contribute. Examining how the power spectra of alternative storage technologies respond to changes in cost parameters and system conditions may yield broadly useful insights.

Finally, there is clearly a need for efficient computational models that can be used to optimize the operation of real storage systems under realistic stochastic processes of demand and intermittent generation, with realistically imperfect foresight.

A Real Options Analysis of the Effects of Oil Price Uncertainty and Carbon Taxes on the Optimal Timing of Oil Field Decommissioning

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The issue of oil (and gas) field decommissioning is a topical one in the contemporary energy landscape. For both oil and gas operators and governments, the question of the optimal timing of decommissioning is a critical one because of its significant implications for field economics (i.e. from the operator perspective) as well as taxation (i.e. from the government perspective).

This paper examines how three important sources of oil price uncertainty affect the optimal timing of oil field decommissioning. These are (1) the long-run equilibrium oil price, (2) the speed of reversion of oil prices to the long-run equilibrium price, and (3) the degree of oil price volatility. The levels and trends of these sources of oil price uncertainty encapsulate many of the factors that affect the dynamics of the global oil markets which then ultimately impact the optimal timing of the decommissioning of fields.

The paper finds that lower levels of equilibrium oil prices and speed of reversion to equilibrium prices have the effect of fostering early decommissioning of oil fields. Oil price volatility however has the opposite effect. These findings provide valuable insights into how policymakers may identify windows of opportunity for policy interventions leading to (1) an acceleration of the drive towards sustainable energy transition; and/or (2) the maximisation of economic recovery (MER) from petroleum resources. In respect of the former, the paper notes that there has been a significant shift in the global political economy of the upstream oil and gas sector away from policies providing fiscal support to the sector, to rather, the imposition of new carbon taxes and/or the expansion in the level and/or scope of pre-existing such taxes on the sector. Norway for example recently announced a significant hike on upstream carbon taxes. A carbon tax of about $250/tCO2 by 2030 is targeted. This effectively quadrupled the pre-existing level of only $58/tCO2. The Canadian federal government has also announced a steep rise in carbon taxes, with a target of about $135/tCO2 by 2030 sought. Post COP26 (Glasgow 2021), it is expected that the trend in the imposition of higher carbon taxes would continue.

In addition to the examination of the effects of oil price uncertainty therefore, the paper examines the effects of the imposition of carbon taxes on the optimal timing of oil field decommissioning. It shows that the imposition of these taxes fosters early decommissioning to a significant extent. In the most unfavourable oil price environment and under an aggressive carbon tax regime for example, decommissioning may occur at a very early period in oil field operations, owing to close to 50% of oil reserves being uneconomic to produce. The results highlight the effectiveness of

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carbon taxes as policy lever in jurisdictions that seek accelerated decarbonisation, climate change mitigation and energy transition goals.

The Energy Kuznets Curve: Evidence from Developed and Developing Economies

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The energy environmental Kuznets curve is effectively an environmental Kuznets curve augmented by adding one or more energy-related variables. We suggest that the energy Kuznets curve (EKC) can be estimated separately from the conventional environmental Kuznets curve as a quadratic function of income. It is demonstrated that the environmental Kuznets curve implies and is implied by the EKC. The empirical results show consistently that both the environmental and EKC are valid for developed (high income) countries but not so for developing (low income) countries where the relations are positive and monotonic. The importance of considering energy consumption in conjunction with the environmental Kuznets curve is that economic growth on its own does not put an end to environmental degradation unless the underlying country is on the downward-sloping sections of both the environmental and EKC.

Promoting CCS in Europe: A Case for Green Strategic Trade Policy?

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According to IEA study *World Energy Outlook* from 2018, there is a huge gap between the optimal utilization of Carbon Capture and Storage (CCS) technologies to lower global CO_2 emissions and the current, negligible diffusion of this technology. A number of factors may explain this big mismatch, for example, the price of carbon may be by far too low; costs of renewables may have decreased more rapidly than expected; and there might be market imperfections in the CCS value chain of capture, transport and storage that slow down the speed in CCS development. Because of impediments, the IEA study *Technology Roadmap: Carbon Capture and Storage* from 2013 argues that a key action to kick off innovation and diffusion of CCS is to introduce financial CCS support mechanisms.

There are two business models to spur CCS. One option is to support purchasers of CCS technologies by covering a part of the additional investment cost of CCS. The alternative model is to focus on the CCS technology suppliers by supporting their research, development and production costs. Our first research question is to what extent promotion of CCS in Europe should be through subsidising development and production of CCS technologies—an upstream subsidy—or by subsidising the purchasers of CCS technologies—a downstream subsidy.

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In the electricity sector, the CCS technology can be applied both to coal power and gas power. These two technologies are likely substitutes in demand. Our second research question is therefore to what extent the EU should give priority to one of the CCS technologies, that is, whether the subsidy to CCS coal power should exceed the subsidy to CCS gas power.

We study the two research questions both with simple theory models and within a framework where a numerical version the theory model is soft-linked with LIBEMOD, a large-scale numerical model of the European energy markets. The link between the two models is the prices of CCS plants: In LIBEMOD, these are (exogenous) cost parameters, whereas in the theory model, prices of CCS plants are (endogenous) model-determined variables. In the analyses, we take into account that competition between CCS technology suppliers is imperfect as there is only a few potential suppliers in the world.

Both the theory models and application of the numerical framework suggest that from an EU perspective, the upstream subsidy should exceed by far the downstream subsidy. The main reason is simply that an upstream subsidy shifts production and profits from non-EU CCS suppliers to EU suppliers, thereby increasing EU welfare. In addition, both upstream and downstream subsidies stimulate total production, thereby lowering the initial economic welfare loss due to product prices exceeding their marginal costs.

Furthermore, we find that subsidies to CCS coal power plants should (from an EU perspective) exceed subsidies to CCS gas power plants. The reason is partly that the pure economic value of CCS coal power plants exceeds the pure economic value of CCS gas power plants. This is reinforced by the fact that coal has a higher CO_2 emissions coefficient that natural gas, and hence it is more valuable to replace conventional coal power with CCS coal power than to replace conventional gas power with CCS gas power. In addition, suppose demand for natural gas and demand for coal increase equally much. Then the price of natural gas tends to increase more than the price of coal. Combining this empirical result with the fact that the EU is a net import of both natural gas and coal, provides another reason for why CCS coal power plants should receive a higher subsidy than CCS gas power plants.

Rockets and Feathers Revisited: Asymmetric Retail Gasoline Pricing in the Era of Market Transparency

Emmanuel Asane-Otoo[a] and Bernhard C. Dannemann[b]

Retail fuel pricing, in general, remains an area of significant interest for motorists, the media, and regulatory authorities in many countries. This is partly due to the widespread and persistent public perception that oil companies are quick to adjust retail prices and profit margins in response to input cost increases rather than decreases—a behavior characterized as the rockets and feathers phenomenon. With the market transparency unit becoming active in the German retail fuel market in 2014, the market has achieved full transparency with regards to consumer prices by providing a platform where prices can be compared in real-time via mobile apps or online portals.

Based on daily observations of gasoline retail price data for 12,804 fuel stations in Germany between 2014 and 2018, we assess whether, in the era of market transparency, input cost increases are still passed on to the customer more swiftly than input cost decreases. We use a pooled-panel

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asymmetric error correction model framework that allows for the direct comparison of the adjustment to input cost increases and decreases. Across different specifications, we test the robustness of the main findings to (i) the inclusion of controls for price changes of neighboring fuel stations, local weather conditions and demand shocks caused by public and school holidays, (ii) sample variation by areas of different population density, (iii) different pricing strategies across major brands, or (iv) the effect of spatial and temporal aggregation of the data set.

The results show that the pattern of rockets and feathers is the norm rather than the exception. We find evidence supporting the perception that input cost changes that squeeze the retail margin are passed on to consumers more swiftly than equivalent changes that stretch the margin. Ultimately, increased market transparency also works to the advantage of firms since they can effortlessly compare prices both within and outside their local markets and adjust prices accordingly, making tacit collusion or price coordination more likely. Finally, results further highlight substantial differences between the nature of adjustment exhibited by low- and high-frequency data—clearly, temporal aggregation of station-level data matters in appraising the prevailing adjustment mechanism.

Modelling Required Energy Consumption with Equivalence Scales

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Energy consumption is necessary for an acceptable quality of life. However, energy consumption also contributes to household expenses. Therefore, when households are poor, energy consumption may be compromised for other purchases. In other words, there is a concern that a non-negligible proportion of the world population is not able to purchase enough reliable energy for their needs and are therefore energy poor. However, although 'enough reliable energy' is understood at an intuitive level, it is necessary to estimate 'need', in order to determine if enough is available.

In the literature, need is based on required energy consumption (REC), which is often debated and remains difficult to estimate. One modelling approach focuses on energy demand, underpinned by engineering methods. These rely on detailed data related to domestic energy usage (in kWh), appliances and/or building characteristic. One such example is the United Kingdom's Building Research Establishment Domestic Energy Model (BREDEM). The BREDEM requires extensive engineering calculations that are localized to account for dwelling characteristics and energy usage. Such detailed data is not widely available, or even available at all in many countries. Another modelling approach is underpinned by purposive surveys that incorporate the relevant aspects of energy usage; however, such surveys are expensive to conduct, and, therefore, difficult to replicate widely. A further approach uses actual energy expenditure, instead of required. Although actual expenditure is expected to capture localized conditions and differences across households, it is unlikely to correctly capture need, because some households will reduce energy consumption to fulfill other needs.

This research develops a method for the determination of required energy consumption that: (i) is underpinned by readily available data, (ii) accounts for household heterogeneities, (iii)

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captures localized conditions and (iv) incorporates relevant aspects of energy usage. Our method is underpinned by equivalence scales, and makes use of income and expenditure data, which is available in most countries around the world. Thus, our method is especially useful, when detailed engineering energy modelling and usage data are not available, as is the case in most developing country contexts. Specifically, we use semiparametric regression - a nonlinear multivariate regression paying attention to potential endogeneities via control functions - to incorporate a range of both household characteristics and energy usage factors into a model of household energy shares, and we use the estimates from that model to determine the household's energy equivalence scale. We use that scale to adjust a baseline energy consumption value, and determine household required energy consumption.

We apply the method in a case study of South Africa. We find estimated required energy consumption values for low- and mid-income households to be well above their actual energy expenditure. We also find that required expenditure is below actual expenditure for upper-income households. Each of these results is intuitively appealing, because South Africa is an unequal country, where poverty is rife; thus, we would expect poor households to require more energy than they are currently using. We further find that required energy expenditure is nearly independent of household expenditure, which is also appealing, as required energy expenditure should capture need, rather than the ability to purchase.

The proposed method offers policymakers a fairly easy way to determine household energy requirements, as well as potential energy subsidies/taxes that could be applied differentially. Importantly, those requirements would be based on local circumstances, rather than on the circumstances that were relevant to the UK or even South Africa. The method can offer researchers and policymakers more accurate comparisons, if they are interested in comparing domestic energy consumption across regions, since our adjustment allows for the incorporation of regional heterogeneity. Importantly, the definition of baseline energy is flexible, and can be adjusted to suit policy goals; for example, one might be interested in subsidizing solar water heating, as that is an important driver of energy consumption.

Furthermore, since our method offers a way to estimate required energy, it offers a way forward, when it comes to energy poverty measurement, which is usually defined for required energy rather than actual. Such information can also help policymakers identify and more efficiently target subsidies to the benefit of households that are energy poor, and thus, mitigate energy poverty.

Changing Market Structure and Evolving Ways to Compete: Evidence from Retail Gasoline

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Firms constantly innovate, and innovations force changes in the competitive landscape. Firm innovations have been remarkable, particularly in the retail sector, and the introduction of automation is one example of firm innovations, altering the optimal allocation of resources of buyers and sellers. In this paper, I use a case-study approach to examine the competitive effects of an innovation in a retail-gasoline market and jointly investigate how an innovation changes ways firms compete on price: the introduction of self-service technology in retail gasoline in Korea.

My setting is unique in that I have high-frequency, station-level data starting in 2010, when self-service sellers were very rare, and continuing through 2015, when they accounted for a quarter of the market. I study sellers' pricing by service level, and find that gas stations that continue to of-

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fer full-service differentiated themselves by offering bundled products and services and raised their prices during this period.

I first perform a test of whether the monopolistic competition theory – greater competition lowers price – explains the increasing the full-service premium. If the gasoline market is segmented by service level, then the increase in the full-service premium could be explained by the falling number of full-service stations and the increased number of self-service stations. However, in a difference-in-difference specification, the changes in the service composition of gas stations barely explain the increasing full-service premium in this market. The trend of full-service premium is very robust to measures of the competitive environment.

In the meantime, I find that self-service stations offer competitive prices and drive down prices of nearby competitors. Self-service stations charged 5% less per gallon on average, and price elasticity of competition is much higher in absolute value when competitors are self-service than when they are full-service. This finding confirms that self-service stations compete for price-sensitive customers who may prefer only a low-priced gasoline component to a bundle of gasoline and service.

I further show descriptive evidence that full-service stations differentiate on one or more non-price dimensions. Product differentiation is generally implemented by full-service stations whose gasoline prices are significantly higher than the average price for full-service. As the market is transformed from full-service to self-service, more full-service stations are increasingly differentiated to charge a high premium for their full-service gasoline. The price gap between full-service and self-service increases over time as a result. I claim that such product repositioning is the new strategic choice of high-cost marginal sellers in response to the emergence of low-price competitors, and document that the strategic choices of stations evolve in different ways when the market is undergoing a significant restructuring; thus, each type of station is using its unique position to its advantage.

This study has important implications. First, the strategic choices for incumbents vary by firm characteristics. Neither exiting market nor adopting new technology, sellers can differentiate their product on some other dimensions to avoid price competition. Seller characteristics that sometimes are unobservable to the econometrician are important to understanding price competition among differentiated sellers in real-world markets. Second, the advent of innovation like digital transformation breaks boundaries among traditional industries, and firms attempt to create a synergy effect by merging various industries. Amazon Go is a good example of combining automation with traditional convenience stores. Quantifying the across-industries effects of the new competitive landscape created by innovation is an attractive and emerging field for research.

Green Growth, Carbon Intensity Regulation, and Green Total Factor Productivity in China

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Huge primary energy consumption and coal-based energy consumption structure make China the world's largest emitter of CO_2. Instead of reducing the total amount of emissions, low-

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ering CO_2 emissions per unit of GDP (CO_2 intensity) is set as an important CO_2 emissions control target by the Chinese government. Meanwhile, the CO_2 intensity constraint is used to act as a major policy tool for controlling CO_2 emissions. Compared with economic instruments such as carbon tax and carbon emissions trading, the carbon intensity standard, as a command-and-control instrument, is a relatively reliable tool under uncertainty condition, ensuring the smooth realization of an established emission control target, although its cost efficiency to achieve the target is relatively poor. However, considering the importance of total factor productivity to economic growth, the question is more about whether the CO_2 intensity constraint policy promotes the growth of China‘s green total factor productivity.

Based on the input-oriented Malmquist productivity index and parametric decomposition method, this paper measures the green total factor productivity and its growth sources using a dataset of input, output and CO_2 emissions of China mainland’s 30 provinces (excluding Tibet) from 1997 to 2014, and assesses the impact of the carbon intensity regulation on China’s green total factor productivity by using the two stage least squares approach.

When measuring the green total factor productivity under the input-oriented Malmquaist productivity index framework, the output varibales are values-added of primary industry, secondary industry, and tertiary industry, and the input variables include labor, capital, primary energy use, CO_2 emissions, and wastewater. When evaluating the effect of CO_2 intensity constraint on the green total factor productivity, the explanatory variables include dummy variable of CO_2 intensity policy, R&D intensity, FDI, foreign trade, industrial structure change, infrastructure, and government size.

The results show that the green TFP has been growing at a yearly averaged rate of -1.51% during this period. The results also indicate that the policy of CO2 intensity regulation does not generate significant effect on the green total factor productivity of China’s provinces when using the 2SLS estimator to control for the potential endogeneity biases. On the other hand, there exists significant heterogeneity in the effect of the CO2 intensity regulation on the green TFP of China’s provinces. Specifically, the CO2 intensity regulation promotes the green development performance of provinces in the eastern area, while it does not generate obvious impacts on the green TFP of provinces in both central and western areas.

The Social Efficiency of Electricity Transition Policies Based on Renewables. Which Ways of Improvement?

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The need for carbon emissions reduction in economies has been introduced into the policy agendas in most of the developed world. It is increasingly common to consider climate and energy policies in joint packages targeting simultaneously CO2 reductions and explicit shares of renewable energies (RE) for a given horizon.[c]

Direct climate policy instruments (addressing CO2 emissions) provide “first-best” solutions regarding the long term coordination between gas turbines and non-emitting flexibility sources

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c The most recent examples are the National Energy and Climate Plans (NECP) requested by the European Commission to the Member States covering the period 2021-2030. Further information on the NECP is available at: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union/national-energy-climate-plans

in order to limit the use of fossil fuels (Abrell, Rausch, and Streitberger 2019). In the EU, even if concerns with reducing CO2 emissions exist, in practice, very few reforms have succeeded in implementing direct climate policy instruments effectively. Only indirect technology-oriented instruments such as renewables obligations, energy efficiency mandates or coal phase-outs have been effectively put in place.

As a result, renewables development (formulated as targets on the share of electricity generation) has become an objective in itself and may take precedence over the objective of decarbonization, without questioning the economic rationality of this inversion of objectives and its environmental effectiveness. This could indeed lead to an unbounded development of renewables, which would result in a high opportunity cost, in particular in countries where the nuclear option is still open, but also to potential conflicts with the carbon mitigation goal. Large scale deployment of variable renewables (VRE) needs complementary production by fossil fuel plants and flexibility resources, including gas turbines, to maintain security of supply and to provide system stability.

This problem can only be addressed appropriately by using detailed models of the power system that can take into account the dynamic interactions between all the production units including large amounts of VREs, in real time, the provision of system services, hour by hour supply and demand balances, while in the long-run the modelling should comply with capacity adequacy requirements. We use a detailed model of the power system for a "greenfield" optimization in 2050, with the particularity of considering the nuclear option as open alongside the development of renewables and fossil-fueled power plants. The last are potentially used for back up purposes and for providing system flexibility if cost effective. We optimize capacity investment and system operation using different combinations of policy instruments, namely a RE obligation (similar to a Renewable mandate) and a CO2 cap per MWh (equivalent to imposing a screening carbon price). In this way, we seize the interplays between policy instruments and compute the minimum cost solutions for various combinations, and we rank the resulting solutions regarding their climate effectiveness and their social efficiency. Thus, we obtain first and second-best solutions regarding the CO2 savings and the costs overruns achieved with respect to the reference case (BAU).

A detailed model of the power system helps to capture the complex interactions between policies targeting very high shares of RE technologies, CO2 reduction targets, and the possible recourse to new sources of new flexibility technologies enhancing system integration on one side, and captures their environmental effectiveness on the other side. Assuming technology costs for 2050 from official reports (i.e., low RE costs, high nuclear cost), only modest levels of VRE (around 11%) are developed in the system without subsidies in the optimal mix, whatever the emissions cap or the carbon price level. The flexibility sources increase the optimal shares of VRE from 11%¨to 18%. Different tests on the renewables shares required (supposed to be the main instrument to reduce the power system emissions) show trade-offs between increasing VRE shares, economic efficiency and environmental effectiveness of the respective policies, with some unexpected effects. For the severe norm of 50 g/kWh needed to maintain environmental performance, a policy targeting 80% renewables is 45% more costly than the BAU case, while the additional cost is only 13% if RE share is only forced up to 50%.

Tests including new flexibility sources (i.e. different storage techniques, demand - response) show that their optimal deployment logically reduce the overall cost and improve CO2 performance to a certain extent, but this does not hold true in every situation. Indeed, moving from an 50% to an 80% RE obligation leads to a total emission rebound, even with the development of flexibility resources. This effect results from the fact that from a certain penetration of RE the carbon policy becomes unbinding (e.g., a carbon market with oversupply of emission allowances), thus,

the time arbitration capabilities of storage and demand response improve the economics of fossil equipment, as mid-merit suppliers, by providing them with higher load factors, which may bring on additional emissions. This effect can be countered by strengthening the carbon constraint when pushing to very high RE shares, but it leads to a non-linear increase in the overall cost at the same time. At the end it is possible to rank the different combinations of RE obligations and carbon caps.

Our findings are at the crossroads of different strands of the literature on VRE integration and on model-based climate policy assessments. We aim to make each strand converge into the evaluation of joint climate-energy packages. This includes papers on the economic values of VRE which decline as their capacities develop "out-of-the-market" (Hirth, 2015, Bruninx et al. 2016), those that identify the optimal share of VRE in an electricity mix (Hirth, 2015, 2016), those that compare the overall costs of the system for different penetration rates of VRE under carbon constraints (Hirth, 2015, Delarue, Van den Berg. 2016), and those assessing the economic value of storage and demand response to improve the economic integration of renewable energy sources (Zerahn et al, 2015; Hirth, Ueckerd, Edenhofer, 2016; Sisternes et al, 2016). These papers often do not consider one or more aspects of the problem: some reduce the range of low-carbon technologies (e.g. without a nuclear option), others ignore some sources of flexibility (such as demand response) or simplify the links with the carbon policy by adopting exogenously fixed CO2 prices. Here we consider a wider range of technology options on the supply-side, and focus on the interactions between policies targeting the large scale development of RE technologies, a carbon policy using CO2 caps, and the possible recourse to new resources of flexibility, in order to assess different energy-climate policies targeting the power sector, we propose a framework to rank them regarding their environmental and economic performance, and present the implications of our findings in view of the theoretical and energy policy literature (Abrell, Rausch, and Streitberger 2019; Newbery, Reiner, and Ritz 2019; Percebois and Pommeret 2019).

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Market Segmentation and Energy Efficiency: Evidence from China's Regional Economies

Liang Nie[a] *and ZhongXiang Zhang*[b]

With widespread local air pollution throughout China and an urgent need to address global climate change, increasing energy consumption and CO_2 emissions have made China's energy efficiency the topic of a growing number of studies. In recent years, as China's economy has progressed toward high-quality growth, the literature on how to improve energy efficiency has shifted its focus from demand-side to supply-side factors, and there is now a general consensus that suboptimal resource allocation in factor markets is the key to limiting China's energy efficiency. However, suboptimal resource allocation is merely a phenomenon created by delayed reforms in China's energy markets, and few studies have investigated the origin of this phenomenon and its impact on energy efficiency under China's current administrative structure. To fill the gap of literature, this paper investigates the impact of market segmentation driven by competition among local governments on energy efficiency.

Theoretically, we clarify how market segmentation impacts energy efficiency directly, and the indirect transmission mechanisms that exist between them. Empirically, the epsilon-based measure model, which combines the merits of radial and non-radial data envelopment analysis, is used to measure energy efficiency in China, and the price index method, which has been widely employed to measure market segmentation in recent studies, is further improved in this paper. After collecting data from 18 provincial-level administrative entities in mainland China, we use fractional regression models to study the influence of market segmentation on energy efficiency.

Our analysis provides evidence that market segmentation has a significant negative effect on China's energy efficiency. This remains robust even if the independent and dependent variables are measured with new indicators, extreme observations are replaced, and samples prior to the 2008 financial crisis are removed. Additionally, the inhibitory effect varies depending on the region and market segmentation distribution. The impact mechanism test reveals that energy price distortion, enterprise technology innovation and industrial agglomeration are three mediating mechanisms through which market segmentation affects energy efficiency.

Based on the above findings, the Chinese central government should work to eliminate local protections and accelerate market integration to the greatest extent possible. It is critical to remove the intermediary mechanisms through which market segmentation inhibits energy efficiency. Furthermore, the advancement of a local official should be evaluated in terms of economic, social, energy, and environmental performance across the entire jurisdiction, rather than focusing simply on economic growth.

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Energy Efficiency and Energy Governance: A Stochastic Frontier Analysis

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The success in the implementation of Energy Efficiency (EE) policies may be conditioned by several factors, like the existence of regulatory failures or by an inadequate coordination between the government and the private sector. In this vein, the International Energy Agency states that the success of energy policies is closely related to the performance of energy governance. Unfortunately, the impact of such governance on the energy sector has been poorly analyzed due to the lack of suitable indicators. This paper uses the Energy Efficiency Governance Index (EEGI), recently developed by Barrera-Santana et al. (2020), to quantify, for the first time in the literature, the impact of energy governance on EE in a representative set of OECD countries between 2000 and 2015.

To this aim, we draw upon the Stochastic Frontier Analysis (SFA) framework, which provides a frontier that represents the optimal level of energy demand. The location of each country with respect to this frontier provides a relative measure of EE. We consider the EEGI as an explanatory factor of the EE level in the three SFA specifications most widely used in the literature: Battese and Coelli (1995), and Greene's fixed and random effects models (Greene, 2005a and 2005b)**.** In order to overcome each of the particular econometric pitfalls of these methodologies, we have also considered several novel alternatives approaches (Chen et al. 2014; Belotti and Ilardi 2018).

The results indicate that the EEGI is positively correlated and very significant in explaining the EE in our set of OECD countries. Furthermore, in relation to the magnitude of this effect, we find that a change of 10% in the average EEGI score can contribute to increasing EE by 9.2% to 27%, depending on the estimated model and the initial EE level of the country. Concretely, the imposition of measurable targets and the adoption of extensive methods to evaluate the results seem to be the energy policies accounting the most positive and significant effect on EE.

Our work breaks new ground in the energy economics literature. First, we provide a comprehensive assessment of the effect of energy governance (and its elements) on EE in a broad set of OECD countries. We also examine the effect of specific energy policies. Secondly, this work also contributes to the definition and estimation of EE. Methodologically, we use novel SFA approaches, which overcome some of the problems raised by traditional methods. Furthermore, a comprehensive endogeneity analysis is conducted. This kind of analysis is relatively new and novel in the SFA framework, especially in the energy economics literature.

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Investor Attention to the Fossil Fuel Divestment Movement and Stock Returns

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The fossil fuel divestment (FFD) movement aims to urge investors—particularly institutional investors—to divest their holdings of investment in firms that extract coal, gas, and oil. The FFD movement was born within U.S. universities in 2010 and has become increasingly popular over time. Even though the real amounts divested from fossil fuel companies are still moderate, the FFD movement might have side effects such as the stigmatization of the fossil fuel industry. A potential consequence of this stigmatization process is the reduction of investor demand for fossil fuel–related stocks that might drive down their stock prices.

Notwithstanding the expansion of the FFD movement worldwide, we still have limited knowledge of their potential implications for fossil fuel–related stocks. In particular, we do not know whether the FFD movement, as a symbolic tool of stigmatization, affects returns on fossil fuel stocks. In this study, we shed light on this question by examining how investor attention to the FFD phenomenon might affect the prices of fossil fuel–related stocks.

As with all social movements, it is arguable that the strength of the FFD movement depends, at least in part, on the investor attention it generates. Therefore, to address our main question, we empirically assess the effect of investor attention to FFD on the weekly excess stock returns for U.S. firms that supply coal, gas, or oil in comparison with U.S. non–fossil fuel firms. In an original manner, we use three complementary indicators of investor attention to the FFD movement: (1) the U.S. weekly Google Search Volume Index on the topic "fossil fuel divestment," (2) the U.S. weekly media coverage of FFD, and (3) the number of weekly visits to the Wikipedia page "fossil fuel divestment."

Contrary to what might be potentially expected by the FFD campaigners, our econometric estimations report a positive relationship between investor attention to FFD and the excess returns on fossil fuel–related stocks from U.S. firms. This positive effect is remarkably robust even after controlling for firm-level and energy-level variables as well as for widely accepted risk factors, such as market, size, value, and momentum. This finding also holds when we consider alternative investor attention proxies and alternative empirical approaches including difference-in-differences analyses.

One potential explanation of this key finding is that the FFD movement draws attention to the undervaluation of fossil fuel–related stocks, which makes them attractive to profit-motivated investors. Our empirical investigation of the potential channels supports this explanation by revealing that fossil fuel stocks are structurally undervalued and that, at the same time, the FFD movement leads to greater investor attention to these securities.

These findings are relevant for profit-motivated traders, climate change–conscious investors, and FFD campaigners. Profit-motivated traders might find it financially profitable to invest in fossil fuel–related stocks and divest from non–fossil fuel firms when attention to the FFD movement is abnormally high (and the opposite when attention is abnormally low). Climate change–conscious investors—who are inclined to exclude fossil fuel–related stocks from their investment universe—

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should be aware that when attention to the FFD movement increases, this exclusion strategy is likely to impact their portfolio returns. Finally, FFD activists—who are doing their best to reveal the negative environmental effects of fossil fuel firms' activities—should realize that, from a purely financial perspective, their efforts contribute to increase returns on fossil fuel firms.