The Evolution of the Interfuel Substitution: A Study of the US Electricity Sector

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Overview

Working on strategies for the energy transition, policymakers all around the world keep reconsidering the role of various energy resources such as natural gas and nuclear power to serve as a "bridge" to carbon-neutrality. The discussion about the potential CO_2 reduction through fuel switching highlights the questions on economic costs and technical feasibility that have not been fully addressed in the existing literature calling for further investigations.

The objective of this study is twofold: 1) to offer an approach for estimating and projecting the interfuel substitution and 2) to analyze the dynamics of interfuel substitution in the U.S. power sector, which accounts for ~25% of the country's carbon emissions, so to better understand the implications of emission reduction. In attempt to fill in the gaps and resolve some pitfalls of previous studies, we present a novel procedure allowing for joint estimation of the interfuel elasticities and parameters of production function with multiple input factors. Focusing on the evolution of the oil, natural gas, coal, and nuclear power generation mix in the U.S. over the past three decades, we develop and apply the approach accounting for uneven, or biased, technological advances in electricity production. With the unique dataset on individual state's power generation and spending on each energy input, we integrate budget considerations into our model analyzing both the income and substitution effects.

Considering the developments associated with renewable energy, the behavior and transition of the conventional power sector depends crucially on interfuel substitution among "traditional" inputs. In this context, our approach helps 1) track the elasticity of substitution, 2) analyze and project its dynamics together with production efficiency, and 3) understand the fuel price coupling mechanisms, - all of which are critical in determining the energy transition path.

Hence, the contribution of this paper goes well beyond the development of new methodology, it is to inform energy market participants about the on-going structural transformations and to provide policy-makers and regulators around the world with the tool to test and adjust energy and environmental policies in order to ensure economic affordability and technical feasibility for the proposed solutions.

Methods

Until now there was no procedure allowing for the estimation of the input substitution elasticities under biased technological change in energy economics. The need for a similar procedure in other branches of economic science has been recently addressed in macroeconomics to explore the elasticity of substitution between capital and labor. The new estimation method has been formulated and tested with the Monte-Carlo simulations by León-Ledesma et al. (2010), building up on the analysis by Klump et al. (2007) and the intuition developed by Acemoglu (2002).

We start by adopting the constant elasticity of substitution production function assumption, of which Cobb-Douglas function is an ultimate case. In order to apply the procedure, we have to introduce and integrate several "nests" accounting for the four different power generation technologies, namely gas (G), coal (C), oil (O) and nuclear (N), which can be used interchangeably. The general form of the production function does not require us to specify which inputs are used for a base- vs. peak load, applying various nesting, e.g., "gas-oil" versus "coal-nuclear", enables us to test and verify our results on the elasticities.

Knowing about the true nature of technical bias (fuel-use efficiency) from the collected data, we are able to corroborate our findings for the biased technological change situation, comparing them to the estimation results for the commonly used neutral technical growth assumption. We show first, theoretically and then, empirically the importance of technological change assumption, highlighting the role of technology in the energy transition.

Furthermore, we analyze how the elasticities of substitution and production efficiency evolve over time by applying a "moving time window" routine. That allows us to track the changes in income shares, the efficiency of price coupling mechanisms, the influence of changes in the pace of technological progress and the current state of the energy transition. Finally, we complement our approach with an exercise helping identify the deviation in the relative fuel usage, e.g., finding whether more natural gas has been used relative to coal beyond what is expected based on the price and technology developments. Hence, we offer a way to detect and quantify the effect of regulations and various economic measures brought to shift the consumption towards lower carbon fuels. By comparing the predictions to reality, we can test whether market participants stick to optimality conditions or have their decisions influenced by outside factors.

Results

We demonstrate the applicability and confirm the validity of our approach, using the U.S. state-level data on electricity production and energy consumption from the EIA from 1990 to 2019. First, we estimate elasticities of substitution for two-input models, including G-C, G-O, G-N, C-O, C-N, O-N, and then, repeat the exercise increasing the number of inputs running three and four-input models. We compile and compare the results to make conclusions about the robustness of our results. Next, to reveal and study the dynamics of the interfuel substitution, we apply a moving time window procedure and report how the elasticities of substitution change over time. Finally, we use the estimated parameters to detect the effects of energy and environmental regulations and various incentives, which shall manifest in elasticity values deviations from the value suggested by our model.

We find that the elasticities of substitution are close to or above 2.5 for all pairs of inputs for all the tested models, suggesting considerable substitutability (Table 1). The highest values are estimated for G-C substitution, which however, have been decreasing lately signaling about the on-going transition away from coal. Nuclear power appears to be a good substitute for coal-fired baseload but not so much for natural gas or oil suitable for peak load. Our estimate also reveals a dramatic change in income shares, which we interpret as the evidence of the energy transition.

Four-Input Substitution Elasticities in the US Electricity Sector (1990-2019)
S = 2, N = 26, Individual NC

	Dependent variable:	
	(Gas-Petro)-(Coal-Nuclear)	(Coal-Petro)-(Gas-Nuclear)
σ	4.33***	3.60***
	(0.38)	(0.29)
η	2.66***	2.61***
	(0.06)	(0.10)
ζ	5.94***	5.88***
	(0.64)	(0.54)
N	780	780
R^2 (Y)	0.78	0.78
R^2 (FOC's 1)	0.87	0.66
R^2 (FOC's 2)	0.72	0.77
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 1: Four-Input Model

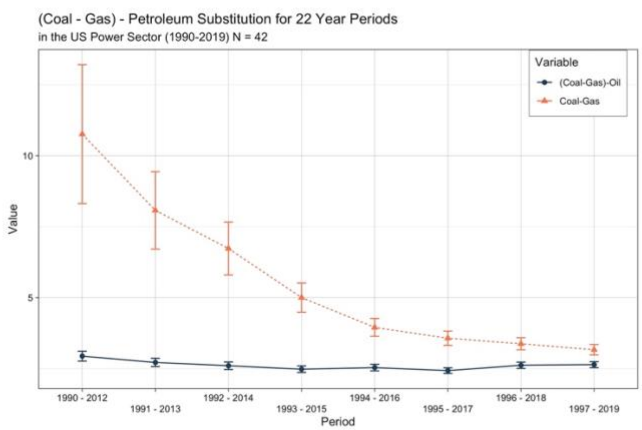

Figure 1: Elasticities over time

Considering the evolution of the fuel elasticities over time (Figure 1), we find that G-O and C-O elasticities do not change much, but show a slight downward trend, confirming the choice of the production function form. In contrast, the gas and coal elasticity jumps up before transitioning to a decline.

Predicting the relative consumption of different inputs, we find that states tend to deviate from our calculations (optimality conditions) depending on overall economic performance and expectations for the future. We find that states tend to use more natural gas compared to coal beginning in the early 2000's but coming back to optimality conditions after the economic crisis in 2008.

Conclusions

Our study demonstrates the usefulness of the novel procedure that overcomes the limitations of the traditionally used approaches in the estimation of the elasticity of substation. Applying the procedure to US data we have been able not only to investigate the evolution of elasticities, income shares and the pace of technological progress, but also reveal signs of the ongoing but slowing down energy transition. The approach has number of limitations and calls for further global investigation with the energy data for various countries and sectors.

References

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