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Analysis

The Implications of Industrial Development for Diversification of Fuels

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ABSTRACT

The central role of energy in economic growth and development is substantiated by both theory and data. Much of the analysis of energy in economics has focused on the study of the aggregate output. Here, we deviate from this approach and study the role of fuel diversification in industrial development. We build the energy space describing the space of energy technologies, which a country can use in the production of manufacturing goods. As countries grow, they diversify their industries, producing more diverse products over time. We show that the process is accompanied by diversification of fuels, which countries use in the manufacturing sector. In particular, countries move in the energy space by adopting novel fuels, while their movements can be linked to structural changes in the industry. Over time, countries build unique production capabilities, which drives divergence in fuel diversity between countries. Our results provide insight into the limits of fuel substitution in the manufacturing sector, as well as they carry important implications for the assessment of potential reductions in CO_2 emissions in the future.

1. Introduction

The central role of energy in economic growth and development is substantiated by both theory and data (e.g. Cleveland et al., 1984; Ayres and van den Bergh, 2005; Brown et al., 2011). Much of the analysis of energy in economics has focused on the study of the aggregate output. In this paper, we take a different, historically-driven approach and study changes in diversity of fuels in manufacturing. Our aim is to show that structural change can be understood more clearly by explicitly accounting for the physical constraints on the economic production. We deviate from the mainstream approach and analyze fuel diversification in industrial development. In particular, we build the energy space describing the space of potential energy technologies that a country could use. We show that as countries grow and diversify structures of their industries, they move in the energy space by diversifying fuels.

It has been long recognized that the industrial fuel mix changes because of structural change, i.e. the process during which different sectors in the industry grow at different rates (Thoreson and Rowberg, 1985). For instance, changes in industrial fuel mixes can result from the exit of coal-intensive cement firms and the entry of electricity-intensive aluminum firms, rather than from the inter-fuel substitution typically assumed in macroeconomic models (Steinbucks, 2012). In this context, studying historical patterns of fuel diversification can be helpful in the assessment of the future changes in fuel mixes, and thus can provide important insights to the future emissions and potential for their reduction (Fouquet and Pearson, 2012).

Achieving climate change goals requires preventing the global mean temperature from increasing >2 °C above the preindustrial levels (GEA, 2012). This requires a combination of improved energy efficiency and increased use of renewable energy in the industry. We argue that changes in fuel mixes are driven by structural change in the economy, which can create an obstacle to the diffusion of specific fuels. For instance, cement production requires intense use of coal and petroleum coke, while steel production relies on the use of coal. As a result, the diffusion of renewable energy may not be feasible in the short run in countries where these sectors grow rapidly, e.g. China. The diffusion of renewable energy depends on the growth of electricity-intensive sectors. On the other hand, much attention has been devoted in the literature to decompose changes in energy intensities between technological and structural change, using structural and index decomposition analysis (see for the discussion Hoekstra and van den Bergh, 2003). It has been shown that reductions in energy intensity can be contributed to technological change, while structural change often increases energy intensity (Nie and Kemp, 2013). In this context, studying patterns of fuel diversification can help unravel periods during which improving energy intensity may not be feasible because of industries undergoing a structural change.

From another angle, fuel diversity has long been a major focus in discussions of supply security (Stirling, 1994; Grubb et al., 2006). Combining energy technologies that differ with respect to baseload, capital and operating costs allows for better responding to fluctuations in demand and may reduce the total cost of electricity generation (Awerbuch, 2006; Joskow, 2006). Grubb et al. (2006) show that all carbon-reducing scenarios considered in the UK are characterized by the greater diversity of fuels compared to the reference case of zero CO_2 reductions. Typically,

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fuel diversity has been measured using the Shannon-Wiener index (Templet, 1999; Grubb et al., 2006; Stirling, 2007). Diversity calculated from this index has two components: richness (or variety), which captures the number of energy technologies, and evenness, which is a measure of how evenly fuels are distributed across the energy portfolio. This approach fails to account for how diverse fuels are (Stirling, 1994, 2007). As a result, two fuel mixes, which are characterized by the same number of components and their evenness, may appear similar even if they are made up of very different elements. In addition, changes in the evenness and variety may cancel each other over time, and thus the Shannon-Wiener index is often considered to be insufficient to study dynamics of the system (Odum, 1969).

None of the discussed measures allows to meaningfully compare fuel mixes between countries; neither to study their changes over time. For this reason, in this paper, we examine changes in the diversity of fuels using alternative measures to entropy-based heuristics. In particular, we use two measures of fuel diversity: (1) we adapt Hidalgo et al. (2007) measure of product proximity; and (2) we use the Jaccard similarity index to compare fuel mixes between countries. This is motivated by the fact that two countries may use very different fuel mixes, even if they are characterized by the same entropy.

We employ Hidalgo et al. (2007) methodology, developed for studying product diversity, to identify patterns through which countries diversify their fuels. Accordingly, fuel diversity measures how many fuels a country uses intensively in the manufacturing sector out of 54 distinct fuels. Subsequently, we construct the energy space, which allows us to locate countries in the space depending on their fuel mixes. We study the evolution of fuel mixes over time, in particular if countries add fuels that are 'close' to fuels, which they already use. The measure of proximity between fuels relies on the idea that if two fuels are 'close to each other' then a country is likely to adopt one depending on having the other fuel already in its fuel mix. The ability to add energy technologies close to technologies already in use would be indicative of historical patterns in fuel diversification, which would allow us to study the relation between fuel diversification and structural change.

We find that developed countries diversify fuels by adding fuels, which are close to those that are currently is use, while poor countries adopt fuels loosely connected to other fuels. This can create a barrier for developing countries to reach the level of fuel diversification of rich countries. Results from the statistical analysis reveal also that between 1960 and 2010, the growth of manufacturing sector has been accompanied by an increase in fuel diversity. In addition, we find the negative correlation between the average fuel ubiquity and fuel diversity between countries. Fuel diversity indicates how many fuels a country uses intensively in the industry, while fuel ubiquity measures how many countries use a specific fuel. This implies that rich countries with highly diversified fuel mixes, employ on average more specialized energy technologies. This in turn can be explained by the fact that developed economies have more production capabilities, which allows them to develop new products, from combining existing capabilities. The reader may think about production capabilities as of a set of skills and capacities used in different industries, which involve also the use of specific energy technologies.

Our study provides the evidence that industrial development affects patterns of fuel diversification. Once new manufacturing plants are installed they cannot easily switch to alternative fuels. In addition, certain technologies require specific fuels as inputs or their combinations. In favor of this, we find that changes in shares of different sectors in manufacturing are a significant predictor of changes in fuel diversity in the panel data regressions. The remainder of the paper is as follows. In Section 2, we discuss alternative measures of fuel diversity. In Section 3, we describe the methodology, followed by the discussion of empirical findings on the relationship between fuel diversity and structural change in Section 4. Section 5 concludes.

2. Measures of Economic Complexity and Energy Diversity

The concept of diversity is of considerable general significance in economics (Weitzman, 1998). The emergence of new products and services underlies the creation of new industries, which drives economic development (Saviotti and Pyka, 2004, 2008). In turn, diversity of options is crucial for innovations that take the form of recombining existing technologies or cross-technology spillovers (Arthur, 1994; Zeppini and van den Bergh, 2011). For instance, in Weitzman's (1998) idea-based growth model, growth relies on new ideas emerging from combinations of existing ideas. He shows that if the number of such combinations is the only limiting factor in knowledge production, super-exponential growth may result. The importance of the variety of products and inputs has achieved an increasing attention recently in the new trade theory and the economic growth literature (Hidalgo and Hausmann, 2009; Hausmann and Hidalgo, 2011; Hidalgo et al., 2007). It has been shown that more complex countries accumulate more factors of production over time, which allows them to make more diverse products and to diversify their production further.

So far, the role of fuel diversity in industry dynamics and economic growth has been ignored. This can be explained by the fact that energy is typically considered as a small percentage of inputs used in production, and thus treated either as irrelevant or qualitatively no different from other natural resources. This view is inaccurate, because energy is required to maintain all economic structures (Cleveland et al., 1984). In fact, fuel diversity limits economic production because fuels differ in the amount of economic work. Yet, most economic forecasts about future emissions are derived based on aggregated models, which results are sensitive to the values of substitution elasticities between fuels in production. As a result, the impacts of climate policies may be overestimated because of high values of substitution elasticities commonly assumed in conventional models (Okagawa and Ban, 2008). In reality, changes in inter-fuel mixes are likely to involve the installation of new capital, and thus cannot be solely explained by fluctuations in fuel prices (Burniaux and Truong, 2002). Moreover, maintaining diversity of options may also improve the "adaptability" of the system, minimize the risks associated with unforeseen contingencies, and prevent lock-in of a dominant technology under increasing returns. In energy policy, diversity plays an important role in ensuring energy security, efficiency of energy use and adaptability of energy system (Stirling, 2007).

Typically, technological and economic complexity has been measured using entropy-based statistics (Theil, 1967; Weitzman, 1992, 1998a; Őnal, 1997; Frenken et al., 1999; Saviotti, 2001; Hausmann and Hidalgo, 2011; see also Safarzynska and van den Bergh, 2010 for the discussion). The entropy statistics address balance and variety, but they fail to account for disparity between different technologies (Stirling, 1994, 2007). For instance, the entropy-based Shannon index is defined as $\mathrm{H} = -\sum_{i=1}^{n} \mathrm{p_i} \ln(\mathrm{p_i})$, where n is the number of technologies, and p_i is the share of the ith technology. $H = 0$ indicates the lowest diversity. The Simpson index takes the form of the sum of the squared shares of each option in the portfolio: $H = \sum_i p_i^2$. This measure is equivalent to Herfindahl–Hirschman index, commonly employed to measure the degree of market concentration. A related entropy measure is that of Őnal (1997), who defines the structural diversity index as: $V(x) = 1 - \frac{1}{2(n-1)} \sum_{i,j} |s_i - s_j|$ (n is the number of technologies, and s_i, s_j are shares of i and j technologies respectively). For a given pair of groups i and j, $|s_i - s_j|$ measures the relative diversity between the two groups. Maximum diversity occurs when all groups in an assembly have equal numbers of elements, while a minimum value is realized if one group contains all of the elements.

Alternatively, Weitzman's (1992, 1998) index emphasizes the distance between entities. The measure can be applied to both discrete