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Energy paths in the European Union: A model-based clustering approach

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A B S T R A C T

This paper examines typical "energy paths", i.e. the intertemporal development of the energy mixes of the member states of the European Union over 1971–2010. We apply model-based clustering to detect major energy profiles and their compositional dynamics. The seven identified clusters show typical combinations of energy carriers dominating the primary energy consumption of a country. We find that countries tend to take a path towards higher quality energy mixes over time, however path inertia and dependencies arise from both infrastructure and resource endowments. Higher energy quality profiles are usually associated with higher national income and energy use per capita, providing some evidence of the existence of a national-level energy ladder. We also find convergence in energy intensity over time, and a relationship between a country's own resources and import dependency.

1. Introduction

The composition of national energy mixes tends to exhibit specific patterns and dynamics over time and along the income spectrum (Burke, 2010 & 2013). While countries generally transition towards higher-quality energy carriers over time (Csereklyei et al., 2016), the pace of this process varies due to path dependencies caused by infrastructure, labor and capital lock-in (Sovacool, 2016), by prevailing perceptions (Lee and Gloaguen, 2015), policy inertia (Pierson, 2000), and by the abundance of indigenous resources (Burke, 2013). The degree to which countries rely on diversified energy carriers (IEA, 2014a), and are dependent on external resources (Jewell, 2011) during this transition, greatly influences their national (energy) security strategy (Cherp and Jewell, 2014). We argue that model-based cluster-analysis could provide completely new insights into this process. Specifically, we propose to cluster country-year energy profiles of the European Union over 1971–2010 in order to identify typical compositions and their behavior. The detected country profiles are investigated with regard to the changes they exhibit internally, and are used to test existing theories about the presence of an national-level energy ladder, energy intensity convergence and endowment lock-in effects.

The energy profile of a country is generally captured by the notion of the energy mix. This may refer to various underlying concepts: the contribution of different energy carriers to electricity generation (called the electricity mix), to primary energy consumption, or to primary energy production. Primary energy production tends to be dominated by indigenous energy carriers, while consumption often includes imports of non-indigenous resources.[1] To gain however a full picture of a country's energy profile including its long-term energy security implications (IEA, 2014a), in this study we investigate the composition of primary consumption.[2]

The composition of national energy mixes may remain stable or exhibit systematic changes over time. We will call this behavior an energy path. The term path already suggests the possible presence of path dependencies (for the social sciences see Pierson (2000), for technological development see Araujo and Harrison (2010), Araújo (2014), and Sovacool (2016)), meaning that countries having trodden some

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[1] The extent to which energy import dependent countries' energy consumption mix differs from their production mix depends on many factors, including national income, geography, existing infrastructure, and other market factors.

[2] Primary energy consumption is defined in our study as the IEA (2014)'s TPES measurement, calculated as indigenous production + imports − exports − international marine bunkers − international aviation bunkers +/− stock changes.

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path are facing substantial costs in changing to a significantly different composition. Important voluntary changes in the energy mix imply considerable financial costs, and may be so pronounced that we observe inertia and stable compositions over comparatively long periods such as in cases of Malta, Cyprus or Poland.[3]

Changes in the energy mix may be driven by natural market forces, such as the supply cost of competing resources on one hand (Chabrol, 2016), or by political decisions including subsidies or government ownership (German Energiewende, France's deployment of nuclear power in the 1970s) on the other hand. Accordingly, these changes may take place slowly as countries become richer (Tahvonen and Salo, 2001; Burke, 2013), or policies may cause abrupt modifications in the energy mix, such as the German phase-out of 8GW of nuclear power in 2011. Such changes may lead to a relatively sudden substitution by new energy carriers, or to a gradual substitution by one, several or many other energy carriers, allowing for differential strategic diversification.

The growing importance of national energy security,[4] including energy supply and consumption diversification in the face of potential supply disruptions since the first oil crisis (Yergin, 2006), coupled with the desire for cleaner, more efficient and safer energy forms (Burke, 2013), may also drive such transitions and increase the share of certain energy forms in the mix. Currently, EU member states intensify their quest of environmental protection, climate change mitigation and energy supply security, even though Stramboa et al. (2015) note that there are as many inconsistencies as there are synergies in these policies. If we are to analyze the viability of these ambitious EU plans, it is necessary to generalize experiences about energy paths across both time and countries.[5]

Therefore we investigate the patterns of energy mix changes and energy carrier transitions in the member states of the European Union between 1971 and 2010 using a model-based clustering analysis of the European Union's energy mix. The objects of our cluster modeling approach are not countries, but country-years. The novelty of this method, which—to the knowledge of the authors—has not been applied to the problem before, allows us to identify distinctive energy profiles (represented by clusters) over time and across the EU, and to trace the dynamics of the movements (trajectories) of countries across these energy profiles, including the presence of possible path dependencies. We also examine whether the data structures discovered by a machine learning algorithm support existing theories of energy transitions and the energy-GDP relationship, or not.

We find seven typical clusters based upon what combination of energy carriers dominate the primary energy mix of a country, which we rank from the highest fossil fuel clusters (meaning that the combined share of coal, oil and natural gas usage is the highest) towards the lowest fossil fuel clusters. We find that over the examined period and in the absence of path dependencies countries tend to take a trajectory towards higher quality energy profiles. We also find that higher-quality energy mixes are associated with higher national income per capita and energy use per capita, supporting some evidence of the existence of a national-level energy ladder. We observe beta convergence in energy intensity, and clear path dependencies caused by high indigenous resource endowments.

This paper is structured as follows: Section 2 introduces the current literature. Section 3 introduces our data, hypotheses and the underlying methodology of model-based clustering. In Section 4 our results are presented, while Section 5 concludes and presents our policy implications.

2. Background and theory

What are typical energy paths and what determines the trajectories countries take as they develop? Is there an evidence of an energy ladder, defined as a gradual transition to higher quality fuels, as nations become richer? What steps do nations take to diversify their energy mixes? The answers to these questions are of crucial importance in determining the right policies to combat climate change and to enhance energy security. Besides the historical energy transitions referring to entire "eras" such as the "coal era" of the 19th century or the transition to crude oil at the beginning of the 20th century, the energy ladder concept allows us to investigate the short- and mid-term dynamics and patterns of national energy mixes.

The concept of a national energy ladder may be summarized as follows: low income, developing countries tend to rely heavily on biomass energy, including wood and charcoal for cooking (IEA, 2013; Burke and Dundas, 2015). Household energy use is very inelastic to GDP at lower income levels, mostly due to the dominance of primary solid biofuels in the mix (Burke and Csereklyei, 2016). As countries become richer, new technologies enter the market, and they substitute towards higher quality energy sources (Csereklyei et al., 2016). Based on empirical findings by Burke (2013), the ladder proceeds from biomass, hydro, oil, coal, natural gas, and nuclear energy to geothermal, waste and wind energy.[6] During this process, as energy consumption in total is growing, the absolute amount of fuel inputs may not decrease, only the composition of the mix is changing (Csereklyei et al., 2016). Arising from this dynamics, Pearson and Fouquet (2012) note that even a major transition to low-carbon technologies might not warrant a reduction in world fossil fuel consumption.

Currently there are few empirical studies investigating the macro-level presence of an energy ladder. The most comprehensive study covering 134 countries between 1960 and 2010 is that of Burke (2013), who finds empirical evidence for the presence of a "national-level energy ladder" with the increase of per capita GDP. While Csereklyei and Stern (2015) find the role of fossil fuel resources ceteris paribus significant in increasing the growth of per capita energy use in a dataset covering 93 countries over 40 years, Burke (2010 & 2013) notes the importance of national resource endowments in shaping the transitions on the energy ladder. Countries with large endowments are found less likely or slower to climb to the upper rungs of this ladder. Fossil-fuel rich counties are thus less likely to utilize nuclear power and modern renewables (Burke, 2013). Large indigenous resource endowments may also form the basis of an energy security strategy. Burke (2013)'s findings are also consistent with earlier evidence from Burke (2010)[7] and Tahvonen and Salo (2001).

[3] While most countries take advantage of biomass and conventional fossil fuels, the deployment of geothermal energy, solar, wind or nuclear energy is still limited. On the other hand the extent to which certain energy forms are deployed may also vary considerably. France for example covered 42% of its primary energy consumption from nuclear energy in 2010, while Malta used oil to meet 99% of its energy demand. Poland relies heavily on its indigenous coal, while Norway is a leading country in exporting North Sea Oil, yet has at the same time abundant hydro-reserves. Any energy mix will be influenced by both domestic endowments and external supply availability.

[4] Already at the beginning of the 20th century, Winston Churchill claimed that "safety and certainty in oil lie in variety and variety alone" (Yergin, 2006). The diversification of the energy mix, and the reduction of energy import dependency (especially from a single supplier) has been an important political goal in the European Union. Diversification as a strategy can be applied to the entire energy portfolio—leading to decreased dependence on one specific form of energy, or to the choice of suppliers (Jewell, 2011). Jewell (2011) among others notes the importance of political stability in the supplying countries, and the sufficient number of entry points and suppliers.

[5] With its clear goals to enhance secure and sustainable energy systems and to combat global climate change, the European Union's 2030 Framework for climate and energy defined three major targets, including a 40% decrease in greenhouse gas emissions compared to the 1990 levels, a minimum of 27% share of renewables in energy use, and a 30% increase in energy efficiency compared to business as usual. The European Commission estimates that the cost of meeting these long-term goals will not significantly differ from the costs that would be needed to replace older energy technologies at the end of their life-cycle (European Commission, 2014a).

[6] Burke (2013) finds that parallel with economic development countries transition "*from biomass towards commercial fossil fuels, and hydroelectricity. At higher income levels, countries increasingly adopt low-carbon energy sources such as nuclear power and certain modern renewables such as wind power*" (Burke, 2013: p500).

[7] Burke (2010) provides on the one had empirical evidence for the presence of an "electricity ladder", on the other hand presents a simple stylized model of income, resources and the electricity mix, providing an analytical framework to explain historical patterns.