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Energy policy of fossil fuel-producing countries: does global energy transition matter?

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Abstract

The concept of energy transition can be interpreted in different ways depending on the nature of the agent involved. However, practitioners and existing literature agree that a country's energy transition is the variation of fossil fuel share in the total primary energy supply (TPES). Public policies mostly focus on changing the energy mix directly or indirectly. However, the production of fossil fuels depends mostly on market-related determinants, including prices and investment in the means of production. But what is the contribution of global energy transition? The objective of this paper is to estimate to which extent public policies related to energy transition affect fossil fuel production in producing countries. For this purpose, we consider as a proxy of energy transition the evolution over 40 years of the TPES of a large panel of fossil fuel–exporting countries, which we compare to its total primary energy production (TPEP). Moreover, we analyze these effects to determine if they differ according to country characteristics, such as its level of development or its membership in OPEC. Finally, we describe the long-run and short-run effects by studying separately the effects of production investments and those of R&D investments in RES technologies.

JEL classification: Q40, Q41, Q42

Keywords: Energy transition, Energy mix, TPEP, TPES, Renewable energy

1. Introduction

Energy transition can result in different outcomes depending on the nature of the agent, the country, or even the context. Thus, energy transition can (or not) lower energy consumption, lower energy intensity, replace the nuclear power industry, decentralize the power generation, or substitute certain resources for others. There is, however, one point on which the consensus is quite broad: to bring about the progressive replacement of fossil fuels by other resources. Thus, the notion of total primary energy supply (TPES), otherwise known as the energy mix, is at the heart of a quantitative assessment of energy transition. In particular, the evolution of the share of fossil fuels in primary resources is a critical indicator of the pathway taken by a country toward a low-carbon economy, as well as the speed with which it moves there. This indicator is very stable for the world (see Table 1); however, the situation varies greatly depending on the country: some have already started a trend reversal, and others have

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not yet. But that does not mean they have not engaged in an energy transition. Other indicators may change. For example, the level of fossil fuel consumption is declining in North America (−5% between 2006 and 2016) and Europe (−10%), but it is still rising in other regions of the world (see Table 1). The ratio of coal to natural gas shares decreases everywhere thanks to the substitution effect. Finally, the share of renewable energy sources (RES) in the TPES is growing rapidly everywhere. However, the examination of the global level of fossil fuel production shows that it is still rising (+15% between 2006 and 2016), at least for oil and natural gas, whereas it has been falling for coal since 2013, as has its price since 2011. This contradiction raises questions: how is the energy transition affecting fossil fuel–producing countries? To deal with this issue, we chose to test the impact of the various energy transition indicators on the production mix (total primary energy production; TPEP) of the main fossil fuel–producing countries. The impact of political instability on production has also been taken into consideration.

Table 1: Energy transition indicators

	Share of fossil fuels in TPES (%)		**Fossil fuel consumption (Mtoe)**		**Coal/natural gas ratio**		**Share of hydro and RES in TPES (%)**	
	2006	**2016**	**2006**	**2006**	**2016**	**2016**	**2006**	**2016**
World	87	86	9,851	11,354	1.28	1.16	6.9	10
North America	86	83	2,434	2,321	.86	.44	6.3	9.0
Europe	83	79	2,517	2,264	.53	.49	7.2	12
Asia	92	89	3,596	4,961	5.16	4.24	5.1	9.2
Fossil fuel producers	93	87	5,974	7,288	1.59	1.40	5.5	7.8

Source: Authors, from BP (2017) data.

Section 2 of this paper describes the latest developments in the literature, Section 3 details the methodology and data used, Section 4 analyzes and discusses the results obtained, and Section 5 concludes and draws implications in terms of economic policy.

2. Literature review

The concept of energy transition is not consensual, and it is the subject of several interpretations that vary according to the country, the composition of its government, or even the speaker who defines energy transition. This concept can also encompass notions of carbon intensity, liberalization of the electricity market, deployment of RES installations, or nuclear power substitution (Bridge *et al.*, 2013). From the point of view of the public authorities, energy transition will depend on the strategic vision: economic growth, climate change, health, energy access, and security or a combination of these outcomes. Other motivation for this transition could be the bottom-up pressure from society or reflected in local or individual initiatives, but some participants of the energy discussion recently suggest that the transition was now running independently of policy, where some key low-carbon technologies have reached competitiveness and maturity (International Energy Agency [IEA], 2017). Energy transition can, however, be shown to be restricted to three main trends: a change in per capita energy use, substitutions in primary resources, and changes in the means of power generation (Fouquet and Pearson, 1998). Thus, the notion of TPES is central in the evaluation of the effects of energy transition. Analyzing the UK's TPES from 1800 to 2008, Fouquet (2010) highlights energy transitions that affected this market for different uses (heating, power, transport, and lighting). The author concludes that transitions resulting from technological breakthroughs require several decades to succeed and that price is a key driver in accelerating the adoption of new resources. In the case of a transition to a low-carbon economy, consumers are willing to accept additional costs, but government support for the sectors is necessary (Fouquet, 2010). In general, recent studies on the energy transition all point to the key role of a government-led energy policy (Andriosopoulos and Silvestre, 2017; Grubler, 2012; Strunz *et al.*, 2016). But this factor is not enough to explain the evolution of the TPES. Thus, the share of coal in German energy production has remained stable for 20 years despite an energy policy that is extremely favorable to RES (Renn and Marshall, 2016).

Several authors have proposed theoretical models to estimate the impact of technological changes on substitutions between energy resources. Dasgupta and Heal (1974) propose a model of the optimal depletion of exhaustible resources, relying in particular on an isoelastic utility function and a CES-type production function.[1] This

[1] Letting K be the stock of reproducible commodity and R the flow of exhaustible resource, the production functions with constant elasticity of substitution σ can be written in the following form: $F(K,R) = \left[\beta K^{(\sigma-1)/\sigma} + (1-\beta)\, R^{(\sigma-1)/\sigma}\right]^{\sigma/(\sigma-1)}$, with $0 < \beta < 1$ and $\sigma \geq 0$.

model predicts that, if the elasticity of the substitution between reproducible commodity stock and exhaustible resource flows is constant, whatever its value, if it is finite, then the resource will not be exhausted; however, the price of this resource relative to output should grow quickly. However, observations do not confirm this prediction because of technological advances. By introducing time-uncertain technological breakthroughs in their model, Dasgupta and Heal (1974) postulate that, in order to properly manage this uncertainty, the existing stocks of capital and of exhaustible resources must be devoid of value at the time of the technical change. Chakravorty *et al.* (1997) sought to model the extraction of fossil fuels under alternative regimes of technological change. Their model is based on depletion equations using the Hotelling rule, for each resource i and each use j, with neoclassical demand functions of the Cobb-Douglas form (see Appendix A). Their results suggest that, provided that the rate of reduction of solar energy production costs is maintained, extraction growth would continue for another three decades and would be followed by a sharp decline caused by the transition of the electricity and transportation sectors to solar energy. This paper, however, does not take into account the technological changes that also affect fossil fuels, which skews the analysis. Moreover, the substitution between energies is not constant and follows a concave law with a possible asymptote. To correct the shortcomings of the Chakravorty *et al.* (1997) model, Tahvonen and Salo (2001) have developed a sharper model in which, first, energy resources are differentiated between fossil and renewable in order to better deal with the interactions between the two; second, the growth is endogenous with the natural resources; and, third, technical change is concurrently endogenous. Thus, their specification takes into account endogenously not only the costs of renewables but also the extraction costs. However, technical changes may introduce effects contrary to the Hotelling rule, as already described in the literature (see, e.g., Attala *et al.*, 2017; Berk and Roberts, 1996). Tahvonen and Salo (2001) then introduce technical changes in extraction and renewable energy production with two variables denoting the level of extraction technological knowledge and the level of knowledge associated with the level of productive capital. According to this model, graphical representations of energy use as a function of GDP per capita with technical change show an increasing monotonous relationship, and this relationship takes the shape of an inverted U for fossil fuels. This result is consistent with some previous observations, such as Schlamensee *et al.* (1998)

on panel data from 47 countries over the period 1950–1990. The model of Tahvonen and Salo (2001) also predicts negative growth rates for the use of fossil fuels over time, while remaining positive for renewables and total energy consumption. More recently, Court *et al.* (2018) propose another model with endogenous technical change (see Appendix A) that leads to a stagnation of world GDP from 2050 to 2110, depending on the model calibration, or even a decrease when introducing a carbon tax. Finally, Blazquez *et al.* (2017) were particularly interested in Saudi Arabia. From a general equilibrium model, they postulate that a partial deployment of RES in Saudi Arabia would have a positive impact on the welfare of the country, provided that their integration costs into the grid are moderate, as well as the decrease in subsidies to fuel consumption.

We may suspect a cyclical effect of political instability on the production of fossil energy. However, the literature rather shows a weakness, even an absence of impact of political stability on energy production. Campos and Nugent (2002) conclude that there is no causal relationship, based on two indicators of sociopolitical instability (severe and moderate) on economic growth data from 1960 to 1995. By detailing political instability from four more accurate indices (political violence, mass civil protest, instability within the political regime, and instability of the regime), Jong-A-Pin (2009) succeeds in showing a negative effect of its fourth index (instability of the regime) on economic growth during 1974–2003, but it is very weak in magnitude; moreover, the criteria of instability differ from those that underpin most crises in fossil fuel–producing countries.

Some empirical studies have looked at the energy consumption of fossil fuel–producing countries, such as Mehrara (2006), which evidenced that GDP per capita strongly Granger-causes energy consumption, similar to OECD countries (see, e.g., Apergis and Payne, 2010; Salim *et al.*, 2014[2]). Others have looked at the impact of the energy efficiency on oil exports (Bhattacharyya and Blake, 2010). Matar *et al.* (2017) model what would be the effects of a disruptive energy policy on Saudi Arabia's energy mix, based on a partial equilibrium model. They conclude that such reforms would reduce the consumption of oil and natural gas by up to 2 million barrels of oil equivalent per day by 2032 and increase the share of nuclear power and renewables in

[2] It should be noted that, in addition to confirming the bidirectional short-run causality between GDP and non-renewable energy consumption, this study reveals a unidirectional causality from GDP to RES consumption.

power generation to 70%. However, the country's dependence on oil exports would increase. Nonetheless, to our knowledge, none has yet estimated the impact of the global energy transition on the policy of the main fossil fuel producers.

3. Empirical strategy and data

3.1 Empirical specification

We model the relationship between the share of fossil fuels in energy production and energy transition in consumption as:

$$SFP_{i,t} = \beta_i^{ETC} ETC_{i,t} + \beta_i^X X_{i,t} + u_{i,t} \tag{1}$$

where $SFP_{i,t}$ is the share of fossil fuels in energy production (TPEP) of country i in year t, ETC is the variable of energy transition in consumption, X is a vector of control variables, u_{it} stands for the unobservable factors, and, finally, for each explanatory variable $k = ETC, X$, there is a parameter coefficient β_i^k, which is allowed to differ across countries to take into account the heterogeneity of the reaction to energy transition across countries. For each explanatory variable, the parameter of interest is the mean of individual slope coefficients $B^k = E(\beta_i^k)$.

To account for other forms of heterogeneity among countries, we model the unobserved effects u_{it} as a function of country-specific effects α_i, and a set of common unobserved factors f_t with country-specific factor loadings λ_i and an error term ε_{it}:

$$u_{i,t} = \alpha_i + \lambda_i f_t + \varepsilon_{i,t} \tag{2}$$

Taking into account common factors f_t is a central feature of our empirical setup. Indeed, these common factors are a combination of "strong" factors, which affect all countries (e.g., the 1970s oil crises), and "weak" factors, which affect subsets of countries (e.g., economic interactions) (Chudik *et al.*, 2011). That is, fossil fuel production strategies are interrelated and not independent among countries. Hence, we should take into account these factors and not only consider them as omitted variables. In addition, these common factors not only drive transition in energy production but also the transition in energy consumption, which highlights the endogeneity issues related to the variable of energy transition in consumption ETC.

To handle these issues, following Eberhardt and Presbitero (2015), we employ an error correction model (ECM) as follows:

$$\Delta SFP_{i,t} = \beta_{0i}^{ETC}\Delta ETC_{i,t} + \beta_{0i}^{X}\Delta X_{i,t} + \lambda_{0i}\Delta f_{i,t} + \rho_i\big(SFP_{i,t-1} - \beta_{1i}^{ETC}ETC_{it-1} - \beta_{1i}^{X}X_{i,t-1} - \lambda_{1i}f_{i,t-1}\big) + \alpha_i + \varepsilon_{it} \qquad (3)$$

where β_{0i}^{k} represents the short-run relationships between the explanatory and the dependent variables, β_{1i}^{k} represents the long-run relationships, and ρ_i is the error correction coefficient or adjustment coefficient. The error correction coefficient (ρ_i) takes a value between -1 and 0 and represents the speed of adjustment in cases of disequilibrium. Indeed, $\big(SFP_{i,t-1} - \beta_{1i}^{ETC}ETC_{it-1} - \beta_{1i}^{X}X_{i,t-1} - \lambda_{1i}\Delta f_{i,t-1}\big) = 0$ when the equilibrium holds, but this term is no longer zero during the periods of disequilibrium. If this term is positive, it means that $SFP_{i,t-1}$ has moved above its long-run equilibrium path, and this should decrease $\Delta SFP_{i,t}$ to turn back toward the equilibrium. Hence, $\rho_i$indicates how much of the equilibrium error is corrected each period.

The ECM enables us then to distinguish between short-run and long-run determinants of transition in energy production. Energy transition could have short-term effects through $\beta_{0i}^{ETC}\Delta ETC_{i,t}$, as well as long-term effects through $\beta_{1i}^{ETC}ETC_{it-1}$.

One way to account for unobservable common factors $f_{i,t}$ in Equation (3) is to employ cross-section averages of all variables in the model (Eberhardt and Presbitero, 2015; Eberhardt and Teal, 2013; Pesaran, 2006).[3] In addition, adding lags of the cross-section averages to the model enables handling endogeneity of explanatory variables (Chudik and Pesaran, 2015). Thus, following Eberhardt and Presbitero (2015), our model takes the following form:

[3] In our case, $\lambda_{1i}f_{i,t} = \gamma_{4i}\overline{SFP}_t + \gamma_{5i}\overline{\Delta ETC}_t + \gamma_{6i}\overline{\Delta X}_t$ and $\lambda_{0i}\Delta f_{i,t} = \gamma_{1i}\overline{\Delta SFP}_t + \gamma_{2i}\overline{\Delta ETC}_t + \gamma_{3i}\overline{\Delta X}_t$. These variables control then for unobserved events that influenced the share of fossil fuels on energy production in several countries at the same time t.

$$\Delta SFP_{i,t} = \beta_{0i}^{ETC}\Delta ETC_{i,t} + \beta_{0i}^{X}\Delta X_{i,t} + \rho_i SFP_{i,t-1} + \delta_i^{ETC} ETC_{it-1} + \delta_i^{X} X_{i,t-1} + \sum_{l=0}^{p}\gamma_{1il}\overline{\Delta SFP}_{t-l} + \sum_{l=0}^{p}\gamma_{2il}\overline{\Delta ETC}_{t-l} + \sum_{l=0}^{p}\gamma_{3il}\overline{\Delta X}_{t-l} + \gamma_{4i}\overline{SFP}_{t-1} + \gamma_{5i}\overline{ETC}_{t-1} + \gamma_{6i}\bar{X}_{t-1} + \alpha_i + \varepsilon_{it} \quad (4)$$

where $\delta_i^k = \rho_i \times \beta_{1i}^k$. Hence, we can compute the long run from the coefficients from Equation (4) estimates as $\beta_{1i}^k = \delta_i^k/\rho_i$. Note that if $p = 0$, Equation (4) becomes a Pesaran (2006) common correlated effects (CCE) mean group (MG) estimator; whereas if $p > 0$, it yields to the dynamic CCE-MG estimator (Chudik and Pesaran, 2015).[4]

3.2 Data and stylized facts

Because the focus of our article is the fossil energy producers, we start by identifying the most important producers of this type of energy during the period 1971–2015. We selected those countries that belong to the upper quartile of fossil energy production for at least one year during the period of our study. Our dataset comprises a panel of 43 fossil energy producers,[5] and these countries account for about 95% of fossil energy produced over the period 1971–2015.

As a first approach, the impact of consumption on production can be visualized on the TPES and TPEP graphs. Figure 1a depicts the world TPES (left) and TPEP (right) for the period 1990–2015. Two observations emerge: (1) the TPES and the TPEP are balanced, which is expected at the global level, whereas they are generally unbalanced at the country level; (2) they are fairly stable over this period, although there are very strong variations and structural breaks at the country level. If we take the example of Norway (Figure 1b), we can see that its TPES and TPEP are very different and variable over the period considered.

[4] This estimator has been recently used in the literature for different analyses, such as the effects of R&D policy (Minniti and Venturini, 2017), public debt (Eberhardt and Presbitero, 2015), and trade (Kim *et al.*, 2016) on growth, as well as on the economic impact of Brexit-induced reductions in migration (Portes and Forte, 2017) and credit growth and current account balances (Unger, 2017), among others.

[5] These countries are: Algeria (DZA), Angola (AGO), Argentina (ARG), Australia (AUS), Azerbaijan (AZE), Brazil (BRA), Canada (CAN), China (CHN), Colombia (COL), Czech Republic (CZE), Democratic Republic of Korea (PRK), Egypt (EGY), France (FRA), Germany (DEU), India (IND), Indonesia (IDN), Iran (IRN), Iraq (IRQ), Japan (JPN), Kazakhstan (KAZ), Kuwait (KWT), Libya (LBY), Malaysia (MYS), Mexico (MEX), Netherlands (NLD), Nigeria (NGA), Norway (NOR), Oman (OMN), Poland (POL), Qatar (QAT), Romania (ROU), Russia (RUS), Saudi Arabia (SAU), South Africa (ZAF), Syria (SYR), Thailand (THA), Ukraine (UKR), United Arab Emirates (ARE), United Kingdom (GBR), United States (USA), Uzbekistan (UZB), Venezuela (VEN), and Viet Nam (VNM).

Figure 1a: World TPES and TPEP, 1990–2015

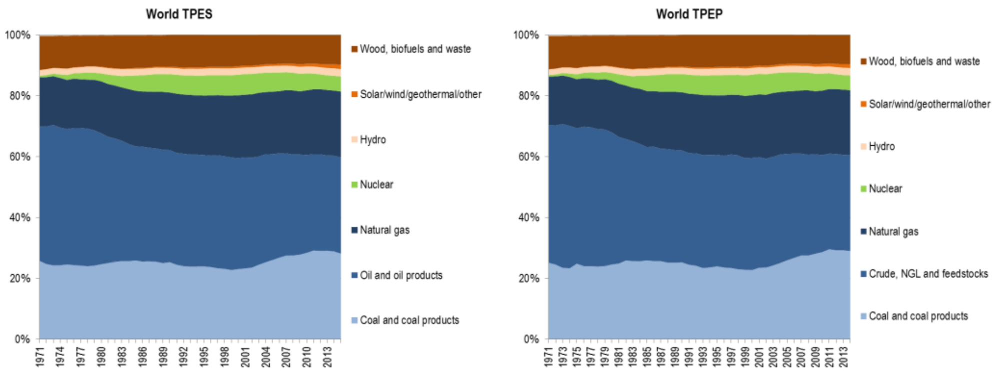
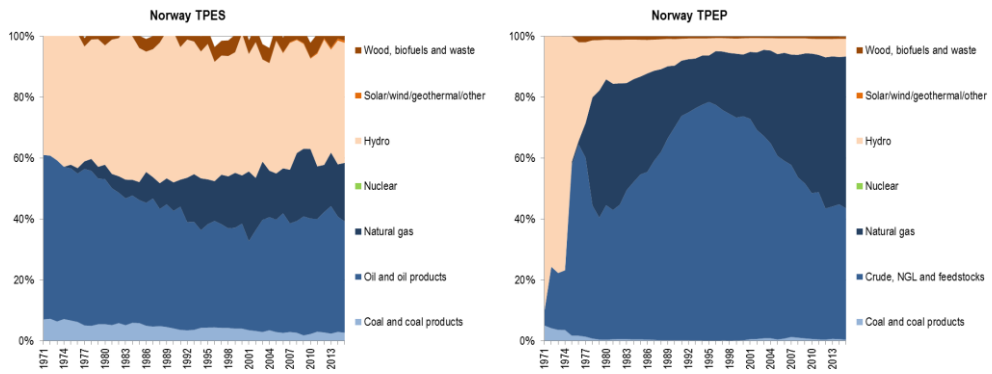


Figure 1b: Norway TPES and TPEP, 1971–2015



Source: Authors from International Energy Agency database

The TPES and TPEP graphs of the main fossil fuel–producing countries are presented in Appendix B1 (the others are available upon request). These graphs show that, apart from China, Nigeria, and Mexico, very few of these countries have significantly reduced their share of fossil fuels in their TPEP, even when this share was declining in their own consumption (Canada, Russia, and the USA). However, the relative proportion of each of fossil fuel (oil, natural gas, and coal) has often changed considerably (Algeria, Australia, Canada, Indonesia, Iran, Malaysia, Norway, Qatar, Russia, and the USA). In addition, the TPEP graphs show a certain insensitivity of the fossil fuel energy indicator to geopolitical crises, according to studies on political instability. For example, although oil production in Iran fell sharply after the 2012 international blockade, this decline was offset by natural gas production. This trend had already begun in the early 1980s. None of the producers in the Middle East who suffered from several political crises saw their share of fossil fuels decline over the period considered. Conversely, examination of the TPES graphs of the main consuming countries shows a clear downward trend in fossil fuel share, with the exception of the particular case of Japan, which substituted its nuclear energy for fossil fuels after Fukushima (Appendix B2).

To measure the share of fossil fuels in energy production (our dependent variable), we use the ratio of fossil fuels to TPEP, expressed in a net basis according to IEA conventions (IEA, 2015a, 2015b). We also distinguish among three different types of fossil fuel: coal, natural gas, and oil. For each of these types, we estimate its share in TPEP. Data on energy production come from the International Agency Energy (IAE) database. We use two different variables for energy transition on consumption (ECT) using World Bank data. First, to take into account the importance of non-fossil energies in energy consumption, we define the variable *Fossil consumption*, which corresponds to the share of fossil fuels in energy total consumption. Second, to take into account the volume of energy consumption, we define a variable *Energy use per capita*, which is the logarithm of energy use per capita in kilogram oil equivalent (kgoe). Finally, as control variables, we use the log of GDP per capita, the carbon dioxide (CO_2) damage as percentage of GNI, and the fossil fuel rents, which are measured as the difference between the value of production at world prices and the cost of production in percentage of GDP. Data for control variables come from the World Bank. Table 2 shows the descriptive statistics and the correlation matrix.

Table 2: Descriptive statistics and correlation matrix

Variable	Obs.	Mean	S.D.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) S of Fossil	1663	0.816	0.244	1								
(2) S of Coal	1663	0.213	0.302	0.05	1							
(3) S of Gas	1663	0.176	0.208	0.29**	−0.31**	1						
(4) S of Oil	1663	0.428	0.344	0.49**	−0.66**	−0.13**	1					
(5) Fossil cons.	1663	0.815	0.216	0.61**	0.14**	0.28**	0.14**	1				
(6) Energy use	1663	7.532	0.951	0.21**	0.12**	0.29**	−0.13**	0.47**	1			
(7) GDPpc	1444	8.978	1.354	0.07**	0.004	0.17**	−0.06*	0.34**	0.85**	1		
(8) CO_2 damage	1423	0.019	0.023	0.21**	0.18**	0.20**	−0.11**	0.20**	−0.03	−0.41**	1	
(9) Fossil rents	1500	0.103	0.135	0.39**	−0.39**	-0.12**	0.67**	0.09**	−0.03	−0.10**	0.12**	1

Notes: S of Fossil = Share of fossil fuels in energy production, S of Coal = Share of coal in energy production, S if Gas = Share of natural gas in energy production, S of Oil = Share of oil in energy production, Fossil cons. = Share of fossil fuels in energy consumption, Energy use = Energy consumption per capita, GDPpc = GDP per capita, CO_2 damage as a % of GDP, Fossil rents as a % of GDP.
** Significant at 5%, ** significant at 1%.*
Data sources are International Energy Agency database for (1) to (4), and World Bank database for (5) to (9).

4. Results and discussion

We start by estimating Equation (3) imposing parameter homogeneity across countries. First, we use ordinary least squares (OLS) methods and then a pooled CCE model. The results are presented in columns 1 to 3 of Table 3. Column 1 estimates control for fixed effects through the first difference, column 2 includes country fixed effects (α_i) in addition to the first difference (see Equation 3), and column 3 presents the pooled CCE model.

The results suggest that, in the short and long run, increasing the share of fossil energy consumption leads to an increase in the share of fossil energy production. In addition, results suggest that increasing energy use decreases the weight of fossil energy on energy production. The results also show that the coefficient of the error correction term is negative, between -1 and 0, and statistically significant, which is consistent with error-correcting behavior. That is, following a shock, the share of fossil fuels in energy production returns to the long-run equilibrium path, and then there exists cointegration among the variables in levels. The root-mean-square error (RMSE) shows that adding common correlated effects to the model improves the goodness-of-fit compared to the OLS and 2FE estimates. However, the Pesaran (2004) CD test statistics indicate empirical misspecification, and thus that our estimates are biased. Indeed, the null of cross-section dependence cannot be rejected in these three models.

We relax parameter homogeneity across countries allowing for differential relationships. We start by estimating the Pesaran (2006) CCE-MG estimator. Column 4 of Table 3 illustrates the average results. These indicate that both variables of energy transition are significant at 5% in the short run as well as offer a significant error correction. However, the CD test is still above 1.96, so we cannot reject the null of cross-section dependence. Moreover, there is still potential endogeneity among explanatory variables that could lead to biased results.

Table 3: Effects of energy transition in consumption on the share of fossil fuels in energy production

Dependent variable	*Share of fossil fuels in energy production*							
Estimator :	OLS	2FE	Pooled CCE	CCE-MG	Dynamic CCE-MG (1 lag)	Dynamic CCE-MG (2 lags)	Dynamic CCE-MG (2 lags)	Dynamic CCE-MG (2 lags)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Short run:								
Δ Fossil consumption	0.517** (0.055)	0.522** (0.080)	0.551** (0.064)	0.536** (0.079)	0.494** (0.071)	0.464** (0.067)	0.560** (0.089)	0.554** (0.081)
Δ Energy use per capita	−0.007* (0.003)	−0.008 (0.004)	-0.011** (0.003)	−0.023** (0.008)	−0.021* (0.010)	−0.032** (0.012)	−0.036 (0.020)	−0.036 (0.023)
Δ GDP per capita							0.004 (0.016)	0.000 (0.016)
Δ CO_2 damage							0.265 (0.187)	
Δ Fossil rents								0.055* (0.027)
Long run:								
Error correction	−0.002 (0.003)	−0.083* (0.032)	−0.122** (0.037)	−0.269** (0.038)	−0.268** (0.042)	−0.313** (0.040)	−0.421** (0.075)	−0.448** (0.064)
Fossil consumption	−3.319 (7.778)	0.902** (0.209)	0.909** (0.188)	0.471** (0.155)	0.447** (0.160)	0.435** (0.138)	0.562** (0.208)	0.334* (0.162)
Energy use per capita	−0.500 (1.199)	0.000 (0.020)	−0.014 (0.019)	−0.016 (0.011)	−0.020 (0.012)	−0.006 (0.009)	−0.033 (1.042)	0.016 (0.023)
GDP per capita							−0.026 (0.027)	−0.014 (0.024)
CO_2 damage							0.100 (0.050)	
Fossil rents								−0.102 (0.082)
Observations	1663	1663	1663	1663	1624	1589	1028	1161
RMSE	0.016	0.014	0.012	0.010	0.008	0.007	0.007	0.006
CD test	13.521	12.755	−3.049	−2.071	−2.163	−1.665	−0.928	−0.679

*Notes: * Significant at 5%, ** significant at 1%. The estimators are: OLS – Ordinary least squares, 2FE – Double fixed effects, Pooled CCE – pooled common correlated effects, CCE-MG – Pesaran (2006) CCE mean group estimator, and dynamic CCE-MG is the Chudik and Pesaran (2015) dynamic CCE-MG estimator with the number of lags within brackets below the name of the estimator. Robust standard errors reported in brackets below coefficients' value. RMSE is the root-mean-square error. CD test reports the Pesaran (2004) test, which under the null of cross-section independence is distributed standard normal. All regressions include a constant, OLS and 2FE include year dummies, pooled CCE includes cross-section averages of all variables and interactions between country dummies and cross-section averages, and CCE-MG and dynamic CCE-MG include cross-section averages of all variables not reported here.*

To handle endogeneity issues, we use the Chudik and Pesaran (2015) dynamic CCE-MG estimator. That is, we add one lag (column 5) or two lags (column 6) of the cross-section averages to the model. The results suggest that to avoid cross-sectional dependence, we need to include two lags of the cross-section averages. The two energy transition variables are statistically significant in the short run, but only fossil fuel consumption is significant in the short run. To analyze if there is not an omitted variable bias, we proceed to include further variables (GDP per capita, CO_2 damage, and fossil rents) to the model (columns 7 and 8). The results suggest that among the energy transition variables, only Fossil consumption is statistical significant, and it influences the structure of energy production in both the short and the long run. More precisely, the results suggest that, on average, reducing the share of fossil fuels in energy consumption by 10% would lead to a reduction of about 5.5% of the share of fossil fuels in energy production in the short run and between 3.3% and 5.5% in the long run. Among the control variables, fossil rents provide a significant determinant of the weight of fossils on energy production.

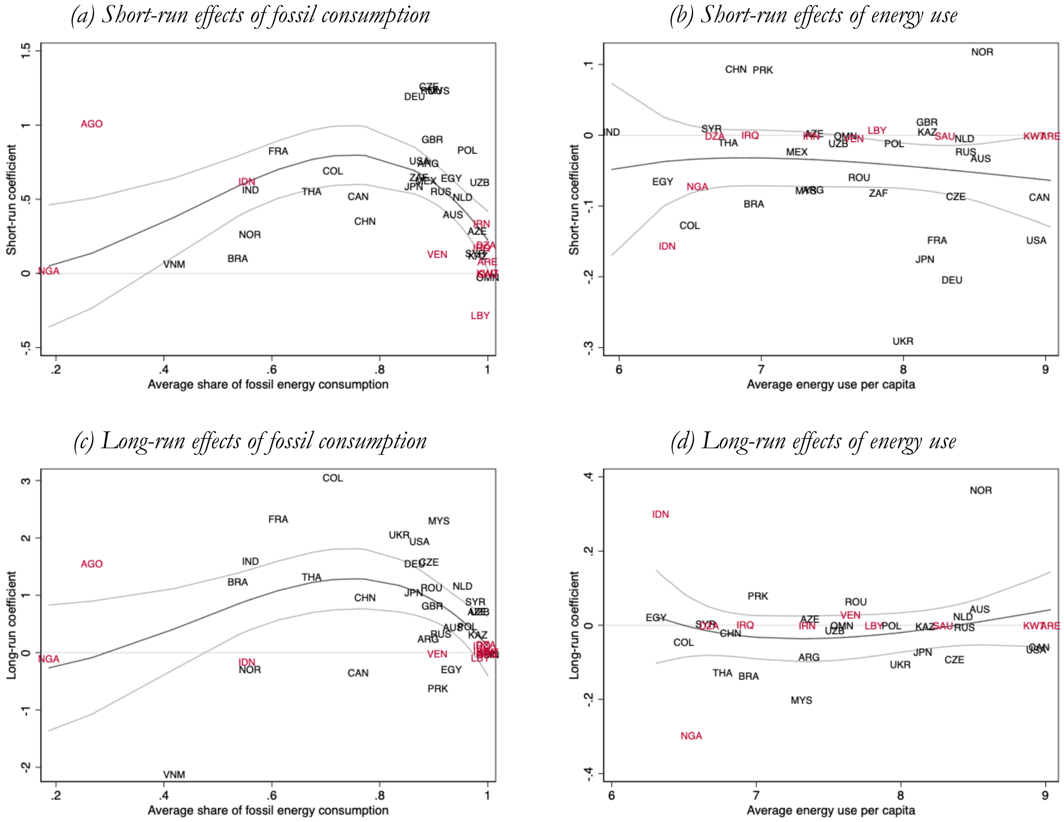
The reported estimates in columns 4 to 8 concern the CCE-MG and the dynamic CCE-MG estimators. Hence, non-significant estimates do not imply the absence of any significant effects, but rather highlight the heterogeneity across countries with dynamics on average cancelling out. Indeed, these estimates correspond to the average coefficients.[6]

Figure 2 displays a series of plots of the country-level coefficients of the estimates in the dynamic CCE-MG model with one lag presented in column 6 of Table 3. These plots illustrate the cross-section dispersion of the coefficients of all variables. The curve lines correspond to fitted polynomial regression lines of short- and long-run coefficient values of the share of fossil fuel production against average fossil fuel consumption (a and c) and against average energy consumption (b and d). OPEC countries are displayed in red.[7]

[6] In the case of the long-run coefficients, we estimate first the average ECM coefficients and then compute the long-run average as $\beta_{1i}^{k} = \delta_i^k/\rho_i$. The standard errors are then computed following the Delta method (see Eberhardt and Presbitero, 2015).

[7] Indonesia, which was a member from 1962 to 2008, then for a few months in 2016, was attached to the group of members.

Figure 2: Patterns for coefficient estimates on the effects on fossil fuel production



Notes: We plot the country-specific coefficients for each transition in consumption variable taken from the dynamic CCE-MG model with one lag (column 6 of Table 2) against the country-specific average of each variable. The lines correspond to fitted polynomial regression lines of short- and long-run coefficient values of fossil fuel consumption against average fossil fuel consumption for (a) and (c), and short-run and long-run coefficient values of energy consumption against average fossil fuel consumption for (b) and (d). OPEC countries are displayed in red. Following Eberhardt and Presbitero (2015), we omit those countries for which the robust regression method indicates as outliers based on their coefficient. We exclude then the following countries by figure: AGO in (b) and (d); DEU in (d); FRA in (d); GBR in (d), IND in (d); MEX in (c) and (d); PRK in (a); UKR in (a); VNM in (b) and (d); and ZAF in (c) and (d).

Plot (a) displays the short-run effect of the share of fossil fuel consumption on the share of fossil fuel production ($\beta_{0i}^{Fossil\ cons.}$); it shows that for most of the countries there is an expected positive relationship in the short run, with an average of 0.490. Less predictably, the plot suggests that this relationship is non-linear and takes the shape of an inverted U: the effect increases when fossil consumption is below 75%, and then it decreases after when fossil consumption is higher than 75%. However, if we split the countries into two categories, OPEC members and non-members, we see two distinct trends: the relationship between the share of fossil fuel consumption and the share of fossil fuel production is clearly positive for non-OPEC countries, with an average of

0.60, whether they are developed or emerging economies, whereas it is only 0.21 for the OPEC members, and 0.07 when excluding Indonesia and Angola from OPEC.

Plot (b) displays the short-run effect of the consumption level energy use per capita on the share of fossil fuel production ($\beta_{0i}^{Energy\ use}$); it shows a slight difference in the distribution between OPEC members and non-members: the effect is null for most of the former, but it is, as expected, negative for most of the non-OPEC producers, with an average of −0.05.

Plot (c) displays the long-run relationship between the share of fossil fuel consumption and the share of fossil fuel production ($\beta_{1i}^{Fossil\ cons.}$). The shape of this relationship is similar to the short-run relationship between these two variables. There is a strong difference between the OPEC member and non-member countries: whereas the relationship is insignificant for the former (excepting Angola), it is positive as expected for most of the latter, with an average of 0.85. Note, however, that the relationship between fossil fuel consumption and production is negative for some producers, such as Canada and Norway. This negative sign is opposite to that of the short-term relationship and can be explained by the general downward trend of fossil consumption, whereas fossil fuel production is quite stable over the 40 years of observation, unlike other countries (see Figure 1b and Appendix B1). Nevertheless, the relationship remains positive within the sub-periods delimited by the structural breaks of the TPES and TPEP.

Plot (d) displays the long-run relationship between energy use and fossil fuel production ($\beta_{1i}^{Energy\ use}$); it shows that variation in energy consumption has no effect for most of the countries in the long run. However, there is a significant effect for some countries, which can be highly positive (Indonesia and Norway) or negative (Nigeria and Malaysia). The positive sign of Norway is contrary to expectations but in line with the short-term effect, too, which is also positive for this country and means that the increase in energy consumption per capita has resulted in an increase in the share of fossil fuels in energy production. The case of Indonesia, however, is very atypical: this country has a significant and very negative short-term coefficient, which denotes the expected impact of the energy transition, whereas in the long term, this coefficient is positive. These results suggest that Indonesia uses non-fossil energy to satisfy an increase in demand in the short run, but in the long run, the production of fossil energy is going to increase faster than that of non-fossil energy. This observation is linked to the strong development of coal for energy production since the 1990s to substitute other forms of fossil fuel (see Appendix B1).

We proceed to analyze if the effects of the energy consumption variables on fossil fuel production are the same for the different types of fossil fuel. In addition, we analyze if there are substitutions or complementarity among fossil fuels. Table 4 shows the results using two different specifications for each dependent variable. Columns 1 and 2 illustrate the results using the share of coal on energy production as the dependent variable. These results suggest that fossil fuel consumption increases the share of coal in production, but only in the short-run. In addition, the results suggest a negative relationship between the share of gas on energy production and the share of coal on energy production.

Columns 3 to 4 show the results when using the share of natural gas on energy production as a dependent variable. An increase in fossil fuel consumption also increases the share of natural gas in production only in the short run. In addition, there is a substitution effect in the short run between natural gas production and other forms of fossil fuel production. Contrary to coal, for which rents have non-significant effects, gas rents have a significant effect on the weight of natural gas in energy production in both the short run and the long run.

Finally, we replicate our estimates using the share of oil on energy production as a dependent variable (columns 5 and 6). In the short run, the share of oil on energy production would increase if fossil fuels consumption or oil rents increase. However, it would decrease in both the short and long run if natural gas production increases.

Table 4: Effects of energy transition in consumption and substitutability on the share of fossil fuels in energy production for each type of fossil fuel

Dependent variable	Share of coal in energy production		Share of gas in energy production		Share of oil in energy production	
	(1)	(2)	(3)	(4)	(5)	(6)
Short run:						
Δ Fossil consumption	0.285** (0.065)	0.049* (0.023)	0.274** (0.057)	0.348** (0.071)	0.299** (0.059)	0.385** (0.078)
Δ Energy use per capita	−0.007 (0.013)	−0.005 (0.008)	−0.001 (0.015)	−0.010* (0.004)	−0.011 (0.015)	−0.018 (0.010)
Δ Share of coal in production			−0.798** (0.299)	−0.394** (0.120)	−2.570 (1.516)	−0.591** (0.130)
Δ Share of gas in production	−0.343* (0.138)	−0.479** (0.116)			−0.807** (0.111)	−0.890** (0.104)
Δ Share of oil in production	−0.213 (0.238)	−0.390** (0.090)	−0.485** (0.133)	−0.725** (0.093)		
Δ Rents		0.001 (0.001)		0.009* (0.004)		0.002* (0.001)
Long run:						
Error correction	−0.364** (0.061)	−0.424** (0.068)	−0.352** (0.067)	−0.389** (0.068)	−0.296** (0.062)	−0.426** (0.070)
Fossil consumption	0.323** (0.105)	0.046 (0.045)	0.322 (0.178)	0.269* (0.106)	0.325 (0.228)	0.225* (0.093)
Energy use per capita	−0.015 (0.020)	−0.008 (0.020)	−0.000 (0.035)	-0.012 (0.023)	−0.147 (0.092)	−0.010 (0.020)
Share of coal in production			0.709 (1.256)	−0.360 (0.208)	−1.228 (0.825)	−0.648* (0.286)
Share of gas in production	0.014 (0.393)	−0.428* (0.169)			−0.997** (0.327)	−0.929** (0.271)
Share of oil in production	−0.523* (0.231)	−0.177 (0.113)	−0.329 (0.218)	−0.673** (0.226)		
Rents		−0.003 (0.003)		0.025** (0.010)		0.002 (0.002)
Observations:	1490	1117	1490	1117	1490	1117
RMSE	0.004	0.003	0.004	0.003	0.005	0.003
CD Test	−0.128	0.405	0.325	0.987	1.039	0.672

*Notes: * Significant at 5%, ** significant at 1%. For each fossil type, economic dependence variable is the weight of rents of the fossil fuel type on a country's GDP. All the estimates obtained using the Chudik and Pesaran (2015) dynamic CCE-MG estimator with two lags. Robust standard errors are reported in brackets. RMSE is the root-mean-square error. CD test reports the Pesaran (2004) test, which under the null of cross-section independence is distributed as standard normal. The regression includes a constant and cross-section averages of all variables not reported here.*

5. Conclusions and policy implications

With net energy consumption, the total primary energy supply (TPES) is the main indicator used to monitor the effectiveness of energy transition around the world. In particular, the share of fossil fuels in the TPES is very significant. Globally, this share has remained stable for 10 years; however, the study of the TPES of major energy-producing and -consuming countries shows very large disparities among them. Numerous studies on energy transition have examined the role of energy policies or technological breakthroughs on the TPES, including for fossil fuel producers, but none has studied the impact of changing consumption on fossil fuel production. To answer this question, we consider the share of fossil fuels in the production mix (TPEP) and estimate the impact of a shock from the TPES, as well as from the level of energy consumption. This analysis has been conducted on the 43 main producers of fossil fuels, distinguishing OPEC members from others. The results suggest that, on average, reducing the share of fossil fuels in energy consumption by 10% would lead to a reduction of about 5% of the share of fossil fuels in energy production in the short run and long run. The relationship between these two variables is clearly positive for non-OPEC countries, whether they are developed or emerging economies, whereas it is null for most of the OPEC members. In addition, a dissociated analysis for the shares of each of the three fossil fuels (coal, natural gas, and oil) reveals negative dependence relationships among them, which highlights strong substitution effects among these resources. In particular, natural gas production has a significant substitution effect on coal and oil fuels. Finally, the results suggest that the rents (as a percentage of GDP) are a significant element for continuing to produce fuel energy, in particular for gas and oil. This study shows that a weakening of fossil fuels in the TPES is driving a reduction of fossil fuel on most of the energy producers; however, this is not the case in the OPEC countries, which are the main fossil fuel–producing countries.

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Appendix A: Theoretical framework

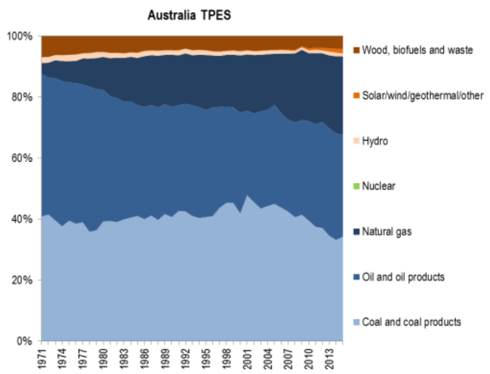
In the Chakravorty *et al.* (1997) model, the stock flow of the resource i and the use j is defined by $\dot{Q}_i(t) = -\sum_{j=1}^{J} \frac{d_{ij}(t)}{v_{ij}}$, where $d_{ij}(t)$ represents the net supply of the resource i for sector j and $v_{ij} = \frac{d_{ij}(t)}{q_{ij}(t)} \in [0; 1]$ is the efficiency factor. In the Cobb-Douglas demand function $D_j = A_j P_j^{\alpha_j} Y_j^{\beta_j}$, α_j, and β_j being the price and income elasticities, the aggregate income (estimated by world GDP) is written $Y_{j,t}^{\beta_j} = \left(\frac{Y_0}{1+g_1}\right)^{\beta_j} \left(\sum_{n=1}^{L}(1+g_t)^{n\beta_j}\right)\left(\prod_{m=1}^{t-1}(1+g_m)^{L\beta_j}\right)$, where g_t is the GPD growth rate for year t over L years. Thus, the price of energy service j is specified $P_{j,t} = \left(\frac{D_{j,t}}{\gamma_{j,t}}\right)^{1/\alpha_j}$, with $\gamma_{j,t} = A_j Y_{j,t}^{\beta_j}$, and is constant within each L-year time period.

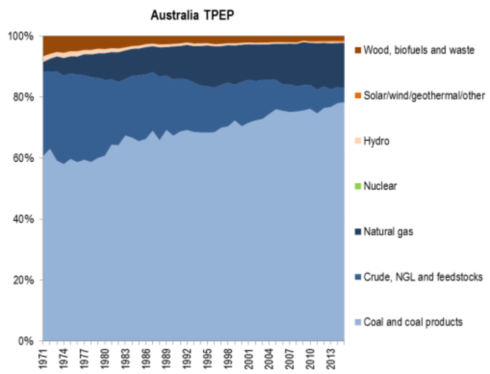
Tahvonen and Salo (2001) believe that this model leads to overestimating the development of solar energy and underestimating the resilience of fossil fuels, which calls into question the prediction of a depletion of fossil fuels within 50–70 years. In their model, the solution that maximizes the social welfare function is given by $\dot{k} = P(k,e) - qC(x) - F(s) - c$, where k is the capital stock, $e = q + s$ the use of energy, q the use of fossil fuels, s the use of renewable or expendable energy sources, $P(k,e)$ a concave production function, $C(x)$ the extraction unit cost, $F(s)$ the cost of using energy sources, and c the consumption. Its current value Hamiltonian imposes as the necessary condition $\dot{\varphi} = \lambda q C' + \delta\varphi$, where φ is the resource rent, λ the output price, and δ the discount rate of the utility function, with $\delta = P_k(k, \bar{s})$ at a steady state. Then, they introduce technical changes with the variables n_1 denoting the level of extraction technological knowledge, defined as $\dot{n}_1 = q$, and n_2 denoting the level of knowledge associated with the level of productive capital, defined as $n_2 = k$. The functions of the optimal solution $\dot{k}$ with knowledge externalities are then specified as follows:

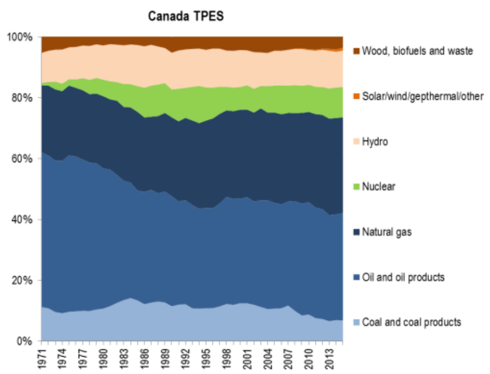
$$\begin{cases} P(k,e,n_2) \equiv k^{\alpha} e^{1-\alpha}, 0 < \alpha < 1 \\ F(s,n_2) \equiv s^{\sigma}(\mu + k^{1-\sigma}), \qquad \sigma > 1, \mu \geq 0 \\ C(x,n_1,n_2) \equiv \dfrac{c_0}{x} + c_1 x + \dfrac{c_2}{c_3 + k}, c_i > 0 \end{cases}$$

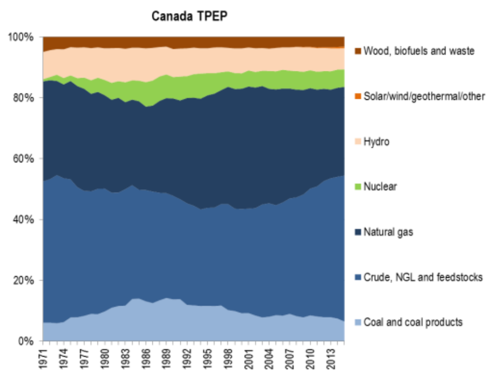
In Court *et al.* (2018), the capital requirements per output unit of renewable and non-renewable energy are both functions of the aggregate technological level at time t, which is specified $A_t = A_0 + \frac{A_{max} - A_0}{1 + e^{-\xi_t \Delta t}}$, where A_0 is the initial level of technology, Δt the time elapsed since the period of maximum technological growth, and ξ_t the speed of technological increases, defined by the ratio of R&D investment to GDP, so that technological change and economic growth are endogenous.

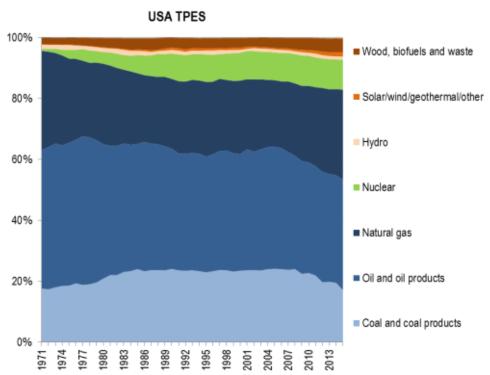
Appendix B1: TPES and TPEP of the main fossil fuel–producing countries, 1971–2014

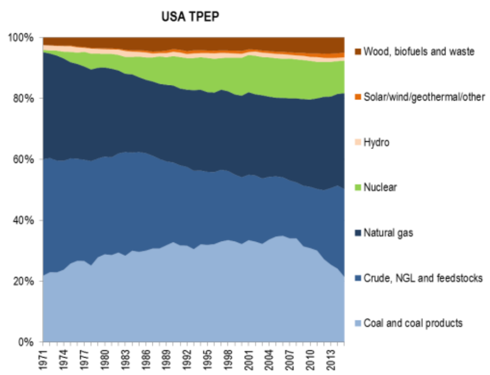


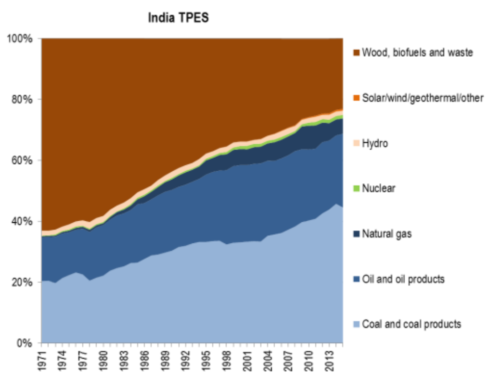


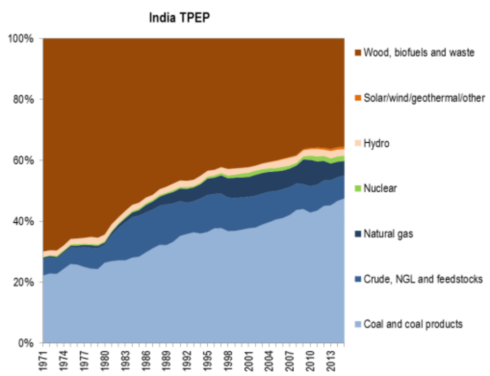


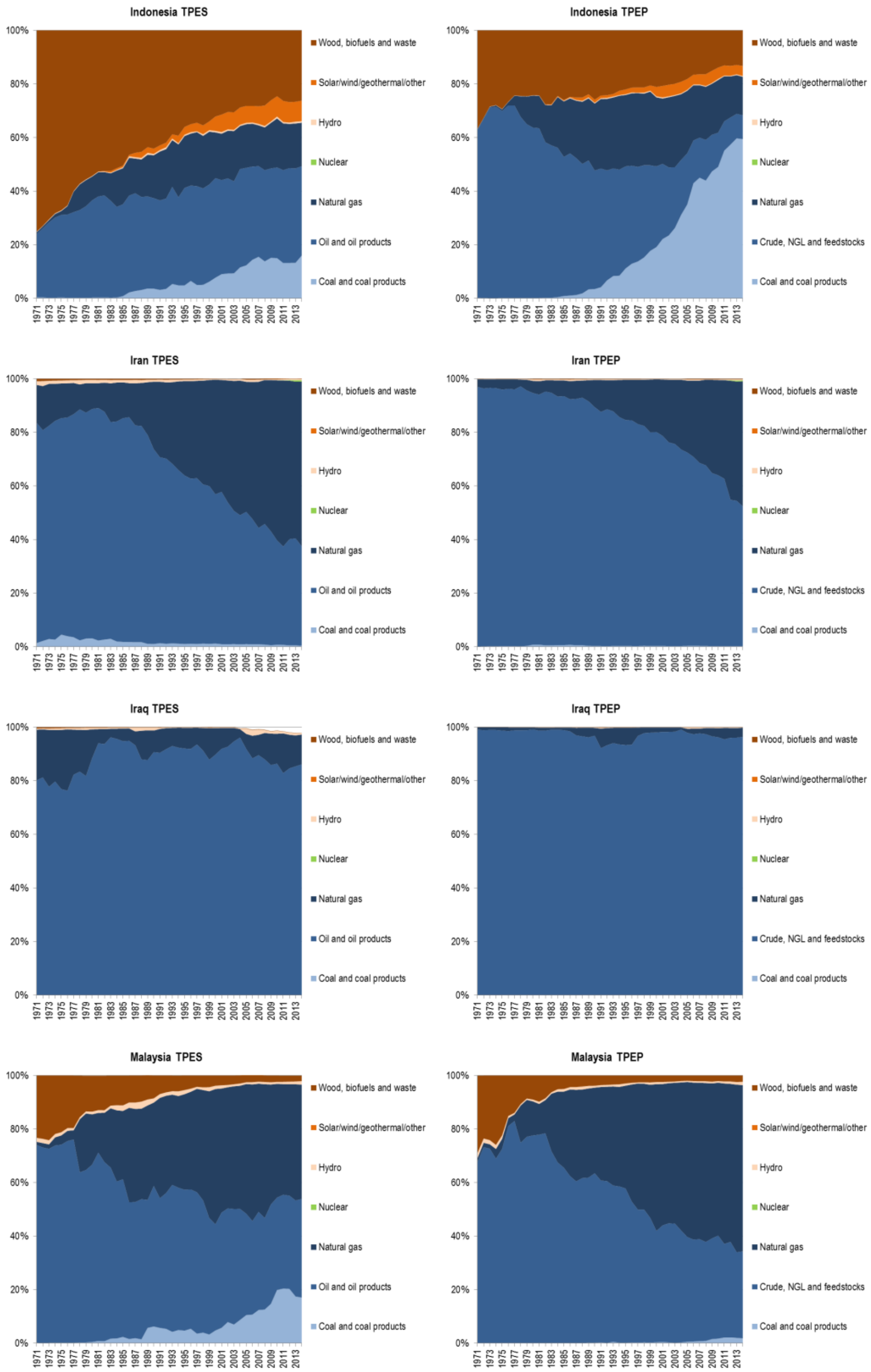












Indonesia TPES
Indonesia TPEP
Iran TPES
Iran TPEP
Iraq TPES
Iraq TPEP
Malaysia TPES
Malaysia TPEP
Wood, biofuels and waste
Solar/wind/geothermal/other
Hydro
Nuclear
Natural gas
Oil and oil products
Crude, NGL and feedstocks
Coal and coal products
100%
80%
60%
40%
20%
0%


Mexico TPES
Wood, biofuels and waste
Solar/wind/geothermal/other
Hydro
Nuclear
Natural gas
Oil and oil products
Coal and coal products
Mexico TPEP
Wood, biofuels and waste
Solar/wind/geothermal/other
Hydro
Nuclear
Natural gas
Crude, NGL and feedstocks
Coal and coal products
Russia TPES
Wood, biofuels and waste
Solar/wind/geothermal/other
Hydro
Nuclear
Natural gas
Oil and oil products
Coal and coal products
Russia TPEP
Wood, biofuels and waste
Solar/wind/geothermal/other
Hydro
Nuclear
Natural gas
Crude, NGL and feedstocks
Coal and coal products
Saudi Arabia TPES
Wood, biofuels and waste
Solar/wind/geothermal/other
Hydro
Nuclear
Natural gas
Oil and oil products
Coal and coal products
Saudi Arabia TPEP
Wood, biofuels and waste
Solar/wind/geothermal/other
Hydro
Nuclear
Natural gas
Crude, NGL and feedstocks
Coal and coal products
USA TPES
Wood, biofuels and waste
Solar/wind/geothermal/other
Hydro
Nuclear
Natural gas
Oil and oil products
Coal and coal products
USA TPEP
Wood, biofuels and waste
Solar/wind/geothermal/other
Hydro
Nuclear
Natural gas
Crude, NGL and feedstocks
Coal and coal products

Appendix B2: TPES of main fossil fuel–consuming countries, 1990–2015