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Challenges for Widespread Renewable Energy Deployment: Fossil Fuel Price Responses

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Key Points

Renewable energy policy supports the deployment of renewable power generators so as to reduce their costs through scale economies and technological learning.

Some expect that, once cost parity with fossil fuel generation is achieved, a transition toward renewable power will continue without the need for further renewable energy support.

This reasoning implicitly assumes that the cost of fossil fuel power generation does not respond to the large-scale penetration of renewable power. However, this assumption may not be valid, particularly in the case of coal and gas fired power generation.

It is likely that the cost of fossil fuel power generation will also reduce with large-scale penetration of renewables, thus making the renewable energy transition slower or more costly than anticipated.

More analysis is needed in order to be able to quantify this effect, the occurrence of which should, however, become part of the renewable energy discourse.

Summary

Part of the policy strategy to avert the worst outcomes of global climate change is a transition to low carbon energy on an unprecedented scale. In particular, strong incentives are in place to promote the competitiveness of renewable energy technologies, stimulate their rapid uptake and displace fossil fuel power generation. In this paper we argue that the penetration of renewable energy into the power market can directly result in a price response of fossil fuels which in turn affects the relative competitiveness of renewable power generation, thereby reducing the rate of the renewable energy transition or increasing the cost of the policy support measures required to achieve it. The price response we hypothesise is distinct from the Green Paradox and Carbon Leakage theories, which in different ways address the effect of climate change policy on the extraction and use of fossil fuels. In order to assess the possible existence and scale of the problem, we identify a price response mechanism backed by standard economic theory, based on the specific characteristics of the fossil fuel markets considered, e.g., coal and natural gas.

Our analysis shows that the amount of fossil fuel demand displaced by renewables is likely to be significantly smaller than the equivalent amount of renewable power generation introduced. However, the price effect of this demand shift could be large, depending on the price elasticity of fossil fuel demand and supply: the more inelastic the demand and supply, the larger the price effect. While short-term demand for coal and gas is likely to be inelastic, supply elasticity can vary greatly as we move along the supply curve. In the case of elastic supply, however, a further price drop is possible as fossil fuel producers shift their supply curve downwards to compete for market share. In perfect markets, where price equals marginal cost, a supply curve shift is only possible if the cost of supply can be reduced through production efficiency gains, while in imperfect markets, as is the case of natural gas and coal, rents are also present, which resource owners can renounce to maintain competitiveness.

It is also worth noting that significant shares of coal and natural gas today are still traded based on long-term contracts and on regulated prices, which may limit the extent to which the price of these commodities can respond to the large-scale penetration of renewables. However this is true only in part, as even long-term contracts and regulated prices tend to adjust when they diverge too far from short term market prices.

Our findings support the price response theory and that a fossil fuel price response to the introduction of renewables is likely to occur. This would lead to a higher than anticipated cost of the renewable energy transition. However, the extent of this effect requires further analysis of the structure of fossil fuel markets in order to formulate successful renewable energy policy.

A Perspective on the Price Response of Fossil Fuels to the Deployment of Renewables

Several theories have been put forward to explain the impact of renewables penetrating the energy mix. These are reviewed in Appendix A. These fail to propose a mechanism for the possible price response of fossil fuels to the deployment of renewables. We have, therefore, set out to build a hypothetical price response mechanism based on standard economic theory and to test it based on available evidence. Our approach is based on supply-demand analysis, the use of which can also be found in past studies explaining determinants of oil prices (Hamilton 2008, Horn 2004, Stevens 1995). According to standard economic theory, prices and quantities in a particular market are the result of the balance between supply and demand. In the next paragraphs we will therefore analyze possible shifts in the demand and supply curves of fossil fuels as a result of the introduction of renewables. This will allow us to draw conclusions on the plausibility of the hypothesised price response mechanism, also taking into consideration factors that are specific to the fuel markets considered. Although shifts in the demand and supply curves may occur simultaneously in reality, we will here discuss them in turn for the sake of illustration.

The Fossil Fuel Demand Shift

We start our analysis of the price response of fossil fuels to the deployment of renewables by assessing the extent to which the latter causes a reduction in the demand for fossil fuels for power generation. Let us begin by considering the abstract case of a total annual demand for power that, in the absence of renewables, is constant over time. If power demand did not change as a result of the penetration of renewable energy, renewables would replace an equivalent amount of fossil fuel power, which would result in a commensurate decrease in demand for coal and gas commodities. However, estimating the demand shift of fossil fuels solely on the basis of the renewable power capacity deployed and its capacity factor is incorrect, because demand for power is itself a function of its price. So should the introduction of renewable power result in a reduction in power prices, the overall power demand would increase. This can be expected as, in addition to the low marginal cost of renewables, power prices are also sensitive to the price of fossil fuels used in power generation (IEA 2014), which in turn will decrease as they are displaced by renewables. For this reason, the decrease in fossil fuel power demand will probably be smaller than the corresponding amount of renewable power generation introduced in the electricity sector. A qualitative graphic representation of this effect is provided in Figure 1, where the gradual introduction of renewables is shown to increase total demand for power.

If we now take into account the fact that global power generation has increased by 3.1 percent annually in the last 20 years (BP 2015), and under a business as usual scenario is projected to continue growing substantially (BP 2014), it is clear that the scope for a reduction of fossil fuel demand following the introduction of renewables further decreases. Past energy transitions have shown that new fuels have not significantly displaced demand for the incumbent fuels but instead have mainly satisfied further energy demand growth (Fouquet 2009). In the absence of strong, globally coordinated carbon policy this same effect may in future be observed

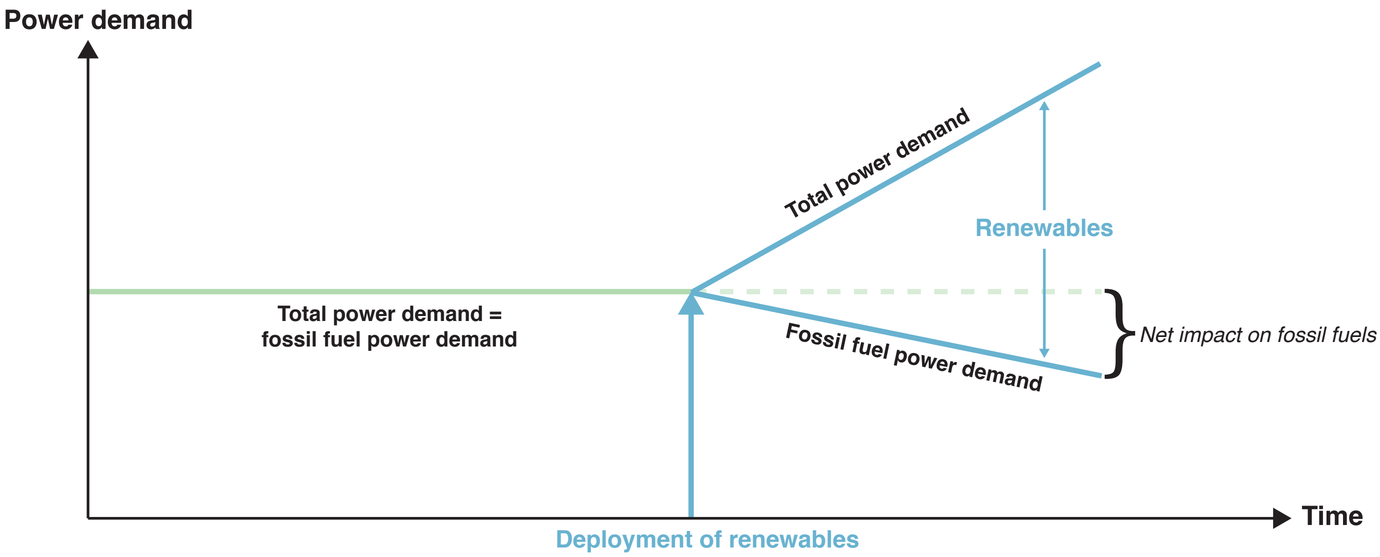

Figure 1. Renewable power deployment and its impact on fossil fuel power demand.

Source: KAPSARC.

with fossil fuels when renewables are introduced: cheaper fossil fuels will likely spur growth in overall power generation. This works well with the projected continued growth of coal and gas particularly in non-OECD countries (BP 2014, IEA 2013) as also envisaged by the Carbon Leakage theory. If we also factor in the effect that a drop in fossil fuel prices has on the demand for other energy uses, i.e., outside of power generation, it can be concluded that the substitution of fossil fuel demand brought by the penetration of renewables is going to be significantly smaller than the equivalent amount of renewable power introduced.

However, although the quantity of fossil fuel displaced by renewables may be small, the impact on fuel price could be high, depending on the price elasticity of supply and demand. In particular, the more inelastic demand and supply, the more substantial the price drop will be for a given reduction in fossil fuel demand. Figure 2 illustrates this effect in the case of price elasticity of supply; we can see from the figure that for equal leftward shifts of the demand curve, a larger price drop is observed in the case of the more inelastic supply curve. Similarly, a more inelastic demand curve results in a higher price drop for the same leftward demand shift (not illustrated).

So if the demand and supply curves of fossil fuels were inelastic, a small amount of displaced fossil fuel could result in a significant drop in fossil fuel prices. Assessing the exact scale of the price drop though is problematic: not only is the demand shift difficult to accurately estimate, but the availability of supply and demand elasticity data is limited. In particular, the supply cost data of coal and natural gas is commercially sensitive and limited data is available in the public domain (BP 2015, Haftendorn, Holz and von Hirschhausen 2010) making it difficult to construct global cumulative capacity cost curves. In Figure 3 we show a global cost curve for coal for the year 2006 based on data collected from a wide range of sources (Haftendorn, Holz and von

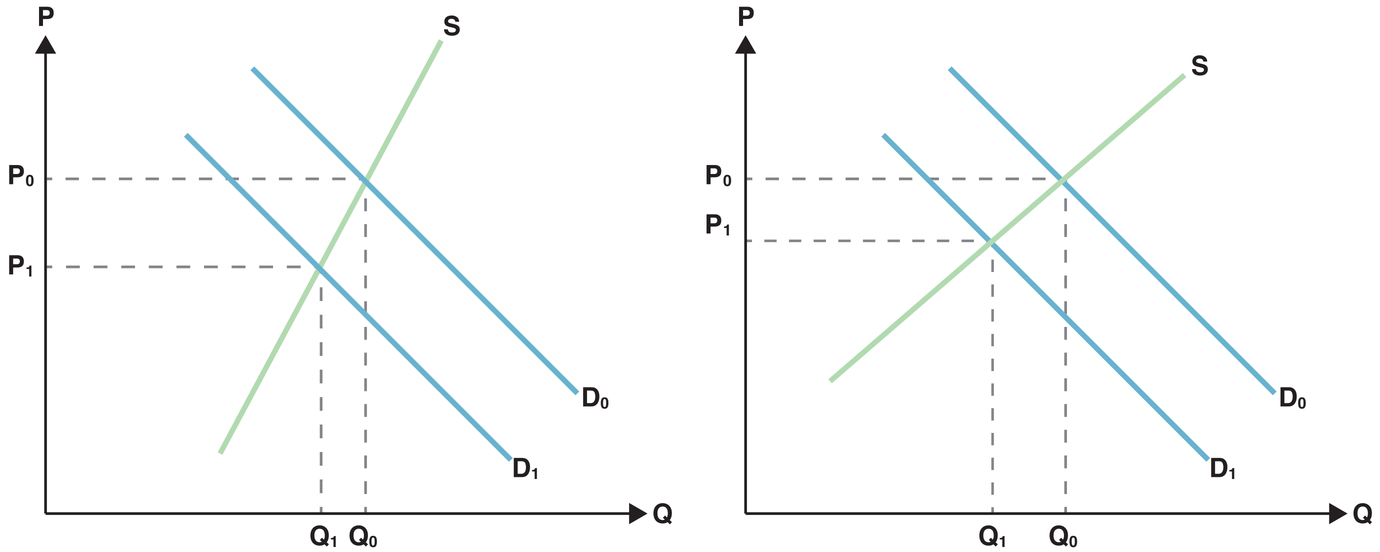

Figure 2. Effect of supply elasticity on the price drop. For the same demand shift D0 to D1, a more inelastic supply (left) leads to a higher price drop (P0 to P1) than in the case of a more elastic supply (right).

Source: KAPSARC.

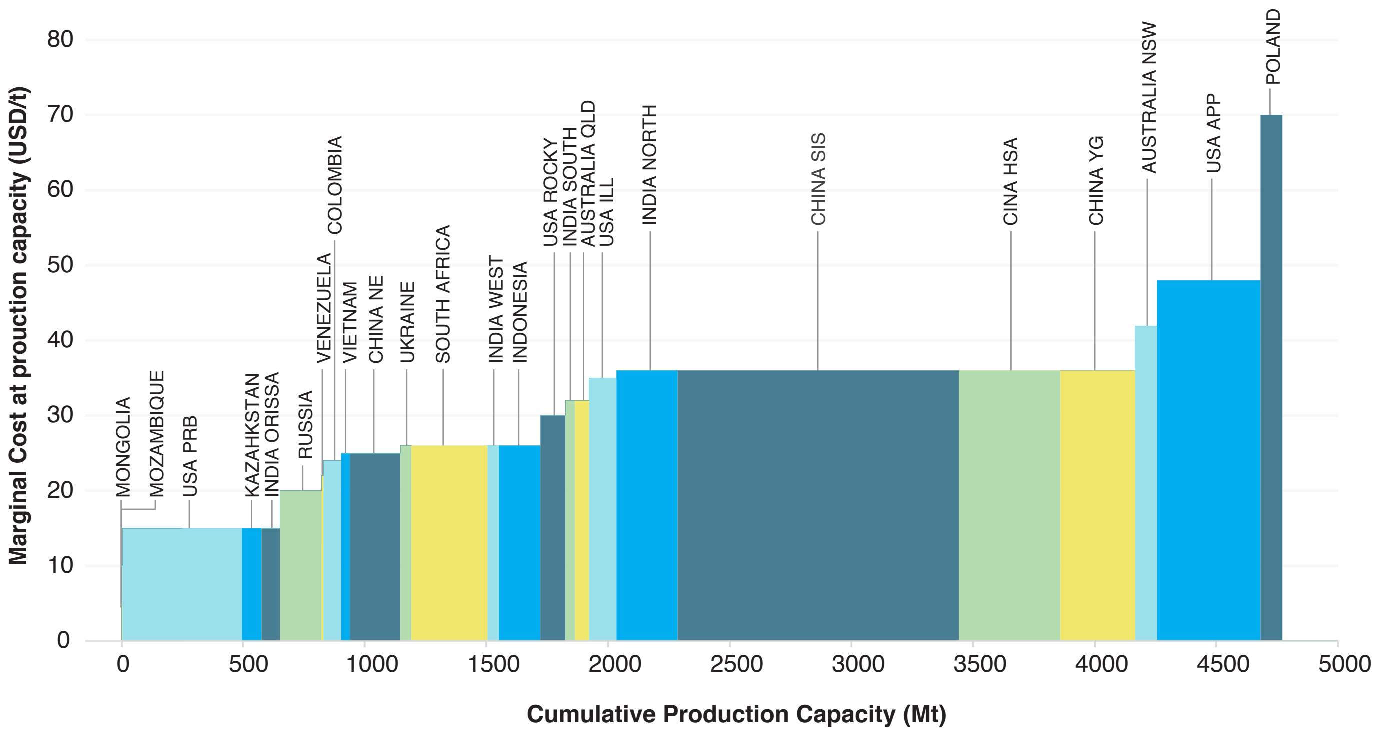

Figure 3. Marginal cost vs cumulative production of major coal mining basins.

Source: Adapted from (Haftendorn, Holz and von Hirschhausen 2010).

Hirschhausen 2010). As can be seen from this example, the elasticity of supply is generally not constant along the curve. It is also worth noting that the profile of the curve can change substantially over time as a result of investment or disinvestment in production capacity.

Moreover, data on the elasticity of demand for coal and gas is particularly sparse. In prior literature, very little effort was made to estimate elasticities due to the high complexity involved in this task. Bohi (1981) suggests that shifts in supply and demand occur too frequently in the markets for a single demand elasticity equation to be accurately traced for an extended period of time. However a recent study of the U.S. Energy Information Administration (EIA 2012), which updates previous similar studies, provides evidence that demand for both coal and gas in power generation is generally inelastic.

The Fossil Fuel Supply Shift

The discussion of the fossil fuel demand shift suggests that such shifts could be small, and yet still lead to a substantial price response in the case of inelastic demand and supply. Since demand is likely to be inelastic, at least in the short term, the scale of the price response will depend on the elasticity of supply, which in turn is a function of the specific circumstances of the market considered. However, a further drop in the price of fossil fuels may occur as producers seek to compete against renewables or among themselves for market share by reducing their supply cost, which corresponds to shifting the supply curve downwards. This is illustrated in Figure 4, where a leftward demand shift prompts a downward supply shift, resulting in a larger price drop than the demand shift alone would have produced.

In a perfectly competitive market where price equals marginal cost, firms can only increase their competitiveness by means of cost reduction through technological development. However, fossil fuel markets in general cannot be regarded as perfect due to the presence of large players with some market power, which gives rise to rents. Indeed, there is evidence that some suppliers have the capability to sell coal or gas at or below the current market price, yet still equal to or above their supply cost (BP 2015, Haftendorn, Holz and von Hirschhausen 2010). This means that fossil fuel producers potentially have the ability to behave strategically and boost their competitiveness by renouncing part of their rents. In doing so, they would be able to supply the market at a lower price and undercut competing low carbon energy sources such as renewables (Gerlagh and Liski 2011).

The extent to which a supply response is possible depends on the particular fossil fuel, the field from which it is extracted, the type of company ownerships in the respective value chains and the pricing mechanism of the market within which the energy is traded. These factors are discussed here in turn. Firstly, costs for coal basins globally vary by approximately a factor of 3 (Haftendorn, Holz and von Hirschhausen 2010), and for gas supplied to Europe specifically by a factor of 4 (BP 2015, Lochner and Bothe 2008). These large variations are a function of: geological and techno-economic factors (BGR 2009); financial conditions, labour and capital structure (Rogner 1997); and the lifetime of a mining basin (Haftendorn, Holz and von Hirschhausen 2010). The large discrepancies in marginal costs of extraction between different suppliers mean that some are in the advantageous position of having significant headroom before market prices reach extraction costs, adding

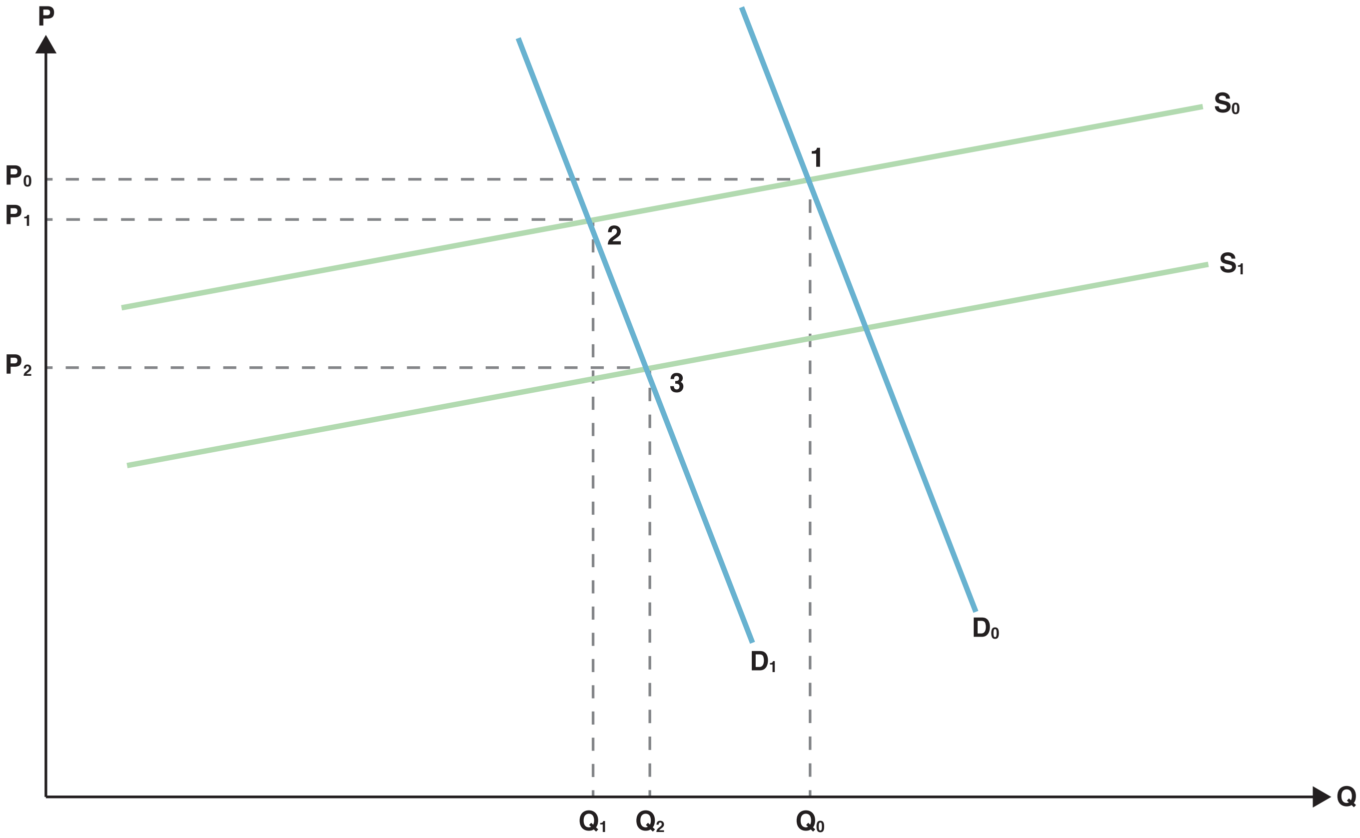

Figure 4. Effect of a supply shift on the price drop. A demand shift (D_0 to D_1) along an elastic supply curve S_0 is followed by a supply shift (S_0 to S_1), leading to a price drop (P_0 to P_2) larger than in the case of the demand shift alone (P_0 to P_1).

Source: KAPSARC.

flexibility to a fossil fuel supply curve to shift downwards toward lower prices in response to rising pressure from renewables.

With regard to ownership, private sector companies will be most responsive to managing and reducing prices in order to maintain competitiveness and market share (Weigelt and Camerer 1988). However, state-owned companies can also react to increased competition and lower prices by reducing their rents in order to sustain production and exploration. In particular, we note that governments of countries rich in fossil fuel heavily tax national production.

Taking the example of Latin America, in 2008 the percentage of total tax revenue from natural resources (mainly fossil fuels) was 13.9 percent in Venezuela, 10.8 percent in Bolivia, 8.8 percent in Ecuador and 8.4 percent in Mexico (UNECLAC 2008). These figures suggest that there is room for governments to reduce their fiscal rents on fossil fuels, thus making it more attractive for industry to increase exploration in new fields and production in mature ones.

The discussion above suggests that, provided there are rents that can be renounced, a fossil fuel supply response is possible and even likely, especially in view of future carbon policy that may restrict the use of fossil fuels, thus magnifying the price effect of the demand shift previously discussed. However, the specific price formation mechanisms of the fossil fuels considered also need to be taken into account, as they can potentially undermine the validity of the price response hypothesis outlined so far.

In particular, only 43 percent of total world natural gas consumed in 2013 was priced using gas-on-gas competition, whereas 19 percent was indexed to the price of oil and 33 percent was priced by governments based on certain criteria (IGU 2014). However, it is important to note that in North America and Europe gas-on-gas competition is now prevalent and oil price indexing is gradually losing its share, which makes it possible for the price response mechanism we have postulated above to occur in these markets. Moreover, in China and India, where prices of domestic natural gas are regulated, the pricing is now increasingly based on “cost of service,” which ensures an acceptable rate of return to firms in the value chain, and that prices are adjusted based on market developments when necessary. China and India also import growing quantities of liquefied natural gas (LNG), more than a quarter of which is priced according to gas-on-gas competition, so the price response mechanism hypothesised can also occur in these countries, although probably to a lesser extent than in regions such as North America and Europe.

As for the coal market, it is generally regarded as a globally competitive market with a relatively transparent spot pricing system. However, the balanced geographical diversification of coal reserves means that only around 15 percent of coal consumed is traded internationally while the vast majority is sold and consumed on regional markets (IEA 2013). Despite this, the huge number of players involved ensures that coal prices are largely determined by demand and supply dynamics (IEA 2013). In particular, the low coal prices experienced since mid-2011 are due to substantial oversupply in the international market. Given that under the current regime producers have had to drastically cut costs and some are selling below production cost, the scope for a further supply shift is very limited and will remain so until market conditions improve.

Effect of Fossil Fuel Price Response on Renewables

Although our initial assessment of the price response mechanism did not allow us to quantitatively assess its likely future scale, it did suggest that a price response of both coal and gas to the large-scale introduction of renewables is likely to occur. Based on the discussion so far, we can state that the hypothesised price response mechanism would impact the cost competitiveness of renewables against fossil fuel generators, making the deployment of renewables more expensive than anticipated and increasing their need for financial support. This idea is qualitatively illustrated in Figure 5, where we suggest that in the presence of a fossil fuel price response, the LCOE of fossil fuel generators could stay below the expected path for a certain period of time, thus increasing the need for cumulative financial support to renewables (green area) above and beyond that expected (blue area) should there be no fossil fuel price response. The magnitude and duration of this effect will depend upon a number of specific market conditions and policy variables, also including the introduction of strong carbon pricing.

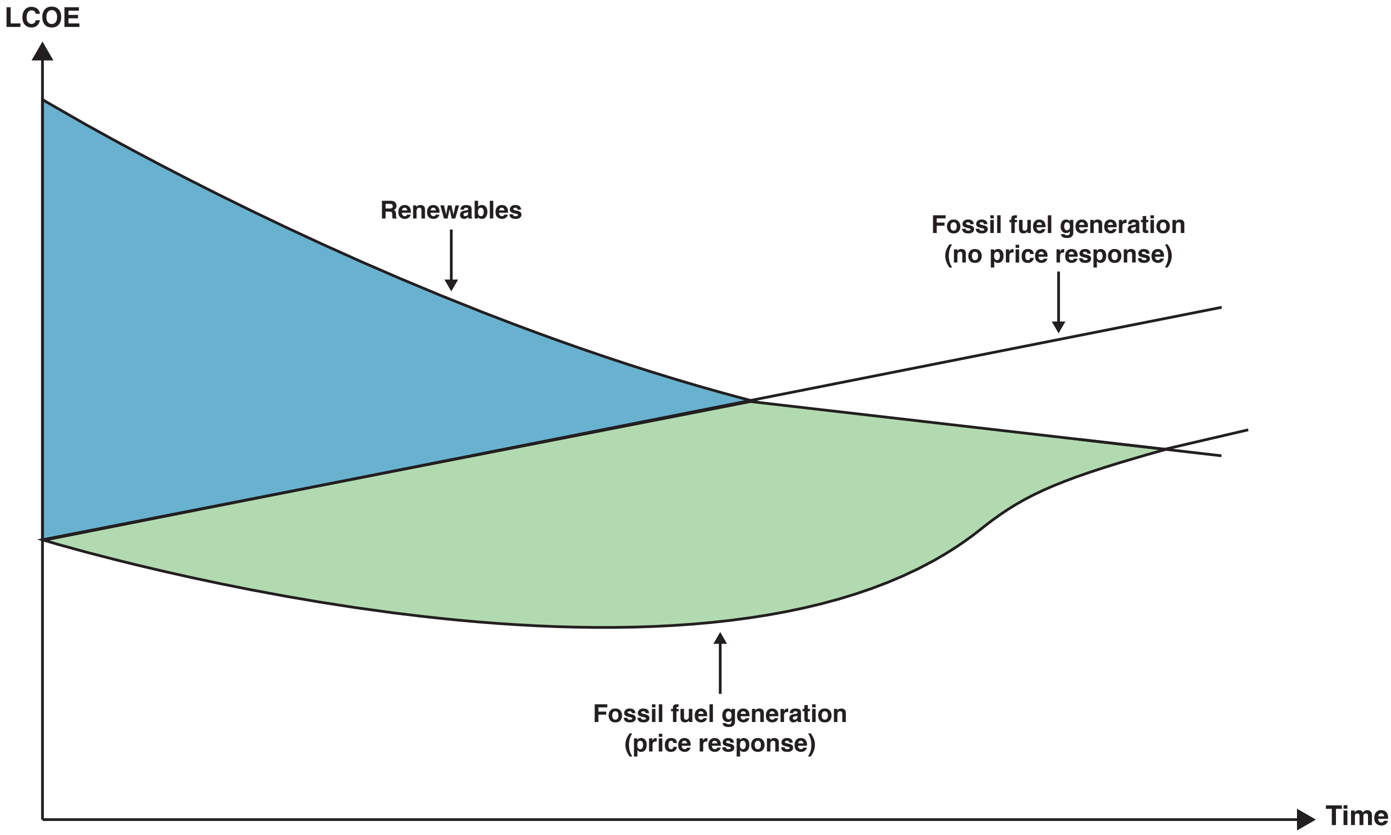

Figure 5. Effect of the fossil fuel price response on the cost competitiveness of renewables. The levelised cost of energy (LCOE) of fossil fuel power generators is lower in the case of fossil fuel price response, affecting the competitiveness of renewables relative to the case of no price response. Blue and green areas express the cumulative financial support needed per unit of renewable power generated.

Source: KAPSARC.

Conclusion

This paper critically discussed the possible occurrence of a price response of fossil fuels to the penetration of low carbon and renewable energy, which could hinder the transition to low carbon energy or make it more costly to achieve than anticipated. Analysing existing literature we have identified two relevant theories: the Green Paradox and Carbon Leakage. These theories, which respectively postulate a time effect and a geographic effect of the penetration of renewables on the extraction and use of fossil fuels, have generated useful insights in the field of climate change policy. However, while implying a price response of fossil fuels, they do not address this potentially important mechanism directly.

In order to assess this likely occurrence and to estimate the magnitude of a possible feedback loop between renewable penetration and competitiveness of fossil fuel power generators, we first propose an analytical framework based on supply-demand analysis, and then further discuss the root causes of the mechanism based on the specific characteristics of the fossil fuel markets considered.

The analysis conducted thus far supports the following conclusions:

> A reduction in demand for coal and gas may occur due to the large-scale penetration of renewables. However, as power demand is itself a function of price, and a reduction in fossil fuel prices reflects on the price of power, and both coal and gas have energy uses outside of power generation, it is likely that the demand reduction will be significantly smaller than the corresponding amount of renewable capacity deployed.

> Despite this, even small reductions in demand for fossil fuels could potentially lead to a large price response, especially considering that demand for coal and gas for power generation appears to be generally inelastic, at least in the short term.

> The price elasticity of supply of both coal and gas however is more uncertain, depending on the particular conditions of the market considered, and can significantly change over time.

> In the case of an elastic supply, the price response to a reduction in demand for fossil fuel is small, however an additional price drop can occur if, as a result of the introduction of renewables, the producers of fossil fuels are able to increase their competitiveness in order to recover part of the market share lost, or in other words shift the supply curve downwards.

> In a regime of perfect competition, such shifts can only be achieved by introducing technological improvements. However, in imperfect markets firms and governments benefit from supernormal profits in the form of resource rents, which could be renounced in order to increase competitiveness.

> There is evidence to suggest that a supply shift is possible, but perhaps limited in the short term by the structure of contracts and current state of the markets on which coal and gas are traded.

Based on our analysis, we conclude that a more detailed assessment of the price response of fossil fuels to the introduction of renewables would require case studies that are specific to particular fuels and markets; where all the key aspects of the problem we have identified are researched in sufficient detail to enable quantitative estimation of price drops, the timeframe over which they would occur, and their effect on the competitiveness of renewables.

Our initial findings, however, indicate that the price response theory is tenable. This in turn has strong implications for the design of policies aimed at delivering a global renewable energy transition. We therefore believe it is important that price response of fossil fuels to the large-scale introduction of renewables becomes part of the energy transitions discourse.

References

Axsen, Jonn, Joseph Bailey, and Marisol Andrea Babiker, Mustafa H. 2005. "Climate change policy, market structure and carbon leakage." *Journal of International Economics* 65 (2):421-445.

BGR. 2009. Energy Resources 2009 - Reserves, Resources, Availability. Crude Oil, Natural Gas, Coal, Nuclear Fuels, Geothermal Energy. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) - Federal Institute for Geosciences and Natural Resources, Stilleweg 2, 30655 Hannover, Germany.

Bohi, Douglas R. 1981. Analyzing Demand Behaviour: A Study of Energy Elasticities. edited by Johns Hopkins Press. Baltimore, MD: Resources for the Future.

BP. 2014. BP Energy Outlook 2035. BP Global.

BP. 2015. BP Statistical Review of World Energy June 2015.

EIA. 2012. Fuel Competition in Power Generation and Elasticities of Substitution. U.S. Energy Information Administration, Department of Energy, Washington, DC 20585.

EnerNex Corp. 2011. Eastern Wind Integration and Transmission Study. Prepared for: The National Renewable Energy Laboratory. A national laboratory of the U.S. Department of Energy. Subcontract Report NREL/SR-5500-47078.

Fouquet, R. 2009. "A brief history of energy." In *International Handbook of the Economics of Energy.*, edited by J. Evans, Hunt, L.C. (Eds). Edward Elgar Publications, Cheltenham, UK, and Northampton, MA, USA.

GEA. 2012. Global Energy Assessment - Toward a Sustainable Future.: International Institute for Applied Systems Analysis, Vienna, Austria and Cambridge University Press, Cambridge, UK and New York, NY, USA.

Gerlagh, Reyer and Matti Liski. 2011. "Strategic resource dependence." *Journal of Economic Theory* 146 (2):699-727.

Gross, Rob, Phil Heptonstall, Philip Greenacre, Chiara Candelise, Felicity Jones, and Arturo Castillo Castillo. 2013. Presenting the Future. An assessment of future costs estimation methodologies in the electricity generation sector. A report for UKERC by UKERC Technology & Policy Assessment Function.

Haftendorn, Clemens, Franziska Holz and Christian von Hirschhausen. 2010. COALMOD-World: A Model to Assess International Coal Markets Until 2030. Freeman Spogli Institute For International Studies, Program on Energy and Sustainable Development, Stanford University, Stanford, CA 94305-6055.

Hamilton, James D. 2008. Understanding Crude Oil Prices. The National Bureau of Economic Research. NBER Working Paper No. 14492.

Hirth, Lion. 2013. "The market value of variable renewables: The effect of solar wind power variability on their relative price." Energy Economics 38:218-236.

Horn, Manfred. 2004. "OPEC's optimal crude oil price." Energy Policy 32 (2):269-280.

IEA. 2007. Tackling Investment Challenges in Power Generation In IEA Countries. International Energy Agency (IEA), Head of Publications Service, 9 rue de la Fédération, 75739 Paris Cedex 15, France.

IEA. 2013. Coal: Medium-Term Market Report 2013. Market Trends and Projections to 2018. International Energy Agency, 9 rue de la Fédération, 75739 Paris Cedex 15, France.

IEA. 2014. The Impact of Global Coal Supply on Worldwide Electricity Prices. Overview and comparison between Europe, the United States, Australia, Japan, China and South Africa. International Energy Agency (IEA), 9 rue de la Fédération, 75739 Paris Cedex 15, France.

IGU. 2014. Wholesale Gas Price Survey - 2014 Edition. A global review of price formation mechanisms 2005-2013. International Gas Union.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jensen, Svenn, Kristina Mohlin, Karen Pittel and Thomas Sterner. 2015. "An Introduction to the Green Paradox: The Unintended Consequences of Climate Policies." *Review of Environmental Economics and Policy* 9 (2):246-265.

Lochner, Stefan and David Bothe. 2008. "Future Costs Of Global Gas Supply - A Model-based Calculation." Briding Energy Supply and Demand: Logistics, Competition and Environment. 31st IAEE International Conference, Istanbul, Turkey.

Long, Ngo Van. 2015. "The Green Paradox in Open Economies: Lessons from Static and Dynamic Models." *Review of Environmental Economics and Policy* 9 (2):266-284.

Pearson, Peter J. G., and Timothy J. Foxon. 2012. "A low carbon industrial revolution? Insights and challenges from past technological and economic transformations." *Energy Policy* 50:117-127.

Pöyry. 2010. Wind Energy and Electricity Prices – Exploring the 'Merit Order Effect'. A literature review for the European Wind Energy Association.

Pöyry. 2011. The challenges of intermittency in North West European power markets. The impacts when wind and solar deployment reach their target levels. Pöyry Management Consulting.

Rogner, H-H. 1997. "An Assessment of World Hydrocarbon Resources." *Annual Review of Energy and the Environment* 22 (1):217-262.

Sinn, Hans-Werner. 2008. "Public policies against global warming: a supply side approach." *International Tax and Public Finance* 15 (4):360-394.

Sinn, Hans-Werner. 2015. "Introductory Comment–The Green Paradox: A Supply-Side View of the Climate Problem." *Review of Environmental Economics and Policy* 9 (2):239-245.

Stevens, Paul. 1995. "The determination of oil prices 1945–1995: A diagrammatic interpretation." Energy Policy 23 (10):861-870.

Strbac, Goran, Marko Aunedi, Danny Pudjianto, Predrag Djapic, Sean Gammons and Richard Druce. 2012. Understanding the Balancing Challenge. A report for the Department of Energy and Climate Change. Imperial College London, Department of Electrical and Electronic Engineering, South Kensington Campus, London SW7 2AZ United Kingdom, and NERA Economic Consulting, 15 Stratford Place, London W1C 1BE United Kingdom.

Tidball, Rick, Joel Bluestein, Nick Rodriguez and Stu Knoke. 2010. Cost and Performance Assumptions for Modeling Electricity Generation Technologies. ICF International, Fairfax, Virginia. Subcontract Report NREL/SR-6A20-48595.

Tirole, Jean. 2012. "Some Political Economy of Global Warming." *Economics of Energy & Environmental Policy* 1 (1).

Ueckerdt, Falko, Lion Hirth, Gunnar Luderer and Ottmar Edenhofer. 2013. "System LCOE: What are the Costs of Variable Renewables?" 32th International Energy Workshop, Paris, June 20, 2013.

UNECLAC. 2008. Ingresos fiscales provenientes de la explotación de productos primarios in ocho países seleccionados de América Latina.: United Nations Economic Commission for Latin America and the Caribbean.

van der Ploeg, Frederick and Cees Withagen. 2012. "Is there really a green paradox?" *Journal of Environmental Economics and Management* 64 (3):342-363.

van der Ploeg, Frederick and Cees Withagen. 2015. "Global Warming and the Green Paradox: A Review of Adverse Effects of Climate Policies." *Review of Environmental Economics and Policy* 9 (2):285-303.

Weigelt, K and C Camerer. 1988. "Reputation and Corporate Strategy: A Review of Recent Theory and Applications." Strategic Management Journal 9:443-454.

Appendix A

Interactions Between Renewables and Fossil Fuels in Literature

We have reviewed the limited literature on the response of fossil fuel value chains to renewable energy penetration, and identified two main theories: the Green Paradox and Carbon Leakage. The Green Paradox theory (Sinn 2008) is based on the idea that, by decreasing future demand for fossil fuels, climate change policy may accelerate their current rate of extraction and may therefore result in higher overall carbon emissions. The Carbon Leakage theory (Tirole 2012), on the other hand, postulates that in the absence of globally coordinated climate change policy, production of goods and services based on fossil fuels will move to countries with less stringent environmental regulation therefore offsetting the carbon emission savings realised in countries where climate change policy is in place. One key difference between the two is that the Green Paradox describes an upstream, supply-side response of fossil fuels while Carbon Leakage essentially describes a downstream, demand-side response. Both theories imply market changes (van der Ploeg and Withagen 2015), either on supply or demand, which ultimately impact fossil fuel prices. However, the theories focus on better understanding the possible future effects of climate change policy, particularly carbon pricing, on global carbon emissions and therefore neither of them specifically addresses the possible effect of the deployment of renewables on the price of fossil fuels. The two theories are summarised in table 1, together with their strengths and current limitations as discussed in the most recent literature (Jensen et al. 2015, Long 2015, Sinn 2015, van der Ploeg and Withagen 2015).

Aside from the above-mentioned theories, renewables also interact with fossil fuel value chains through the effect that their penetration has on electricity markets. A review of the literature in the case of wind power (Pöyry 2010) shows that, due to its low marginal cost, the deployment of this type of renewable generation tends to reduce electricity wholesale spot prices and to displace either coal or gas fired power generation due to its effect on the merit order curve. Finally, other studies address the interaction between fossil fuel and renewable generation technology from the perspective of technological improvements of the former as a result of competition with the latter; this is known as the ‘Sailing Ship’ effect (Pearson and Foxon 2012). However, neither of these literature strands addresses the direct effect that the large-scale introduction of renewable power generation can have on the price of fossil fuels and its potential hindrance to the further penetration of renewables.

Table 1. Theories found in the literature on the interaction between renewable energy technology penetration and fossil fuel value chains.

	Theory	Evidence of occurrence and limitations
The Green Paradox	Change in time period of supply - temporal supply response. Sinn (Sinn 2008) theorized that the extraction and supply of fossil fuels would accelerate, or be brought forward in time, in anticipation of a future reduction in fossil fuel resource rents as a result of incoming carbon pricing. Otherwise stated, leaving carbon-based resources in situ would give rise to an opportunity cost as their future rents may decrease because of carbon policies.	Modelling by Ploeg and Withagen (van der Ploeg and Withagen 2012) indicates that this mechanism can occur. Its validity however suffers from the following limitations: • It is based on Hotelling's Rule, which ignores sunk investments and production constraints, both of which are important factors that determine the supply side response of fossil fuel value chains. • It disregards the effect of alternative technologies themselves and argues that they are imperfect substitutes to the incumbent. • The theory assumes perfect market competition for energy carriers on a global scale, which does not hold for the natural gas and coal markets. The latest studies have sought to address some of these limitations (Jensen et al. 2015, Long 2015, Sinn 2015, van der Ploeg and Withagen 2015). However, the results of modelling studies are sensitive to the assumptions made and the empirical evidence to support them remains limited and contrasting (Jensen et al. 2015, van der Ploeg and Withagen 2015).
Carbon Leakage	Change in geographical location of energy-intensive activities - spatial demand response. Tirole (2012) establishes that carbon leakage can arise from two possible scenarios. Firstly, countries not cooperating in climate policy may be considered to have a competitive advantage due to energy prices to consumers being cheaper. Energy intensive businesses may opt to move to these countries, thereby potentially offsetting emission savings otherwise realised. The other scenario is that a drop in aggregate demand for carbon based fuels decreases the price of energy globally, thus allowing for economies with less stringent environmental policies to take advantage of this and boost output and therefore emissions.	Currently occurs in non-Annex 1 parties of the United Nations Framework Convention on Climate Change, especially China, India and other growing Asian economies. Estimates of carbon leakage rates due to the Kyoto Protocol range from 5 percent to 20 percent (Babiker 2005).

Source: KAPSARC analysis.

Notes

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About the Project

The goal of this project is to understand how policy can expedite renewable energy transitions in a cost-effective way, while allowing competitive national industries to develop. In line with this objective, a wide range of policy instruments, designed and implemented to promote renewable energy, are being assessed. Furthermore, the project takes a holistic approach by analyzing how the competitive dynamics between renewable technologies and incumbent technologies evolve.