Cost Pass–through and International Linkages

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Abstract

Commodity markets are linked through international trade but separated by heterogeneous regulations and input markets. We investigate theoretically and empirically how regional, as opposed to global, cost shocks are passed through into global prices and how they affect production relocation decisions. Regional cost shocks are mitigated by capacity constraints in the short run. Once constraints bind, pass-through of a cost increase is enhanced while for cost decreases it drops to zero. We study the market for ammonia, a commodity largely produced from natural gas, to highlight the nonlinearity of cost pass-through and its implications for unilateral climate policies.

Keywords: pass-through, market integration, energy-intensive trade-exposed industries, ammonia

\textit{JEL:} L13, L65, Q54, Q40

A fundamental challenge of energy economics is to understand how energy prices are passed through into manufactured commodities. But in recent years, this issue has become much more complex. On the one hand, commodity markets are now very tightly linked through trade; accordingly regional price spreads should be low. On the other hand, fossil fuel prices have started to diverge – due to shale oil and gas exploitation – and are set to diverge more drastically in the future as a consequence of climate change policies. Thus, we have to ask which energy price is passed through, as well as how strongly. In this paper, we

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study how a cost shock in one region affects global market prices in a setting with imperfect competition and capacity constraints. In this setting, pass-through is asymmetric. In the short run, cost decreases are less likely to be passed through than cost increases, as capacity constraints bite. In the long run, the asymmetry is reversed, as capacity is diverted to the low cost region, so regional cost decreases are passed through while increases are not. We apply this model to the global nitrogen industry, where the US shale gas revolution caused a large and persistent regional cost shock, and find that these mechanisms provide a compelling account of the industry experience over the past two decades.

Region-specific energy cost shocks are set to increase due to climate policy. Most prominently, the European Union has an ambitious goal to reach climate neutrality by 2050. This is to be achieved largely by cutting consumption of fossil fuels; accordingly, the effective price of fossil-based energy must rise by a lot. However, it seems unlikely that similar policies will be adopted globally, raising the prospect that energy prices in Europe and other regions that introduce some forms of carbon taxation will be much higher than in the rest of the world. What effect this will have, especially on energy-intensive industries exposed to international trade, is unclear. One important way to estimate the welfare effects of such a cost gap is through cost pass-through analysis, which measures how much of their cost increase firms can pass on to consumers through higher prices. Unfortunately, the existing pass-through literature is poorly suited to deal with regional cost shocks in integrated markets.

Existing research suggests high energy cost pass-through, but suffered predictive failure after the shale gas boom reduced energy prices in the US. Based on the available evidence, analysts confidently predicted falling US energy prices would trigger reductions in the prices of energy-intensive manufactured products (Fowlie et al. 2016b; Mason et al. 2015; Bushnell and Humber 2017). However, this completely failed to happen. Perhaps the best examples are nitrogenous fertilizers (Hausman and Kellogg 2015), whose production cost depends almost entirely on natural gas prices. Before shale, both gas and nitrogen prices were at par in Europe and the US. After shale, US gas prices fell drastically compared to Europe, but nitrogen still trades at par (see figure 1). This pattern extends to other industries, such as gasoline (Borenstein and Kellogg 2014; Muehlegger and Sweeney 2020), where falling costs relative to
other markets did not translate into lower relative product prices. Thus, existing models must be missing something. In this paper, we study how international linkages between regional commodity markets affect pass-through to remedy the situation.

With international linkages, theory predicts that the pass-through of region-specific cost shocks is highly non-linear. Starting from a situation where costs are identical across regions, a region experiencing a small local cost increase will experience falling production of energy-intensive products. This is partially compensated by imports from other regions. Due to the increase in imports – referred to in the literature as “carbon leakage” – cost pass-through is limited. As local energy prices rise further, we will experience a drastic effect: either the affected region will stop production entirely (at which point pass-through obviously stops), or the unaffected regions will hit their capacity constraint. In the latter case, cost pass-through is enhanced, as marginal imports go to zero. Similarly, in the case of a local cost decrease, increased domestic production initially displaces foreign production, leading to cost pass-through. However, once domestic capacity is exhausted, further local cost reductions do not stimulate marginal production and accordingly cost pass-through ceases.

Several important points follow from this discussion. First, we have to distinguish between local and global cost shocks. By definition, a global shock does not cause output from one region to substitute that of another and thus leads to higher cost pass-through. Second, with international linkages, a local cost shock need not affect the spread of local vs. foreign product prices. Indeed, when the law of one price holds, no spread can possibly emerge. Thus, we need to explain how prices in the global market respond to local cost shocks. Third, relaxing the assumption of infinite capacity has “drastic” implications for the use of pass-through analysis. It implies that we cannot necessarily extrapolate from the effect of small regional cost shocks to large shocks when the capacity constraint is binding. Also, we cannot assume that idiosyncratic cost increases and decreases have symmetric effects.

The importance of distinguishing between global and firm-specific shocks has been recently highlighted by Muehlegger and Sweeney (2020). The authors test predictions of a simple Cournot model with rich microdata on the US refinery market. They find, in line with other authors (Gaarder, 2019; Lade and Bushnell, 2019) that pass-through of industry-wide
cost shocks is typically estimated around unity. However, when shocks affect individual firms only, competition limits pricing power and the pass-through is much lower. The authors highlight several pitfalls in estimating pass-through in imperfectly competitive markets: the need to include and properly weigh competitors’ costs and caution when interpreting the source of variation in fixed-effects models. Their analysis, however, ignores the role of market linkages and capacity constraints. As we show, drastic regional cost shocks lead to a breakdown of a standard Cournot model and the prices are fully determined by the highest cost producers.

As we document, this leads to failure of empirical models typically used to estimate cost pass-through: Cournot-flavored models that include measures of competitor’s costs (Muehllegger and Sweeney, 2020) and panel models with one-way (Miller et al., 2017) and especially two-ways fixed effects (Ganapati et al., 2020) all collapse when the regional change in costs is sufficiently high.

The mechanism we study is well known in regional electricity and petroleum markets. Fabra and Reguant (2014); Hintermann (2016); Linn and Muehlenbachs (2018) highlight the role of the marginal producer and capacity constraints. Electricity is generated by plants that use different fuels (coal, natural gas, renewables, etc.) at different costs. Whether a change in energy generation cost is passed through into electricity prices depends on the position of the affected plants in the merit order (marginal cost ordered capacity/supply curve). This supply curve allows us to determine the identity of the marginal producer given the demand. Market linkages make similar logic applicable also to internationally traded commodities that, at first glance, might not appear to fit the strict dispatch order nature of electricity markets. Changes in the marginal producers are observed also in local petroleum markets on which pipeline capacity constraints and rigidity of the existing midstream and refining infrastructure in the petroleum industry has also lead to temporary oil gluts (McRae, 2017; Borenstein and Kellogg, 2014; Kaminski, 2014).

Changes in marginal producer are explored also in the exchange rate pass-through literature. There, optimisation decisions of producers along the supply chain are shown to lead
to incomplete cost pass-through when the supplier change is not accounted for (Gron and Swenson, 2000; Hellerstein and Villas-Boas, 2010; Dixit, 1989), while capacity constraints are one of the mechanisms leading to non-linearities and asymmetries of pass-through (Bussiere, 2013; Knetter, 1994). Thus, with a focus on a single industry and analysis of the short- and long-run implications of cost changes, this paper contributes also to this strand of research.

The theory provides a clear guide for empirical work. We know that we need a non-linear model which relates global price to the marginal cost of each producing region. We then apply the model to the nitrogenous fertilizer industry, which is ideally suited for the exercise. First, it was perhaps the most strongly affected by the relative energy price decline in the US, making it a very informative data point. Second, common technology across regions facilitates collecting engineering-based marginal cost estimates across regions for this industry, which makes our analysis straightforward. In other industries, it can be very difficult indeed to get marginal cost estimates, adding to the error bands of any estimates. Third, by the standard energy-intensive trade exposed ("EI-TE") criteria (GHG per value added, trade intensity), this industry is one of the most vulnerable to region-specific climate policy. Lessons from nitrogen can inform the entire EI-TE debate, which is important in its own right.

We find that the level of nitrogen prices – in both Europe and the US – is excellently predicted by a model of international linkages and capacity constraints. The pass-through estimates imply that the shale gas boom was a drastic cost shock for the US nitrogenous fertilizer industry. Ancillary evidence on production quantities, market valuation and capacity investments support this finding.

Our theoretical result of non-linearity of local cost shock pass-through together with the empirical analysis of the impact of a large and persistent difference in production costs on the final good prices and production quantities has significant implications for the still nascent empirical literature on the impact of carbon taxation on trade-exposed energy-intensive industries. Our findings indicate that linear extrapolation of evidence on relatively small shocks to the US cement industry (Fowlie et al., 2016a) or from early phases of the EU ETS (Emis-

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2EI-TE industries were included in the EU ETS since 2013 (Phase III), however, in the subsequent years the emission costs were very low, below 10EUR/t making the impact of the ETS on production costs negligible. A fourfold increase in the allowance prices in 2018 allows to expect more studies in the near future.
sions Trading Scheme) (e.g. Naegele and Zaklan 2019; Koch and Mama 2019) suggesting a very limited price and quantity impact may suffer from predictive failure if the regional cost shocks becomes larger.

The paper is organized as follows. In the next section, we outline our non-linear model of local shock pass-through with international linkages. We apply the model to the nitrogen industry, which we briefly describe in section 2. Section 3 tests multiple predictions of our model and provides evidence from commodity prices and production data. In section 4, we provide ancillary evidence from stock markets and capacity investment and explain the failure of empirical models that ignore market linkages. Finally, section 5 concludes.

1. Pass-Through with International Linkages

This section develops our core theoretical analysis of cost pass-through with international market linkages. We emphasize three key points: first, regional cost shocks have a qualitatively different impact on markets than global cost shocks. Second, regional cost shocks lead to reallocation of production from the high-cost to the low-cost region; this makes capacity constraints especially relevant. In the short run, capacity constraints may limit cost pass-through of a local cost decrease and strengthen the impact of a local cost increase on global prices. Third, in the long run, for permanent regional cost shocks, capacity may move across regions; this can cause the pass-through of a regional cost decrease to be higher than that of a global cost shock of equal size.

To investigate these mechanisms, our analysis builds on the canonical Cournot model. Our key extensions are allowing for cost heterogeneity and capacity constraints. There are a total of \( n \) firms, each producing the same homogeneous good. Production takes place in two regions \( r \in \{A, B\} \), and share \( s_r \) of firms is located in each region. The marginal cost of production in the reference region \( B \) is normalized to \( c \), and in region \( A \) the marginal cost is given by \( c + \Delta \). Hence, \( c \) measures the global component of marginal cost while \( \Delta \) is a region-specific offset (which may be positive or negative). Thus, we shall refer to changes in \( c \) as a “global cost shock” and changes in \( \Delta \) as a “regional cost shock” in the remainder of the paper.
Market Linkages. Markets for the good are completely integrated. Thus, the law of one price holds at all times, and there are no price spreads between regions, as we assume no transportation costs of the good.

However, we allow marginal costs to differ between regions. This can arise for different reasons. For example, one region could introduce a carbon tax. Or there could be regional supply gluts due to export infrastructure or pipeline capacity constraints, e.g. natural gas in US after shale.

Thus our key interest is to understand how $\Delta$, i.e. change of marginal cost in region $A$ only, impacts on market prices in both regions (since markets are integrated). Later we will look at impacts on reallocation of production and investment between regions, as well as the impact of $\Delta$ on firm valuations.

Capacity Constraints. In the short run, the production capacity of each region is fixed at a maximum level $K$. For convenience, we index the capacity level to a multiple of the symmetric equilibrium output when there are no regional cost differences. We denote this multiple by $\theta$. Second, producers have the option to shut down, so the minimum production in each region is zero.

Besides linkages and capacity constraints, the model set-up is entirely standard with $n$ firms globally, of which a share $s_r$ is located in region $r$. Details of the calculations and proofs of the propositions are collected in appendix A1.

The first result to emerge from this analysis is that regional cost shocks have a weaker effect on market prices than global shocks:

Proposition 1. Pass-through of a regional cost shock is weakly lower than of a global cost shock

\[
\frac{dP}{d\Delta} \leq \frac{dP}{dc} \tag{1}
\]
The underlying mechanism is very intuitive: in the case where producers are interior, the Cournot price depends on the market average of marginal costs. Since a regional cost shock does not change the market average one-for-one, its pass-through is lower than that of a global shock. As we show in the appendix, this inequality still holds when some producers are quantity constrained.

For empirical research, it is thus essential to distinguish regional and global cost shocks. For example, one may regress prices on costs in a particular region. Then, by definition, it is impossible to distinguish regional and global shocks. This problem still persists if one uses a panel with region-fixed effects: the estimation considers each region in isolation, and does not distinguish global and regional shocks. There is an important methodological challenge which we take up later.

Note that capacity constraints are more likely to bind with regional, rather than global, cost shocks. This is fundamentally related to Cournot dynamics: as cost differences between regions rise, one region reduces its production while the other increases it. Thus, the lower-cost region may shut down its production, or the higher-cost region may produce at full capacity. This is fundamentally different to the situation with global cost shocks, where quantities in each region move in the same direction.

In our analysis, interesting cases arise when capacity constraints bind. Of course, for arbitrarily large values of $\theta$, spare capacity would be so large that no possible regional cost shock could cause this constraint to bind. Thus, for the analysis that follows, we make a moderate assumption to simplify the exposition: we assume that there is a regional cost shock $\Delta$ such that the capacity constraint becomes binding. We define this as a “potentially binding capacity constraint”:

**Assumption 1.** For a sufficiently large regional cost shock, the capacity constraint becomes binding:

$$\theta < \min \left( \frac{ns_A}{(1 - s_A) \times n + 1}, \frac{(1 - s_A)n + 1}{ns_A} \right)$$

We can now move to the central theoretical result and characterize the short-run pass-
through of a regional cost shock. As we show, the pass-through function is not linear but instead divided into four partitions:

**Proposition 2.** The short-run pass-through of a regional cost difference is characterized as

1. If $\Delta < \Delta_A^C$, region A has a large cost advantage and produces at its capacity constraint ($\bar{C}$); there is no pass-through:

   $$\frac{dP}{d\Delta} = 0$$

2. $\Delta_A^C < \Delta < \Delta_B^C$: Both regions produce positive quantities, neither A’s nor B’s capacity constraints bind. There is a medium level of pass-through:

   $$\frac{dP}{d\Delta} = s_A \times n/(n + 1)$$

3. $\Delta_B^C < \Delta < \Delta_A^S$: Region B is capacity constrained, so marginal quantities can only be produced by region A. Accordingly, pass-through increases to

   $$\frac{dP}{d\Delta} = ns_A/(ns_A + 1)$$

4. $\Delta_A^S < \Delta$: Region A shuts down production ($\bar{C}$), no pass-through

   These results are visualized in figure 2. When the regional cost shock is low, production in both regions is not constrained by capacity or shut down. Then, the Cournot price is determined by world-average marginal cost, as discussed above, and there is a low level of pass-through of a regional cost shock. However, as the cost advantage (negative $\Delta$) of region A rises, i.e. $\Delta$ becomes more negative, and falls below $\Delta_A^C$, firms in region A will eventually produce at full capacity. Once full capacity is reached, any further reduction in cost, of course, cannot stimulate production. Thus, at this point, pass-through stops.

   The pass-through of a regional cost disadvantage (positive $\Delta$) may be mitigated if the rival region is capacity constrained. Consider the situation of a large cost disadvantage for region A. As $\Delta$ increases, region A reduces its production while region B increases production. At
some point, rival region $B$ will produce at full capacity (shown in the figure as $\Delta C^B$). Then, if there are further cost increases, $A$ will continue to reduce output – but at a slower rate, since $B$ does not increase its production anymore. Hence, cost pass-through is increased in this segment.

With sufficiently strong cost disadvantage, production in a region may cease entirely. This is visualized as the flat segment on the right side of the figure. Here, region $B$ produces at full capacity while production in region $A$ has shut down.

The non-linearity highlighted in the proposition has important implications for empirical analysis. With global shocks, marginal cost is passed through linearly; then the empirical challenge is to estimate the slope coefficient. But with regional shocks, one needs to simultaneously determine the state the market is in – drastic cost advantage, non-drastic cost differences, or drastic cost disadvantage – with the estimation of the slope.

Depending on the market state, regional cost shocks may have a stronger impact on firm profitability and valuation than on market price. For example, in the case of drastic cost advantage, changes in marginal cost do not affect output by construction. Hence, there is no pass-through to prices. But unit profitability is affected one-for-one by cost shocks, and accordingly, the valuation of the firm may respond, e.g. if investors expect the cost difference to remain permanent.

**Long Run.** In the long run, the location of capacity is endogenous. This means that in a long-run equilibrium, *all* capacity must be located in the lower cost region. Thus, the higher-cost region eventually loses all production capacity, and accordingly there can be no cost pass-through of a local cost increase. In contrast, the lower-cost region eventually attracts all firms, so the pass-through of a negative regional cost shock exactly coincides with that a global shock in the long run.$^3$

**Proposition 3.** *In the long run, there is no pass-through for a regional cost increase and strong

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$^3$One can argue that in the long run the input prices would adjust closing the gap in marginal cost between the regions. However, examples from many segmented input markets, i.e. labor, show that such adjustment takes place at a very slow rate. Nevertheless, the model long-run prediction also hold with input price adjustments as long as the adjustments take place sufficiently slow or that the capacity costs sufficiently low to justify new investments in the low cost region.
pass-through for a regional cost decrease:

\[
\frac{dP^L}{d\Delta} = \begin{cases} 
0 & \text{if } \Delta > 0 \\
\frac{n}{n+1} & \text{if } \Delta < 0
\end{cases}
\]

This discussion highlighted three important points. First, regional shocks require reallocation of production between regions. This makes it especially likely that capacity constraints become binding.

Second, for regional cost shocks, increases affect cost pass-through differently than decreases. With a regional cost decrease, production increases may quickly hit capacity constraints, which limits the price impact. Similarly, the effect of a cost increase may eventually be enhanced by competitors hitting a capacity constraint.

Third, the short and long run effects of cost shocks are very different. In the long run, a regional cost decrease has a stronger pass-through effect than in the short run. This is driven by plant relocation: as capacity moves to the lower cost region, market-average costs fall and accordingly pass-through is enhanced. Conversely, for a regional cost increase, there is no pass-through in the long run (but positive pass-through in the short run). Again, this result is driven by plant relocation: in the long run, all plants must move to the lower cost region.

**Perfect Competition.** In the case of perfect competition, the pass-through results become particularly strong. As the number of firms increases, the reaction curves become more elastic; accordingly, even a small regional cost shock triggers a large reallocation of production between regions. This implies that capacity constraints are hit faster. In the limit, as \( n \to \infty \), the thresholds \( \Delta^C_A \) and \( \Delta^C_B \) converge to zero. That is, any regional cost shock becomes drastic:

**Proposition 4.** With perfect competition, short-run pass-through of a regional cost shock is

\[
\frac{dP^L}{d\Delta} = \begin{cases} 
1 & \text{if } \Delta > 0 \\
0 & \text{if } \Delta < 0
\end{cases}
\]

In other words, the market price is determined by the maximum of marginal cost among the producing regions. This, of course, follows from the marginal producer principle of perfect
competition.

To conclude, with perfect competition, the pass-through effects of a regional cost shock in the short run are precisely the opposite of those in the long run. This clearly makes it difficult to extrapolate long-run effects from short-run data.

2. Empirical Application to the Nitrogen Industry

Nitrogen fertilizer had a transformative effect on world food production, making dramatic yield increases – necessary to feed a rapidly growing world population – possible. Today, fertilizer is responsible for more than 40% of world grain production (Roberts et al., 2009), and nitrogen products make up more than 80% of global fertilizer consumption (Yara, 2017). All nitrogen production starts with ammonia, which is typically produced from natural gas using Haber-Bosch process – an energy intensive process which allows fixation of atmospheric nitrogen through a reaction with hydrogen. The reaction occurs under very high temperatures and pressure. Energy costs amount to up to 90% of total ammonia production costs (Boulamanti and Moya, 2017).

The total world ammonia production is currently 154 million metric tonnes (FAO, 2017). The largest share of this output is used as fertilizer, either in direct field application or after processing into other compounds, especially urea. Twenty percent of the ammonia production is consumed for industrial use, especially by the chemical industry and for production of explosives.

The ammonia industry is a process industry and marginal cost in process industries is very well approximated by a constant marginal cost function up to capacity constraints. Thus as we discuss below, the market fits very well to the modeling framework outlined in the previous section.

Production in multiple regions: The nitrogen industry is fragmented into a large number of firms. On the one hand, this is facilitated by the fact that the production inputs – air, fossil

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4Typically produced by the steam reforming of natural gas, however, hydrogen for ammonia production can be obtained through oxidation from feedstocks such as coal and naphtha or electrolysis of water.

5Further examples of process industries include sugar (Genesove and Mullin, 1998), electricity (Fabra and Reguant, 2014), cement (Fowlie et al., 2016a) industries, though in the latter case capacity constraint is modeled through a hockey-stick cost function - constant marginal cost up to a certain point and then rapidly increasing.
fuels and capital – are available in many locations. Moreover, economies of scale are limited.\textsuperscript{6} Globally, the ten-firm concentration ratio in the ammonia market is 19% (PotashCorp, 2014).

High capital and transportation costs and strategic importance of nitrogen for food security assure that ammonia is geographically spread and less than 10% of ammonia production is traded internationally. Nevertheless, as Figure\textsuperscript{1}(a) shows, the market remains tightly integrated.\textsuperscript{7} Since the late 1990s, Europe and North America, holding, as of 2013, 9% and 6% of global production capacity respectively (Boulamanti and Moya, 2017), have become major importers of ammonia and account for approximately 60% of the global ammonia imports. Since those large producing regions were also large importers, the global ammonia price is set on those markets. Trinidad and Tobago, Russia and the Middle East and North Africa countries, which enjoy very low local natural gas prices, are the largest exporters. Except for Trinidad and Tobago that specializes in ammonia production and processes most of its natural gas into that commodity, all largest net ammonia exporters are also among the largest net natural gas exporters (BACI Trade database, Gaulier and Zignago, 2010). This allows as to treat the EU and the US as the price setting regions. This view is shared by industry reports (see, e.g., Yara, 2017).

\textit{Segmented input markets:} While the market for ammonia is integrated, market for the main input - natural gas - is geographically segmented.\textsuperscript{8} Ammonia exporters are benefiting from natural gas prices much lower than in the rest of the world, which makes exports always profitable despite relatively high transportation costs.

\textit{Common technology:} The production technology is provided by external engineering and

\textsuperscript{6}According to the USGS (2017), the largest ammonia plant in the US – the Donaldsonville complex owned by CF Industries – had a capacity of 2.7Mt per year, less than 20% of US ammonia consumption.

\textsuperscript{7}However, this low trade share has encouraged the existing literature on nitrogen prices to essentially neglect trade: for example, Beckman and Riché (2015), Etienne et al. (2016) and Bushnell and Humber (2017) independently conduct a cointegration analysis of US ammonia prices with US natural gas prices. However, these models have broken down since 2008, when US natural gas prices started “decoupling” from EU gas prices: the existing relationship between gas and ammonia prices in the US no longer holds, while the ammonia price spread between Europe and North America remains small as before.

\textsuperscript{8}According to USGS data, the US share of imports in ammonia consumption doubled from under 20% in the early 1990s to over 40% in the late 2000s. For Europe the import share has been in the range of 20% - 30%.

\textsuperscript{9}Although thanks to the developments in the LNG technology and gas liquefaction and regasification infrastructure the LNG trade tripled between 2000 and 2018, LNG trade still amounts to just above 1% of the global natural gas consumption. Over two-thirds of the global LNG trade is delivered to South-East Asia.
construction companies that offer proprietary designs for ammonia synthesis plants.\[10\] The differences in the energy efficiency between the technologies are small, implying that the many ammonia producers around the globe use essentially a common technology. This is similar to oil refining, where a barrel of crude oil yields a given quantity of gasoline, diesel or jet fuel.

**Constant marginal cost:** As typical for a process industry, ammonia production lines operate 24/7 at a constant rate, stopping only once a year for a couple of days for maintenance. Output rate is defined by plant design. In theory, the output can be increased with higher pressure and temperature, but for safety and economic reasons such deviations from the optimal process are not practiced. If necessary, output is more likely to be regulated through temporary closures than changes in the process parameters.

**Fixed capacity:** Construction of a new ammonia plant is costly, in range of $1000-$2000 per ton of annual capacity, and completion of a greenfield project takes a minimum of three years. Ammonia plants upon completion remain in operation with minor upgrades for as long as 50 years or more. This assures that capacity adjustments to temporary shocks are practically impossible.

**Energy efficiency:** Energy efficiency is a crucial determinant of marginal cost. Since producers around the world use common technology, there are relatively small differences between the regions, especially between the US and Europe. Industry studies suggest that an average plant in Western Europe uses 30.1 MMBtu of natural gas per short ton of ammonia, while in the US, production requires 32.5 MMBtu per short ton (International Energy Agency, 2007). Energy efficiency is lower in other producing regions, but that is more than fully compensated by lower natural gas prices.

**Transportation costs:** Ammonia transportation costs are high and variable. Transatlantic freight rates stay, typically, above 50USD/t. However, as there is virtually no ammonia trade between the US and Europe, what matters from our modeling perspective is the difference in freight costs from the ammonia exporting regions to Europe and the US. Data revealed by

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\[10\]The main technology providers include Haldor Topsoe (Denmark), Thyssenkrupp (Germany), Ammonia Casale (Switzerland) and Kellogg Brown & Root (USA).
market intelligence firms confirm that the these differences remain very small and the cost ranges provided frequently overlap[11] This justifies the assumption on zero transportation costs in the model section. For natural gas, transatlantic trade was limited due to the lack sufficient export infrastructure in the analysed period.

Other inputs: Although natural gas is the main input, production of ammonia requires also electricity, cooling water, chemicals, catalysts and labor. Furthermore, Haber-Bosch process generates excess CO2, which brings co-product revenues. We don’t account individually for those marginal cost components. Instead, we rely on a very detailed micro-costing study (Boulamanti and Moya [2017]) of 116 ammonia production facilities around the world. The study reveals that those costs are similar around the world, for the US those costs were estimated at $59.8 per ton, for Europe at $68.1 in 2013[12]

Emissions Costs: Ammonia industry has been classified as a carbon-intensive trade-exposed industry and included in Phase III of the European Emissions Trading Scheme (ETS) for years 2013-2019. Thus, since 1 January 2013, all European ammonia producers must surrender a permit for each metric ton of CO2 equivalent they emit.

Although the producers have been allocated free permits[13] they have an opportunity cost, the price at which they can be sold in secondary markets. Thus, we include emissions costs in our estimates of the marginal costs. Emissions costs are always zero for the US producers and in Europe before 1 January 2013. After that date, they are calculated based on the carbon content of natural gas, which is 53kg per MMBtu, and emissions prices[14]

Marginal Cost: This brief description of the ammonia industry justifies a linear marginal cost function. Unit marginal cost is a sum of three components: feedstock cost, determined by

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[11] In its market intelligence report, Argus (2018) shows that freight rates from Point Lisas (Trinidad and Tobago) to US Gulf were in range 37-47 USD/t, while freight rates to NW Europe in range 44-56 USD/t.

[12] We convert values in figure 1 in (Boulamanti and Moya [2017]) from euro to US dollars using the average exchange rate in 2013, i.e. 1.324 USD/EUR.

[13] All existing ammonia producers have been “grandfathered” “benchmarked” allocations. Every year, owners of ammonia installations receive permits proportional to their past production and according to the so-called product benchmarks. Those are calculated as GHG emissions of installation in the 10th percentile of the emissions efficiency distribution per unit of output. For ammonia, this benchmark has been calculated at 1.619 allowances per tonne of ammonia produced. The allocated number of permits decreases annually by 1.74%, a so-called cross-sectoral correction factor, for the entire sector.

[14] Thus production of one short ton of ammonia, using the assumed technology, requires surrendering 30.1 * 0.053 = 1.595 permits (1.759 permits per metric tonne).
regional energy efficiency and natural gas prices; emissions cost driven by carbon intensity and emission permit prices (EUA); and a constant term that covers other inputs. In particular, we calculate regional marginal cost of a short ton of ammonia at:

\[
MC^{US} = 59.8 + 32.5 \times \text{Natural Gas}^{US} \\
MC^{EU} = \begin{cases} 
68.1 + 30.1 \times \text{Natural Gas}^{EU} & \text{Before 2013} \\
68.1 + 30.1 \times \text{Natural Gas}^{EU} + 1.595 \times \text{CO2}^{EU} & \text{Since 2013}
\end{cases}
\]

Where natural gas is price of natural gas per MMBTu and CO2 represents the unit costs of European Emission Allowances and the EU and US superscripts Europe and North America respectively.

2.1. Data

The sample period runs from 1996 through to 2017. We combine data from various industry sources, as detailed here.

Nitrogen prices. We obtained monthly spot price data (from 1996.1 to 2017.12) for ammonia through Bloomberg / Green markets. The data are based on spot prices at the Tampa, Florida trading hub for the US and the Black Sea Port of Yuzhny, Ukraine, for Europe.\(^{15}\)

For natural gas in US, we use the Henry Hub (Louisiana) spot price, as 50-60% of the US ammonia production is concentrated in hub’s proximity, i.e. in Louisiana, Oklahoma and Texas. Throughout the analyzed period, the European natural gas market was dominated by contract rather than spot prices, thus we use long term contract prices instead.\(^{16}\)

\(^{15}\)Ammonia is also traded in New Orleans, however, the monthly data series contained multiple missing observations. Thus we opted for Tampa instead, however, the results remain qualitatively unchanged if we use the New Orleans price series with inputed values for missing observations instead. Throughout the sample period, ammonia in New Orleans traded at an average premium of $21 (median premium: $14) relative to Tampa.

\(^{16}\)According to the International Gas Union, in 2005, only 15% of the natural gas purchased in Europe on a wholesale market was determined by spot gas prices, 78% was determined by oil-linked contracts and the remainder by a variety of non-market pricing mechanisms. By 2015, the share of gas purchased in Europe and priced at spot market prices increased to 64%, but the oil-linked contracts kept a substantial share, 30%, in the gas supply (IGU, 2016). At the same time, 99% of natural gas in the US is purchased at spot markets prices. To calculate contract prices we use Platt’s formula: a weighted average of gas oil (45%) and fuel oil (55%) ARA (Amsterdam-Rotterdam-Antwerp) spot prices at 30% discount. Bushnell and Humber (2017) attempted to perform a similar
Production Quantities: Data on ammonia production is sourced from the International Fertilizer Association (database: IFADATA). The quantities are available by region at an annual frequency only. We focus on Northern America (USA and Canada) and Western and Central Europe. To match the frequency, we calculate annual averages of monthly prices for some analyses. Trends in production and capacity utilization are shown in figures 4(a) and A1 respectively.

3. Results

The central result of our theoretical analysis is that pass-through may be asymmetric and non-linear. While the question of whether pass-through is 0.8 or 1.2 is a very important one, we are interested in a more fundamental question: What is being passed through? We need to know which dependent variable or, in our case, costs from which region to look at.

To recap from the model section, when cost differences are small, we are in the interior (Cournot) region, where market price depends on average marginal cost throughout the producing regions, represented by Regime 2 (R2) in equation 4. In this non-drastic regime an average cost model applies.

When the cost in our region of interest (US and Canada (US)) is sufficiently low, the cost advantage becomes drastic. In this case, the price depends only on the marginal cost of the reference region (Europe (EU) in our case), represented by Regime 3 (R3) in the equation below. In this drastic regime a local market model applies. And finally, when our region has a large cost disadvantage, likewise we may enter the drastic segment and market price will depend on cost in our region alone (R1). This means the model prediction is as follows:

exercise to ours using the European natural gas spot prices, but failed to show any relation. But this is what one would expect as the majority of European ammonia producers in that period were bound by long term contracts. However, as spot prices are becoming dominating in the European gas supply, we recommend to use spot prices in any follow up analysis in the extended sample.
If the market is perfectly competitive (see proposition [4]), or if firms operate at no spare capacity, such that $\Delta C^C_{US} = \Delta C^C_{EU} = 0$ and the two regions have equal market shares, our prediction reduces to:

$$p_t = \alpha_4 + \beta_4 \times \max(MC_{US}, MC_{EU})$$ (5)

In our baseline estimation, we first make an educated guess about the true state of the world based on economic fundamentals. We then test to see if we can reject this assessment. Our dependent variable is the US ammonia price. Prices for ammonia in Europe are used as a robustness test with results shown in Appendix Table A3.

### 3.1. Structural Breaks: Determining the Regime

Crucial for determining the active regime is the magnitude of marginal cost differences between the regions. These are plotted in figure [3]. By inspection, the effect of Shale gas is clearly apparent: before 2008, the differences in marginal cost between Europe and US are small and quickly mean reverting (e.g. after hurricanes). After 2008, marginal cost in Europe far exceeds that of US producers. This suggests that there was a structural break during 2008.

A more formal structural break test, based on the Bai (1994) procedure, confirms that there was a structural break in the year 2008. This coincides with the period when the US producers reached their maximum capacity utilization rates as shown in Appendix Figure A1.

Combining these empirical observations with our model results, we assign – as a maintained assumption – the following states to the nitrogen market:
• Before 2008: Regime 2 (R2)

Cost differences are non-drastic, and neither European nor US producers are capacity-constrained; market price depends on average cost of EU and US producers.

• After 2008: Regime 3 (R3)

US producers have a drastic cost advantage, and are constrained by their production capacity. The market price depends on EU marginal cost only.

We validate our assumptions with the regression results presented in the subsequent section.

3.2. Cost Pass-Through

The evidence of the regime change needs to be reflected in the empirical model. Regime 2 implies the average cost model, which we show in table 1(a). In Regime 3, we regress global prices against marginal cost in the high cost region only with results in table 1(b). Table 1 also highlights that choosing a wrong model hurts. This is especially visible as we present the results of Regime 2 specification for the period where we believe Regime 3 holds and vice versa.

Consider first the period before 2008. By the reasoning above, we expect the market to be in the non-drastic regime (R2), where pass-through is determined by average cost. Accordingly, the results from table 1(a), column (2) apply. The point estimates suggest that a global cost shock would have a pass-through of 1.12, i.e. exceeding unity. However, due to sampling uncertainty, we also cannot reject the hypothesis that pass-through of a global shock is unity, which is what we would expect under perfect competition with constant marginal cost. The implied firm shares are $s_{US} = 35\%$ for the US, which is somewhat below the capacity share of the US, and the remaining 65% of firm shares assigned to Europe. Again, an open question is whether we could reject a 50-50 split between these two regions. The analyzed price series are not stationary, thus to enable economic interpretation we need to find evidence for cointegration. This we show through the Engle-Granger cointegration test, which strongly rejects the hypothesis of no cointegration.
### TABLE 1
Main Results

(a) Average Cost Model

<table>
<thead>
<tr>
<th>Dep. Var</th>
<th>Sample Period</th>
<th>Ammonia Price (US)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Whole</td>
<td>Pre-08</td>
<td>Post-08</td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td></td>
<td></td>
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</tbody>
</table>

**Coefficient Estimates**

<table>
<thead>
<tr>
<th></th>
<th>Intercept</th>
<th>MC\textsubscript{US}</th>
<th>MC\textsubscript{EUR}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>$-44.29^{**}$</td>
<td>$0.22^{***}$</td>
<td>$1.12^{***}$</td>
</tr>
<tr>
<td></td>
<td>$(14.89)$</td>
<td>$(0.05)$</td>
<td>$(0.05)$</td>
</tr>
<tr>
<td></td>
<td>$-16.20^{*}$</td>
<td>$0.39^{***}$</td>
<td>$0.73^{***}$</td>
</tr>
<tr>
<td></td>
<td>$(7.91)$</td>
<td>$(0.06)$</td>
<td>$(0.07)$</td>
</tr>
<tr>
<td></td>
<td>$115.19^{*}$</td>
<td>$-0.82^{*}$</td>
<td>$1.18^{***}$</td>
</tr>
<tr>
<td></td>
<td>$(55.92)$</td>
<td>$(0.34)$</td>
<td>$(0.08)$</td>
</tr>
</tbody>
</table>

**Cointegration Test**

<table>
<thead>
<tr>
<th></th>
<th>ADF Stat</th>
<th>ADF Lags (BIC)</th>
<th>R\textsuperscript{2}</th>
<th>Num. obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$-5.76^{**}$</td>
<td>2</td>
<td>0.79</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td>$-4.71^{**}$</td>
<td>1</td>
<td>0.79</td>
<td>144</td>
</tr>
<tr>
<td></td>
<td>$-5.48^{**}$</td>
<td>1</td>
<td>0.65</td>
<td>108</td>
</tr>
</tbody>
</table>

(b) Regional Cost Model

<table>
<thead>
<tr>
<th>Dep. Var</th>
<th>Sample Period</th>
<th>Ammonia Price (US)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Whole</td>
<td>Pre-08</td>
<td>Post-08</td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
</tbody>
</table>

**Coefficient Estimates**

<table>
<thead>
<tr>
<th></th>
<th>Intercept</th>
<th>MC\textsubscript{US}</th>
<th>MC\textsubscript{EUR}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>$189.32^{***}$</td>
<td>$0.52^{***}$</td>
<td>$1.14^{***}$</td>
</tr>
<tr>
<td></td>
<td>$(25.69)$</td>
<td>$(0.11)$</td>
<td>$(0.05)$</td>
</tr>
<tr>
<td></td>
<td>$-6.05$</td>
<td>$0.77^{***}$</td>
<td>$1.16^{***}$</td>
</tr>
<tr>
<td></td>
<td>$(10.69)$</td>
<td>$(0.06)$</td>
<td>$(0.06)$</td>
</tr>
<tr>
<td></td>
<td>$31.69^{**}$</td>
<td>$0.48$</td>
<td>$1.09^{***}$</td>
</tr>
<tr>
<td></td>
<td>$(11.58)$</td>
<td>$(0.41)$</td>
<td>$(0.08)$</td>
</tr>
<tr>
<td></td>
<td>$-11.05$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$(9.92)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$318.46^{***}$</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>$(71.64)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$(26.09)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Cointegration Test**

<table>
<thead>
<tr>
<th></th>
<th>ADF Stat</th>
<th>ADF Lags (BIC)</th>
<th>R\textsuperscript{2}</th>
<th>Num. obs.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>$-1.83$</td>
<td>3</td>
<td>0.06</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td>$-5.51^{**}$</td>
<td>2</td>
<td>0.78</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td>$-3.73^{*}$</td>
<td>1</td>
<td>0.68</td>
<td>144</td>
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<tr>
<td></td>
<td>$-3.08^{*}$</td>
<td>2</td>
<td>0.72</td>
<td>144</td>
</tr>
<tr>
<td></td>
<td>$-1.81$</td>
<td>2</td>
<td>0.01</td>
<td>108</td>
</tr>
<tr>
<td></td>
<td>$-3.53^{**}$</td>
<td>2</td>
<td>0.62</td>
<td>108</td>
</tr>
</tbody>
</table>

Note: $^{***} p < 0.001$, $^{**} p < 0.01$, $^{*} p < 0.05$. Engle-Granger Critical Values for ADF Test.

Dependent variable: US ammonia spot price (Tampa) in $/ short ton. MC\textsubscript{EUR} and MC\textsubscript{US} are the regional average marginal costs for Europe and US (in $/ short ton) respectively.

For the period after 2008, we expect a drastic cost advantage for US, or Regime 3. Hence, pass-through should be from European costs only, and the results from table 1(b), column (6) apply. As before, the point estimate suggests pass-through somewhat higher than unity, but not statistically different from unity. As for the pre-2008 regime, the Engle–Granger test favors cointegration, this time between ammonia prices and marginal cost in Europe.

Change of the dependent variable to the European rather than US ammonia prices does not affect qualitatively the results as we show in the Appendix Table A3. This confirms robustness of our approach and suggests rather small role of transportation (transaction) costs that are set to zero in our model.

These results so far suggest that the capacity constraints model provides a good account of price behavior in the nitrogen industry. We have identified the structural break using non-sample information, and for each of the periods, the implied regime fits the data well. There is firm evidence for cointegration in both regimes. Economically, the results are consistent with perfect competition. This is because pass-through is not significantly different from unity, which is what we would expect under perfect competition with constant marginal cost.

We now need to assess our explanation against the alternatives. First, we consider regressions by region. As our theoretical analysis shows, there are regimes where the price in one region is determined purely by costs in that region (when the other region is capacity-constrained). Effectively, local market models assume that the market is always in this particular state. Consider table 1(b). For the whole sample period, explaining US ammonia prices with US marginal cost performs poorly, as shown in column (1). There is essentially no evidence in favor of cointegration, suggesting the regression is spurious. Second, the estimated slope coefficient implies low pass-through, and the high intercept suggests large fixed mark-ups per unit. These coefficients would be consistent with a rather uncompetitive industry, which appears implausible based on industry fundamentals.

Conversely, explaining US ammonia prices with European marginal cost only, yields a satisfactory fit over the entire sample period. As column (2) shows, there is good evidence in favor of cointegration; the intercept is not significant. Based on available evidence and our theory, the model is likely to be misspecified. However, since the cost gap between the
US and Europe was rather small throughout the entire period before shale, it gives a good approximation. Indeed, for the pre–2008 period, both European and US marginal cost models perform relatively well. Only in the post–2008 is it possible to clearly distinguish between the specifications. For the US cost model, as shown in column (5), the coefficient is insignificant, and overall goodness of fit is negligible, so even within the sample, local costs essentially do not explain any variation in prices.

Building on these results, we estimate our model for the polar case of perfect competition. As we showed in proposition 4 in this case, the product price depends on the maximal marginal cost between the producing regions. Compared to the imperfectly competitive model, this case yields much stronger predictions as we do not need to estimate thresholds at all and we can apply a single model throughout the entire sample period. In table 2 we present results for this model. Note that in the post–2008 period the natural gas prices in Europe were always higher than in the US, thus the results in column (3) of table 2 and column (6) in table 1(b) are identical.

Column (1) shows very good support for the competitive market model throughout the entire sample period. The ADF statistic is firmly in favor of cointegration. The estimated pass-through of maximal marginal cost is estimated at 1.17, economically and statistically significantly above unity. This is not directly in line with the theoretical prediction. When estimating the model separately for the before and after periods, we find strong support for cointegration in each period. The pass-through coefficients are smaller, at 0.79 and 1.09 respectively, and not statistically significantly different from one. It certainly appears plausible that capacity constraints bind also in the competitive case. Thus some demand driven shocks, e.g. the volatility following the 2008 crisis, cause our estimates to be above unity. As a further benchmark, we estimate the model with the pass-through coefficient restricted to unity (as predicted by theory). For this specification (see appendix table A4), we also cannot reject cointegration.

3.3. Production Relocation

While the discussion so far has been focused very much on prices, the Cournot model makes also strong predictions on quantities. In Regime 2, we expect relative production quantities
TABLE 2
Pass-Through: Perfectly Competitive Case

<table>
<thead>
<tr>
<th>Dep. Var</th>
<th>Ammonia Price (US)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Period</td>
<td>Whole (1)</td>
<td>Pre-08 (2)</td>
<td>Post-08 (3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coefficient Estimates</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>$-37.20^{**}$</td>
<td>$25.01^*$</td>
<td>$3.00$</td>
</tr>
<tr>
<td></td>
<td>$(12.35)$</td>
<td>$(11.80)$</td>
<td>$(26.09)$</td>
</tr>
<tr>
<td>max($MC_{EUR},MC_{US}$)</td>
<td>$1.17^{***}$</td>
<td>$0.79^{***}$</td>
<td>$1.09^{***}$</td>
</tr>
<tr>
<td></td>
<td>$(0.05)$</td>
<td>$(0.06)$</td>
<td>$(0.08)$</td>
</tr>
<tr>
<td><strong>Cointegration Test</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADF Stat</td>
<td>$-8.54^{***}$</td>
<td>$-3.97^{**}$</td>
<td>$-3.53^{**}$</td>
</tr>
<tr>
<td>ADF Lags (BIC)</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.75</td>
<td>0.70</td>
<td>0.62</td>
</tr>
<tr>
<td>Num. obs.</td>
<td>264</td>
<td>144</td>
<td>108</td>
</tr>
</tbody>
</table>

*Note:*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Engle-Granger Critical Values for ADF Test. Dependent variable: US ammonia spot price (Tampa) in $/ short ton. max($MC_{EUR},MC_{US}$) is the highest of the average regional marginal costs for Europe and US (in $/ short ton).


to respond to changes in relative costs. Lack of such a response can be treated as an indicator of Regime 1 or 3.

In the period before 2008, both US and European ammonia production were decreasing with an approximately linear trend. However, visual inspection of figure [4] suggests that relative quantities change in line with the Cournot model. This is especially visible in the years 2000 and 2005. In those years, US was affected by adverse cost shocks and production in Europe increased while production in the US decreased stronger than suggested by the trend. The early signs of the shale gas revolution could be seen already in 2006. Relative cost advantage in that year led to a significant increase in the US output. We don’t see such a pattern after 2008. Further decreases in natural gas prices did not translate into higher production levels. That could be potentially puzzling, but as we can see in the appendix figure [A1] US producers reached capacity constraints. This would confirm the earlier finding that we are in Regime 3. Since quantity data is available in annual frequency data, the observed patterns are indicative rather than definite.
Those initial findings are fully confirmed by a two-way panel regression with region and year fixed effects as shown in Table 3. When analyzing the entire sample (column (1)) we may get an impression that production is relatively elastic. The estimates suggest, that a 10$ increase in marginal costs in one region shifts 37,000 tonnes of production from one region to another\(^\text{17}\).

However, once we split the sample into two periods, before and after 2008, we clearly see that the model collapses after the shale gas revolution. In the period before the shale gas revolution, changes in regional production cost differences explain 66% of the variation in differences in regional changes in production (after demeaning) and our estimates suggest that a 10$ in marginal cost in one region shifts over 140,000 tonnes of production between the regions.

Once the US producers reached their production capacity, they were not able to respond to the favorable market conditions with increased output. As a result, we will not try to interpret our point estimates for which we even get the wrong sign on the coefficient of interest.

### TABLE 3
Ammonia Production Quantities: Panel Regressions

<table>
<thead>
<tr>
<th>Dep. Var</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>Ammonia Production (in ’000 tonnes)</td>
<td>Pre-08</td>
<td>Post-08</td>
</tr>
<tr>
<td>Marginal Cost</td>
<td>$-7.44^{**}$</td>
<td>$-28.57^{***}$</td>
<td>$7.52^*$</td>
</tr>
<tr>
<td>Region FE</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Time FE</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>R²</td>
<td>0.39</td>
<td>0.66</td>
<td>0.50</td>
</tr>
<tr>
<td>N</td>
<td>42</td>
<td>24</td>
<td>16</td>
</tr>
</tbody>
</table>

Note: \(^{***}p < 0.001, ^{**}p < 0.01, ^{*}p < 0.05\).

A two region (US, Europe) panel with annual regional production in US and Europe as the dependent variable and region specific marginal cost as explanatory variables.

Source: Bloomberg/ Green Markets, IFA and authors’ calculations. Annual data 1996 - 2016 (Whole) with sub-samples 1996-2007 (Pre-08) and 2009-2016 (Post-08).

\(^{17}\)We divide the regression coefficient by two, to interpret it this way.
4. Discussion

4.1. Market Valuation

Results so far show that the drastic natural gas price decrease has not been passed through into prices. Thus, natural gas cost differential must imply windfall profits for the US ammonia producers and should be reflected in stock market valuation. To test this hypothesis we construct two separate portfolios, for the listed ammonia producers in US and in Europe.

Construction of the Portfolios. We develop two portfolios for the North American (US) and the European (EU) ammonia producers’ stock prices. In the sample, described in detail in the appendix A1, we include all firms for which ammonia production is a “core” activity and that concentrate their production in a single region. Portfolios are weighted by firms’ ammonia production capacity. To allow for direct comparisons, we normalize the value of portfolios to take value 1 on 1st January 2005. We choose this date as a starting point as this is the first month of the first full year for which we have stock price data for at least two companies in each portfolio. In the US portfolio, we include all public ammonia-producing companies operating in North America. In the EU portfolio, we include all public European ammonia producers that concentrate their ammonia facilities in the European Union (EU28).

The figure 5 shows the return on stocks of the US ammonia producers relative to the European ammonia producers. Comparing it with regional marginal cost gap (dashed line), we can clearly see that the two lines closely follow each other. The stock market valuation of the US-based ammonia producers increases, relative to the European produces, as the gap in the natural gas prices between the two regions increases. After 2015, the cost differential began to decrease, and so did the “abnormal return” of the American stocks. This visual intuition is confirmed by statistical tests that find evidence of cointegration between the two series.

\[ \text{Stock Ratio}_t = 0.6213 + 0.0035 \times \text{Marginal Cost Gap}_t \]

The ADF test statistics on the residuals is 3.46, thus, using the critical values, we reject at 5% the null hypothesis of no cointegration between the series.

---

18 We include only firms for which ammonia revenues exceed 5% of total revenues.
19 To test for cointegration, we perform the two-step Engle-Granger procedure. We obtain the following long run relation.

The ADF test statistics on the residuals is 3.46, thus, using the critical values, we reject at 5% the null hypothesis of no cointegration between the series.
Since ammonia producers are typically multiproduct firms, without detailed knowledge of their portfolios, we did not have an *ex ante* hypothesis on the value of the coefficients.

4.2. Long Run

The analysis in the previous section refers to the short run only, while, our model, with little additional assumptions, allows also for long run predictions.

**Conjecture 1.** *New investments occur only in the region, for which $\Delta \ll 0$. In the long run, only permanent regional cost decreases are passed through into prices.*

In the absence of transportation and fixed capacity investment costs, the first part of the conjecture comes directly from firms’ cost minimization problem. Once all producers are located in one region, costs in the other region do not affect prices anymore. Fixed capacity costs complicate the discussion, thus we refrain from formal analysis. However, even with nonnegligible lump sum investment costs, if production plants have finite lifetime, new investments required to maintain the capacity will always occur in the low cost region. The long run model predictions are in stark contrast to pass-through in the short run, discussed earlier.

With ammonia plant life expectancy well above 50 years, our data set does not allow us to observe production plants throughout their lifetime. However, as we show in figure 6, the investment flows in the last 20 years follow the predicted pattern. To test the conjecture, we have collected information on all investment announcements and all disinvestment decisions in the US and Europe between 1996 and 2016 as reported by the USGS and other industry sources.

The upper left panel of figure 6a shows that in the late 1990s and early 2000s, production capacity decreased in both US and Europe. In that period, ammonia producers in both regions were disadvantaged relative to the rest of the world. Since natural gas prices were, on average, higher in US than in Europe in that period, the disinvestment rate was higher in North America. Eleven ammonia plants were permanently closed between 1999 and 2006 and production capacity decreased by 4mln tonnes, or nearly 25%, in that region. During the same period,

\[20\] See Borenstein (2000) for an excellent discussion of the implications of fixed costs on competitive pricing.
Europe lost only 0.9 mln tonnes of capacity (1.4 mln tonnes was closed and 0.5 mln tonnes added). After the shale gas, we see a completely different picture. The bottom right panel of the figure shows that US experienced a large inflow of new investments. Over 6 mln tonnes of capacity was commissioned between 2009 and 2018 and not a single plant was closed. During the same period, only one plant had been built in Europe, in landlocked Slovakia, while one plant of similar size was closed.

To highlight the role of the regional cost advantage on investment, we plot the exact timing of decision announcements against the marginal cost gap between the US and European producers in figure 6b. The US cost disadvantage in US prior to the shale discoveries is associated with multiple plant closures. In subsequent years, there was a lot of uncertainty and temporary closures. Local producers even commissioned a number of feasibility studies assessing the use of coal instead of natural gas as the feedstock. Those plans stopped with the discovery of shale gas and a significant decrease in the local costs. However, no investments occurred until a wide enough gap opened between the ammonia market price and the expected production costs. Indeed, as shown in Figure 6b no new plants were commissioned before unit profit margins exceeded $200/t. Similarly, new investments ceased once the gap went again below $200/t. This reflects high capital intensity of ammonia production. Greenfield investment costs are typically in the range of $2000/ton of annual ammonia.

4.3. Predictive Failure of Standard Pass-through Models

The presence of market linkages implies that linear pass-through models may be misspecified, and are therefore at risk of predictive failure. This problem is not addressed by linear panel models. To elaborate on this point, we now look at two panel designs – fixed effects and difference-in-difference designs – that have been influential in the empirical literature on pass-through.

First, consider one-way fixed effects models, as in Miller et al. (2017). Here, one allows for a region-specific fixed effect but otherwise assumes that price in each region is determined by regional marginal cost alone. In the case of ammonia, one would estimate

$$\text{Ammonia}_{r,t} = \alpha + \beta \text{MC}_{r,t} + \eta_r$$

(6)
Such an approach may be justified in the absence of market linkages, which is possibly the case for the cement industry analyzed in the discussed study. However, once the final product markets are integrated, this approach fails. Results of the one-way panel regression are shown in columns (1) - (3) in table 4a. The coefficient on the marginal cost in specification (1) in table 4a is just a weighted average of coefficients in regressions of regional ammonia price against regional marginal cost, which are 0.52 for US (see table 1(b), column (1)) and 1.07 for Europe (see appendix table A3(b) column (1)) respectively. The weights are determined purely by the relative variation of marginal costs in the two regions (shown in the appendix table A2). The very plausible value of the pass-through coefficient, estimated at 0.92, is just a coincidence driven by the fact that the variation in the US marginal cost has been just 1/3 of the variation in the EU gas prices throughout the analyzed period. After shale, US gas prices went back to the low level from the late 1990s and early 2000s, while the EU natural gas prices experienced a level change.

In a difference-in-difference model, which adds a time fixed effects to specification from equation 6 as used in Ganapati et al. (2020) and Stolper (2016), market linkages create even more stark issues and a clear violation of the Stable Unit Treatment Value Assumption (SUTVA), a critical assumption for causal inference. SUTVA, in our setting, requires that the change in regional price of the final good would depend only on the change in regional marginal costs and would be unaffected by changes in the marginal cost in the other regions. This is clearly under market linkages as in the case of the ammonia market.

Another consequence of the law of one price is the fact that price differences between regions are negligible. For the case of nitrogen, spreads between Europe and US stay small even as marginal cost gaps widen, to take one example. As table 5, column (4), shows, the two-way regressions explain essentially no variation in prices. The negative coefficient is economically not meaningful. When splitting the sample for the before/after periods, the sign on marginal cost changes, while R2 stays very low. These are symptoms that the model is a very bad fit for a market with international linkages.

Pass-through coefficient in column (1), is thus calculated as $0.522 \times \frac{(5238.551)}{(5238.551 + 14674.123)} + 1.067 \times \frac{(14674.123)}{(5238.551 + 14674.123)}$, where the expression in brackets is a sum of variance of marginal cost in US and and Europe as shown in appendix table A2.
TABLE 4
Panel Analysis

(a) Regressions

<table>
<thead>
<tr>
<th>Dep. Var Method</th>
<th>Period</th>
<th>(1) One-way Panel</th>
<th>(2) Pre-08</th>
<th>(3) Post-08</th>
<th>(4) Two-ways Panel</th>
<th>(5) Pre-08</th>
<th>(6) Post-08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia Price</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Method</td>
<td></td>
<td></td>
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<td></td>
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<td>Period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region FE</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Time FE</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Marginal Cost</td>
<td>0.92***</td>
<td>0.82***</td>
<td>0.95***</td>
<td>–0.03**</td>
<td>0.10*</td>
<td>–0.12***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.05)</td>
<td>(0.03)</td>
<td>(0.10)</td>
<td>(0.01)</td>
<td>(0.03)</td>
<td>(0.02)</td>
<td></td>
</tr>
<tr>
<td>R²</td>
<td>0.37</td>
<td>0.66</td>
<td>0.29</td>
<td>0.03</td>
<td>0.07</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>528</td>
<td>288</td>
<td>216</td>
<td>528</td>
<td>288</td>
<td>216</td>
<td></td>
</tr>
</tbody>
</table>

Note: ***p < 0.001, **p < 0.01, *p < 0.05.
A two region (US, Europe) panel with ammonia spot price in $/ short ton in US (Tampa) and Europe (Yuzhnyy) as the dependent variable and region specific marginal cost as explanatory variables.

(b) Variance Decomposition

<table>
<thead>
<tr>
<th>Price Series</th>
<th>Time FE</th>
<th>Region FE</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>97.68%</td>
<td>1.69%</td>
<td>0.63%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>51.90%</td>
<td>9.54%</td>
<td>38.56%</td>
</tr>
<tr>
<td>Crude Oil</td>
<td>98.99%</td>
<td>0.08%</td>
<td>0.93%</td>
</tr>
</tbody>
</table>

Note: Variance decomposition table shows the proportion of the variation of the regional commodity prices (1996.1 - 2017.12) explained by the fixed effects.
Source: Authors and Bloomberg

To understand the problems with these panel models, a variance decomposition is very helpful. As shown in table 4b, the overwhelming share of variation between regions is driven by a common time effect. However, in the diff-in-diff layouts, the common time and region variation is removed by fixed effects. Thus, less than 1% of the variation in ammonia remains to be used in the estimation. On the other hand, the residual variation in gas prices is much higher. This suggests, as indeed the estimates find, that regional cost spreads cannot explain
regional price spreads – since regional prices spreads are much smaller than cost spreads.

4.4. Decarbonization Potential

Understanding market linkages is crucial for designing carbon taxation. Our model brings clear predictions about the impact of such a policy on the market. In the short run, an increase in carbon tax on the highest cost producer is passed through into global prices. This creates additional rents for producers in the lower cost region. In the case of ammonia, the bill will be picked up by farmers or ultimately food consumers worldwide. Identifying pass-through from fertilizer to food prices and thus the potential impact of a carbon tax on food prices and food security is an exciting topic for future research. Would such a tax stimulate investment in energy efficiency? Producers facing a new investment decision are more likely to choose a low-cost region, at least in the ammonia industry.

Suppose instead that a low-cost region, let say US introduced a decarbonization policy for nitrogen, as analyzed i.a. by Bushnell and Humber (2017). Our results show that, as long as emissions costs implied by the carbon tax are much lower than the difference in marginal cost between US and Europe, we expect no pass-through into the price. Carbon tax would be fully paid by the producers. However, at least in a two-region model, such a tax could inspire investment in energy efficiency.

This analysis highlights the important point that, with international linkages and pre-existing drastic cost differences, decarbonization in the short run (through a decrease in quantity demanded) can only be achieved by the high-cost producer. From that perspective, the leading role of the EU in implementing carbon taxation is easy to understand. Europe already has high energy costs, so there is a good chance that further increases will be passed through into prices, hence reducing emissions, even though the success of such a policy depends mostly on the price elasticity of demand. The discussion has also an interesting political economy angle. With drastic cost differences, a further cost increase on the high-cost producer does not reduce profits further. This limits the incentive to lobby against decarbonization policy. This may explain why climate change policy is so difficult to pass in US, especially since the shale gas boom. Carbon tax in US would destroy a lot of rents, while in Europe, there are no rents left to destroy.
4.5. How to define EITE

For policy, it is important to understand which industries are likely to be affected by a potential carbon policy. The current approach is to offer exemptions to Energy Intensive Trade Exposed (EITE) industries. In the EU, the energy intensity dimension is defined by the impact of carbon tax on production costs. An industry falls into this category if direct and indirect costs induced by the implementation of the ETS directive would increase production cost, calculated as a proportion of the gross value added, by at least 5%. The trade exposure component is rather standard: the inclusion criterion is defined as the sector’s trade intensity with non-EU countries (imports and exports) above 10%. Provisions for industries that fall into this category are explained on page [15].

Our analysis shows that those or similar criteria do not provide a sufficient metric to identify the exposed industries. Under the current EU definition, both the EU and US ammonia industry are deemed to be exposed to carbon leakage. However, the impact of a carbon tax differs between the regions. Had US imposed a federal carbon tax (lower than the marginal cost gap), global prices would remain unaffected and the US producers would bear the entire tax burden. Given the high natural gas prices, a carbon tax is passed through in the prices in that region.

Which part of the criterion fails? The energy intensity component is rather uncontroversial, though operationalization of the criterion is beyond the scope of this paper. Thus, it is the trade exposure part of the definition that requires further scrutiny. Our results suggest that “cost pass-through of region-specific cost shocks” could be more informative about potential impacts. If this is low, it indicates that a given carbon price has a small impact on global quantities. Hence the CO2 reduction through the demand channel would also be modest. Such low pass-through can arise for three reasons. First, the affected region could be a small fish in the global industry. Second, the market can be very competitive and domestic output reductions can be quickly offset with imports. Finally, as in the case with the US ammonia industry, the affected region even with additional levies could remain highly profitable. In the absence of feasible, low-carbon technologies such a tax provides little incentives for emissions reductions. In either case, there is not a lot of good news for the environment, though only in the
first two cases, the tax would have detrimental impacts on the competitiveness of the affected industry. High local-cost pass-through is the more promising case. Indeed, in our framework unit, local cost pass-through implies no carbon leakage. This is because full local cost pass-through can only happen if the industry is perfectly competitive and the rivals are at their capacity constraint. For the demand channel of a decarbonization policy, the latter is clearly crucial.

5. Conclusion

We have presented a theoretical mechanism and an empirical assessment of the impact of local cost shocks on an integrated market. Using more than 20 years of data on the nitrogen industry, we confirm the theoretical predictions that market response is non-linear and asymmetric. When local shocks are relatively small, the impact of a local cost shock is mitigated by production reallocation. However, once the shock is large enough such that the producers in the region with cost advantage reach their capacity constraints, pass-through of a cost decrease drops to zero, while cost pass-through of a cost increase is enhanced. This is especially visible after the shale gas revolution when the drastic decrease in input costs did not translate into lower nitrogen fertilizer prices or higher output levels in the US. The US cost advantage led to a significant change at the extensive margin: new production facilities were commissioned, though their impact on the market is yet to be seen as they came on-line at the very end of our sample period.

Our study informs the debate on the impacts of carbon taxation. In contrast to the existing literature, we study the impact of cost differences between geographically distinct regions – continents. Our focus on natural gas downstream markets allows us to explore significant variation in regional cost gap, an order of magnitude larger than for other energy commodities. The results allow us to question the EI-TE paradigm. We highlight that it is not a degree of trade exposure, but rather profit margins that define industry response to carbon taxation.

Finally, we provide illustrative examples of the failure of frequently used pass-through regressions when market linkages hold. The importance of capacity constraints highlighted in this paper provides a challenge for future research as more attention needs to be paid to
corner solutions.

References


FIGURE 1
Ammonia and Natural Gas Prices

(a) Ammonia Prices

(b) Natural Gas Prices

FIGURE 2
Cost-Passthrough: Regional vs. Global Cost Shocks

Source: Authors

FIGURE 3
Structural Break in Marginal Cost Gap

Note: Plot shows $MC_{EUR} - MC_{US}$. Vertical dashed line represents a structural break in July 2008. 
Source: Authors and Bloomberg/Green Markets
FIGURE 4
Production and Marginal Cost Gap

(a) Regional Annual Ammonia Production

(b) Marginal Cost Gap

Note: In panel (a), ammonia production has been calculated adjusting regional nitrogen production data according to ammonia’s 82% nitrogen content. Under label US we include also production data for Canada. EUR represents Western and Central Europe.

Source: Authors, Bloomberg/Green Markets and IFA
FIGURE 5
US-EUR Ammonia Producers’ Stock Price Ratio and Marginal Cost Gap

Note: Stock Price Ratio is the ratio of regional ammonia producer indices (US Producers Index/ EUR Producers Index). More details on indices construction in the appendix. Marginal Price Gap is the difference between regional marginal costs in USD per short ton of ammonia.
Source: Authors and Bloomberg
FIGURE 6
(Dis)Investments in the Ammonia Industry

(a) Plant Expansions and Closures

(b) Marginal Cost Gap and (Dis)Investment decisions

Note: Red lines: disinvestments (plant closures); Green lines: investments (announcement dates for completed/advanced projects; dashed for plant restarts/expansions, solid greenfield/brownfield projects) in the US ammonia industry. Each line represents a single event. Detailed list of all expansion and closure decisions in the online appendix.

Source: Authors. Data on investment decisions collected from various sources.
Appendix

A1. Derivation of Model Results

This section contains the proofs of the propositions discussed in the main text. The set-up is as before.

Consider a perfectly integrated global commodity market, on which output from two regions, $r = A, B$ is sold.

There are $n$ firms globally, of which a share $s_r$ is located in region $r$. Consumers have a linear demand function, such that $P = a - b \cdot Q$. Out of this, quantity $K_F$ is inelastically supplied from a competitive fringe, which we immediately normalize to zero.

Each firm produces at a constant marginal cost, which is determined by the region it is located in. In principle, we could allow marginal cost differ by firm, as long as the difference is sufficiently small that capacity constraints (shutdown or maximal capacity) do not bind for any firm. This would not affect the results. However, for concreteness, we work with a constant marginal cost determined by region.

Let us denote marginal cost in region $A$ by $c + \Delta$, and marginal cost in region $B$ by $c$. So a shock to $c$ represents a global cost shock, while a shock to $\Delta$ is a region-specific cost shock (with region $B$ acting as the reference region).

Each region has a maximum production capacity $K_r$ available. Firms are equally sized, so each firm $i$ has a capacity $k_i = K_r/(s_r n)$ at its disposal. For computational convenience we define capacity constraints proportionally to equilibrium production capacities in a game in which firms in both regions face the same costs (i.e. $\Delta = 0$), i.e. $k_i = q_i^*(1 + \theta)$, where $q_i^*$ is the equilibrium production quantity when $\Delta = 0$ and $\theta$ is the scaling factor.

For each individual firm, we have a profit function which we can solve to get $q_i^*$. We assume symmetric equilibrium within the region, so that firm $i$ located in region $r$ chooses quantity $q_{i,r}$ to maximize profit $\pi_i$. This yields the profit functions for each region:

$$\pi_{i,A} = q_{i,A} \left( a - b(Q_B + Q_{-i,A} + q_{i,A}) - (c + \Delta) \right),$$

$$\pi_{i,B} = q_{i,B} \left( a - b(Q_A + Q_{-i,B} + q_{i,B}) - c \right)$$
where $Q_r$ represents total output in region $r$ and $Q_{-i,r}$ is production of all producers in region $r$ other than firm $i$.

**Interior Solution.** Choosing optimal quantities and assuming within-region symmetry (i.e. substituting $Q_{-i,r} = (n * s_A - 1) * q_i$ and $Q_{-i,B} = (n * (1 - s_A) - 1) * q_i$ into the first order conditions) gives the first order necessary conditions:

\[
q_{i,A} = \frac{(a - b Q_B^* - \Delta - c)}{b (n s_A + 1)},
\]

\[
q_{i,B} = \frac{(a - b Q_A^* - c)}{b (1 - s_A + 1)}
\]

After further substitutions: $Q_A = s_A n q_{i,A}$ and $Q_B = (1 - s_A) n q_{i,B}$ we solve the system of two equations to obtain the equilibrium production at an interior solution:

\[
q_{i,A}^* = \frac{a - c - \Delta (n (1 - s_A) + 1)}{b (n + 1)}
\]

\[
q_{i,B}^* = \frac{a - c + \Delta n s_A}{b (n + 1)}
\]

This strategy profile is an equilibrium only if the capacity constraints in fact do not bind. Therefore, we now check the parameter values for which this condition is satisfied. For each region, we must check the full capacity ($q_i \leq k_i$) and shutdown ($q_i \geq 0$) constraints. Equations 9 and 10 imply that the full capacity constraints are equal in each region and given by:

\[
k_i = \frac{a - c}{b (n + 1)} (1 + \theta)
\]
How to read the notation: if A’s cost disadvantage exceeds $\Delta_A$, then production in region A is shut down. Likewise, if A’s cost disadvantage exceeds $\Delta_B$, producers in region B are at full capacity and cannot increase their output further. Thus, we have to address the question “which constraint binds first” – the own shutdown constraint or the rival’s full capacity constraint.

Binding constraints imply that the quantity produced in the constrained region is fixed (at 0 or $k_i$), thus we can calculate the optimal rivals’ quantities directly from equations 9 and 10.

By comparing constraints defined in equations 12 - 15 we get the general conditions for the order in which constraints bind as $\Delta$ changes:

- $\Delta_B < \Delta_A$ and $\Delta_A > \Delta_B$ if $\theta < \min\left(\frac{ns_A}{(1-s_A) \cdot n + 1}, \frac{(1-s_A) n + 1}{ns_A}\right)$
- $\Delta_B > \Delta_A$ and $\Delta_A > \Delta_B$ if $\frac{ns_A}{(1-s_A) \cdot n + 1} < \theta < \frac{(1-s_A) n + 1}{ns_A}$
- $\Delta_B < \Delta_A$ and $\Delta_A < \Delta_B$ if $\frac{(1-s_A) n + 1}{ns_A} < \theta < \frac{ns_A}{(1-s_A) \cdot n + 1}$
- $\Delta_B > \Delta_A$ and $\Delta_A < \Delta_B$ if $\theta > \max\left(\frac{ns_A}{(1-s_A) \cdot n + 1}, \frac{(1-s_A) n + 1}{ns_A}\right)$

We can read the conditions in the following way: $\Delta_B < \Delta_A$ implies that B’s capacity constraint binds for lower cost increase ($\Delta$) at A than A’s shutdown constraint while $\Delta_A > \Delta_B$ means that A’s capacity constraint binds for a smaller cost decrease than B’s shut down constraint.

When $\Delta_B < \Delta_A$ and $\Delta > \frac{\theta(a-c)}{ns_A}$ (see equation 15), B produces at full capacity and the region cannot increase production for further increases in $\Delta$. Thus A’s production schedule is given by $q_{i,A} = \frac{a-bK_B-c-\Delta}{b(ns_A+1)}$ and the critical value of $\Delta$ that leads to complete shutdown changes to $\Delta = a - bK_B - c = \Delta_A^S = \frac{(a-c)(n\theta s_A+s_A-\theta)+1}{n+1}$.

Similarly, when $\Delta_A < \Delta_B$ and $\Delta < -\frac{a-c}{ns_A}$ (see equation 14), B shuts down, while further decrease in costs in A lead to increase in output level, the production schedule is given by $q_{i,A} = \frac{(a-c-\Delta)}{b(ns_A+1)}$. The critical value of $\Delta$ at which A reaches its capacity constraint is given by $\Delta = \Delta_A^C = \frac{(a-c)(n\theta s_A+ns_A+\theta-n)}{n+1}$.

Market price is calculated by substituting the regional quantities into the price equation.

Depending on the parameters it can take one of the seven forms, as shown below.
\[ P = \frac{a + \Delta ns_A + cn}{n + 1} \text{ if } \max (\Delta_A, \Delta_B) < \Delta < \min (\bar{\Delta}_A, \bar{\Delta}_B) \] (16)

\[ P = \frac{a + cn(1 - s_A)}{n(1 - s_A) + 1} \text{ if } \bar{\Delta}_A < \Delta < \bar{\Delta}_B \] (17)

\[ P = \frac{a + ns_A(c + \Delta) - bn(1 - s_A)k_i}{n s_A + 1} \text{ if } \bar{\Delta}_B > \Delta > \bar{\Delta}_A^s \] (18)

\[ P = a - b(n(1 - s_A)k_i) \text{ if } \bar{\Delta}_B < \bar{\Delta}_A^s < \Delta \] (19)

\[ P = \frac{a + ns_A(c + \Delta)}{n s_A + 1} \text{ if } \Delta < \bar{\Delta}_A^C < \Delta < \bar{\Delta}_B \] (20)

\[ P = a - b(ns_Ak_i) \text{ if } \Delta < \bar{\Delta}_A^C < \bar{\Delta}_B \] (21)

\[ P = \frac{a + cn(1 - s_A) - bns_Ak_i}{n(1 - s_A) + 1} \text{ if } \Delta < \bar{\Delta}_A^C < \bar{\Delta}_B \] (22)

When cost shocks are such that none of the regions is constraint, the price is as in equation 16. As cost shock increases, if \( s_A \) and \( \theta \) are such that \( \bar{\Delta}_B > \bar{\Delta}_A \), region A shuts down before region B reaches its capacity constraint and for \( \Delta > \bar{\Delta}_A \) price is given by equation 17. When capacity constraints are tighter, such that \( \bar{\Delta}_B < \bar{\Delta}_A, \bar{\Delta}_B > \Delta > \bar{\Delta}_A^s \) implies that B produces at full capacity, while A is still in the market, the price is given by equation 18. Further increase in \( \Delta \) makes firms in region A shutdown, and price is given by equation 19.

For negative shocks, when \( s_A \) and \( \theta \) are such that \( \Delta_A^C < \Delta < \Delta_B \), B’s shutdown constraint binds before A reaches its capacity constraint, thus for \( \Delta_A^C < \Delta < \Delta_B \) price is given by equation 20. Further decrease in \( \Delta \) make A reach its capacity constraint, which happens for \( \Delta = \Delta_A^C \). For such a case, the price is given by equation 21. When, A’s capacity constraints are tighter, such that \( \bar{\Delta}_A > \bar{\Delta}_B \), for cost decreases high enough for A to reach its capacity constraint, the price is given by equation 22.

Given the price equations presented in equations 16-22, it is easy to show that whenever region A’s production is at the capacity constraint or at zero, the pass-through is zero. When the shock is non-drastic and both regions produce according to the interior solution, the pass-through rate is \( \frac{ns_A}{n + 1} \), when A’s production is unconstrained and B’s at 0 or \( k_i \), the pass-through increases to \( \frac{ns_A}{ns_A + 1} \).
Return series

Stock return ratios from figure have been created in the following way.

First, we collected data on all ammonia plants in the US and Europe. US plant ownership data is collected from the USGS Mineral Commodity Summaries. Those annual reports list all US ammonia plants and provide owner and capacity data. Similar public data is not available for Europe, thus we have combined two sources. From the EU Emissions Trading System Operator Holding Accounts we have collected data on all installations registered under the main activity type “production of ammonia”. However, this list is not complete, as some ammonia facilities are listed in a broader category “production of bulk chemicals”. Thus, we complement this list with data from the Global Syngas Technologies Council. Although the latter is also incomplete and covers 80-90% of ammonia production capacity, it allows us to identify some facilities missing in the first list. In contrast to the US data, the combined data set does not provide ownership data at the annual frequency for the entire period. Thus, to construct a panel, we have conducted an extensive Internet search following the news on the facilities on the list.

In the next step, we linked the plant owners with their respective stock market tickers, again using Internet search. Subsequently, we collected financial statements of the listed ammonia producers to identify plant owners for which ammonia production is a “core” activity. Since we don’t have data on ammonia revenues specifically, we calculate potential ammonia revenues, i.e. annual capacity multiplied by region-specific ammonia hub price. This measure is clearly imprecise, on the one hand, firms may not use full capacity, on the other, due to transportation costs, producers are likely to charge a premium over the hub price if the facilities are located closer to agricultural areas. However, this crude procedure allows us to remove firms for which ammonia production is clearly only a side activity (e.g. the German-based chemicals giant BASF or the US potash and phosphate producer Mosaic) from our sample. We set the threshold for the potential ammonia revenues from a single region (Europe or US) at 5% of total revenues. Our results are robust to changes to the threshold level.

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23https://www.globalsyngas.org/resources/map-of-gasification-facilities
For each stock in the list, we obtain monthly returns (growth rates of monthly averages for each stock). To create regional indices we use a cumulative product of capacity-weighted averages of returns for each region separately. Since the capacity and ownership data varies year to year, we adjust the weights accordingly.

Two ammonia producers from our sample own production facilities in both regions. As of January 2019, Netherlands based OCI owns (through a partially owned subsidiary OCI Partners) 0.3 mln tonnes of annual capacity in the US, 1.1 mln tonnes in Europe and over 7 mln tonnes in other regions, thus we exclude this company from the sample (though we keep the subsidiary OCI Partners, which owns a facility in the US). Yara AS owns 0.6 mln tonnes in the US, 4.9 mln tonnes in Europe and 3.6 mln tonnes in other regions. Since the majority of the production capacity is located in Europe, we treat the company as a European producer.

Throughout the sample period, we have identified 28 listed ammonia producers in the two regions. 17 were excluded according to the criteria above leaving 8 in US and 3 in Europe. 2005 is the first full year for which we have at least two firms in each region, thus we start our sample in January 2005. List of producers with the number of years in which they were included in the sample and average weight is shown in table A1. Note that the Norwegian producer, Yara, is clearly dominant in the European sample. However, the results remain qualitatively unchanged if we remove that producer from the sample or use equal weights for all producers.
### TABLE A1
**Listed Ammonia Producers**

<table>
<thead>
<tr>
<th>Ticker</th>
<th>Region</th>
<th>Start Date</th>
<th>End Date</th>
<th>Capacity</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>3NB.BG</td>
<td>EUR</td>
<td>2005-01</td>
<td>2016-12</td>
<td>550</td>
<td>0.085</td>
</tr>
<tr>
<td>YAR.OL</td>
<td>EUR</td>
<td>2005-01</td>
<td>2016-12</td>
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**Note:** Capacity is average annual capacity '000 metric tonnes. Actual capacity data and weights used in the analysis change throughout the sample period. Tickers: 3NB:BG - Neochim AD, YAR:OL - Yara AS, ZAP:PL - Grupa Azoty Pulawy SA, AGU - Agrium, ASIX - AdvanSix, CF - CF Industries, LXU - LSB Industries, OCIP - OCI Partners, POT - Potash Corp., RTK - Rentech Inc., TNH - Terra Nitrogen

**Source:** Authors and USGS
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<thead>
<tr>
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<th>Mean</th>
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<th>Max</th>
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<td>Since 2009</td>
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<td>95.59</td>
<td>201.59</td>
<td>486.95</td>
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<td>Since 2009</td>
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<td>3.20</td>
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<tr>
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<td>1.70</td>
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<td>0.00</td>
<td>40.71</td>
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<tr>
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<td>0.00</td>
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<td>Since 2009</td>
<td>10.18</td>
<td>5.27</td>
<td>4.14</td>
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### TABLE A3
Main Regressions: European Ammonia Price

(a) Average Cost Model

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<tr>
<th>Dep. Var</th>
<th>Ammonia Price (Europe)</th>
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<td>Sample Period</td>
<td>Whole</td>
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<tr>
<td>(1)</td>
<td>(2)</td>
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<tr>
<td>Intercept</td>
<td>$-51.45^{**}$</td>
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<tr>
<td></td>
<td>(15.54)</td>
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<tr>
<td>$MC_{US}$</td>
<td>$0.14^*$</td>
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<tr>
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<td>(0.06)</td>
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<tr>
<td>$MC_{EUR}$</td>
<td>$1.05^{***}$</td>
</tr>
<tr>
<td></td>
<td>(0.05)</td>
</tr>
</tbody>
</table>

Cointegration Test

| | ADF Stat | ADF Lags (BIC) | R² | Num. obs. |
| | $-5.21^{**}$ | 3 | 0.79 | 264 |
| | $-3.58^{**}$ | 2 | 0.72 | 144 |
| | $-5.31^{**}$ | 1 | 0.68 | 108 |

(b) Regional Cost Model

<table>
<thead>
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<th>Dep. Var</th>
<th>Ammonia Price (Europe)</th>
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</thead>
<tbody>
<tr>
<td>Sample Period</td>
<td>Whole</td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>Intercept</td>
<td>$168.57^{***}$</td>
</tr>
<tr>
<td></td>
<td>(24.91)</td>
</tr>
<tr>
<td>$MC_{US}$</td>
<td>$0.43^{***}$</td>
</tr>
<tr>
<td></td>
<td>(0.12)</td>
</tr>
<tr>
<td>$MC_{EUR}$</td>
<td>$1.07^{***}$</td>
</tr>
<tr>
<td></td>
<td>(0.05)</td>
</tr>
</tbody>
</table>

Cointegration Test

| | ADF Stat | ADF Lags (BIC) | R² | Num. obs. |
| | $-1.85$ | 3 | 0.05 | 264 |
| | $-5.25^{**}$ | 3 | 0.79 | 264 |
| | $-2.73$ | 2 | 0.62 | 144 |
| | $-3.29^*$ | 2 | 0.65 | 144 |
| | $-2.06$ | 2 | 0.02 | 108 |
| | $-5.19^{**}$ | 1 | 0.66 | 108 |

Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. Engle-Granger Critical Values for ADF Test. Dependendent variable: European ammonia spot price (Yuzhnyy) in $/ short ton. $MC_{EUR}$ and $MC_{US}$ are the regional average marginal costs for Europe and US (in $/ short ton) respectively. Source: Bloomberg/ Green Markets and authors’ calculations. Monthly data 1996.1 - 2017.12 (Whole) with sub-samples 1996.1-2007.12 (Pre-08) and 2009.01-2017.12 (Post-08).
### TABLE A4
#### Pass-Through: Coefficient Restricted to One

<table>
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<td>(1)</td>
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<tr>
<td><strong>Coefficient Estimates</strong></td>
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<td>(4.96)</td>
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<tr>
<td>max(MC_{EUR},MC_{US})</td>
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<tr>
<td>ADF Stat</td>
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<td>Num. obs.</td>
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</table>

*Note:* ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. Engle-Granger Critical Values for ADF Test.

Dependent variable: US ammonia spot price (Tampa) in $/ short ton. max(MC_{EUR},MC_{US}) is the highest of the average regional marginal costs for Europe and US (in $/ short ton) and the coefficient is restricted to 1.

FIGURE A1
US Capacity Utilisation: Reported

Source: Authors and USGS.