Cost Pass-Through with Capacity Constraints and International Linkages

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Acknowledgements

Abstract

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

Topics: Climate change; International topics; Inflation and prices; Econometric and statistical methods
JEL codes: L13, L65, Q54, Q40

Résumé

Les marchés des produits de base sont liés par le commerce international, mais séparés par des règlements et des marchés d'intrants hétérogènes. Nous menons une investigation théorique et empirique de la répercussion des chocs de coûts régionaux – par opposition à mondiaux – sur les prix à l'échelle mondiale. Les contraintes de capacité atténuent l'effet de tels chocs sur la production à court terme. Lorsque effectives, les contraintes accentuent la répercussion d'une augmentation de coût, tandis que pour une diminution de coût, la répercussion devient nulle. Nous étudions le marché de l'ammoniac, un produit de base fabriqué principalement à partir de gaz naturel, pour faire ressortir la non-linéarité de la répercussion des coûts et ses implications pour les politiques climatiques unilatérales.

Sujets : Changements climatiques; Questions internationales; Inflation et prix; Méthodes économétriques et statistiques
Codes JEL : L13, L65, Q54, Q40

1. Introduction

A fundamental question of energy economics is how energy prices are passed through to the price of manufactured commodities. This pass-through has become increasingly complex in recent years. On the one hand, international output prices are now tightly linked through trade. On the other hand, regional fossil fuel prices have diverged—due to shale oil and gas exploitation—and are set to diverge even more as a consequence of climate policies. We argue that in this environment, the pass-through of energy prices to refined commodities is directly linked to the region's capacity to respond to local cost shocks.

This paper studies theoretically and empirically how a local cost shock in one region affects global market prices in a setting with imperfect competition and capacity constraints. We find that for large local cost shocks, the pass-through is non-linear and asymmetric. In the short run, cost decreases are less likely to be passed through than cost increases as capacity constraints limit producers' ability to respond to lower prices. In the long run, capacity is diverted to the low-cost region and the asymmetry is reversed: regional cost decreases are passed through while increases are not.

We apply the model to the market for ammonia, the elementary compound of the nitrogen fertilizer industry and a key ingredient in global food production, whose marginal costs depend almost entirely on natural gas prices. We show that prior to 2008, North American ammonia producers held significant spare capacity and, jointly with their European competitors, acted as a marginal producer in the global market for ammonia. As the shale gas revolution caused local input prices to fall, North American producers increased production to capacity. Consistent with our theoretical predictions, we find that a significant fraction of local cost shocks are passed through prior to 2008, but that the pass-through decreases to zero as the industry reaches capacity constraints. We also find evidence for a long-term reallocation of capacity towards North American producers.

Our model explains why, contrary to common predictions based on historical pass-through estimates (see, e.g. Fowlie et al., 2016b; Mason et al., 2015; Bushnell and Humber, 2017), falling US energy prices failed to trigger reductions in the price of energy-intensive manufactured products. The ammonia market studied in this paper provides a particularly striking exam-

ple for this effect since its marginal production costs depend almost entirely on natural gas prices. However, a similar dynamic has been observed in other industries, such as gasoline, where falling costs relative to other markets have not translated into lower relative product prices (Hausman and Kellogg, 2015; Borenstein and Kellogg, 2014; Muehlegger and Sweeney, 2021). We show formally that the combination of global integration in refined goods markets, along with a limited capacity of North American producers to exploit lower fossil fuel prices, accounts for this pattern.

The importance of distinguishing between global and local shocks has been recently highlighted by Muehlegger and Sweeney (2021) for the case of the US oil refining market. In line with previous studies, they find that the pass-through of industry-wide cost shocks is typically around unity (Gaarder, 2019; Lade and Bushnell, 2019). For shocks to individual firms, on the other hand, competition limits pricing power and hence the pass-through. This analysis, however, ignores the role of market linkages and capacity constraints.

A key insight from our paper is that with capacity constraints, the standard Cournot model breaks down for large enough local cost shocks. In this model, cost shocks affect the market price through changes in firms' output decisions. Once capacity constraints bind, producers no longer respond to further cost changes and the market price is instead determined by other, higher-cost producers that are not affected by the local shock. This has significant implications for the empirical specification of pass-through models. Popular Cournot-type panel models with one-way fixed effects (Miller et al., 2017) or two-way fixed effects (Ganapati et al., 2020), or models that distinguish between shocks to firms' own or rival costs (Muehlegger and Sweeney, 2021), become unsuitable when the regional cost shock is sufficiently large. In our empirical application to the market for ammonia, we demonstrate this effect directly.

These results have significant implications for the nascent empirical literature on the impact of carbon taxation on emissions-intensive trade-exposed industries. Policy goals, such as the European Union's pledge to reach climate neutrality by 2050, are expected to be achieved largely by curbing demand through higher effective prices of fossil-based energy. However, in the absence of a global framework, carbon taxation and other policies that affect production costs are likely to remain local. Our findings indicate that linear extrapolations of ev-

idence for relatively small shocks to the US cement industry (Fowlie et al., 2016a) or from early phases of the EU Emissions Trading Scheme (e.g., Naegele and Zaklan, 2019; Koch and Mama, 2019) might fail to hold for larger regional cost shocks that cause producers to reach capacity constraints. Our results thus provide a cautionary tale for the ongoing debate around emissions-intensive trade-exposed industries and climate policies.

In our model, the law of one price holds for tradable final goods but can diverge for non-tradable inputs. Standard trade models, such as the Heckscher-Ohlin model, predict that in this setting the production of goods should shift into the region more abundant in non-tradable input factors. A key difference to the classic setup is that we focus on the pass-through of regional shocks in the context of short-term capacity constraints. Our paper thus contributes to the literature of cost shocks to non-tradable energy inputs, which typically does not consider capacity constraints (see, e.g., Fontagné et al., 2018). Moreover, by applying the model to an upstream industry where almost the entire variation in producers' marginal costs originates from regional energy prices, we provide a particularly suitable empirical illustration of the resulting effects.[1]

The importance of capacity constraints in identifying the marginal producer has previously been pointed out for other markets, such as electricity generation (see, e.g. Fabra and Reguant, 2014; Hintermann, 2016; Linn and Muehlenbachs, 2018). In electricity markets, the market clearing price is typically derived by intersecting the so-called merit curve—the cost-ordered, capacity-weighted supply curve—with the demand curve. How a change in energy generation costs is passed through to electricity prices depends on the position of the affected plants in the merit order. We show that market linkages make similar logic applicable to internationally traded commodities that, at first glance, might not appear to fit the nature of the strict dispatch order in electricity markets.

Changes in the marginal producers due to capacity constraints have also been identified for local petroleum markets in the context of pipeline and refining constraints (Borenstein and Kellogg, 2014; Kaminski, 2014; McRae, 2017), as well as in the literature on the exchange-rate

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[1]By contrast, related studies using data from manufacturers (see, e.g., Amiti et al., 2019) need to contend with the issue that some cost shocks could originate from internationally sourced inputs and thus might be correlated across firms.

pass-through. There, optimization decisions of producers along the supply chain are shown to lead to incomplete cost pass-through when the supplier change is not accounted for (Dixit, 1989; Gron and Swenson, 2000; Hellerstein and Villas-Boas, 2010). It has been speculated that capacity constraints could contribute to the observed non-linearity of the pass-through (Knetter, 1994; Bussiere, 2013). We contribute to this literature by introducing a formal model that highlights the role of capacity constraints. By focusing our analysis on an industry that is particularly intensive in emissions and on both the short- and long-run implications of cost changes, we provide further evidence that is particularly relevant for the consequences of climate policies.

2. A Theoretical Model of Pass-Through with Capacity Constraints and 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 different impact on markets than global cost shocks. Second, regional cost shocks lead to a 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 the cost pass-through of a local cost decrease and strengthen the impact of a local cost increase on global prices. Third, for permanent regional cost shocks, capacity may eventually move across regions. Consequently, the long-run pass-through is qualitatively different from the short-run pass-through.

To investigate these mechanisms, we build on the canonical Cournot model. Our key extensions are to allow for cost heterogeneity and for 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 Δ is a region-specific offset (which may be positive or negative). Thus, we refer to changes in c as a "global cost shock" and changes in Δ as a "regional cost shock" in the remainder of the paper.

The key objective of the model is to investigate the impact of changes in the marginal cost in one region, Δ, on markets in *both* regions. We also examine reallocation of production and

investment between regions, as well as the impact of Δ on firm valuations. We next discuss the key assumptions of our analysis.

Market linkages: Markets for the output good are completely integrated and the law of one price holds, implying there are no price spreads between regions. The baseline model thus abstracts from transportation costs. In the appendix, we show that this assumption can be lifted without changing the qualitative results.[2] Marginal costs, however, are allowed to differ between regions. Marginal cost differences can arise for different reasons, such as regional climate policies or localized supply shocks, such as recently observed during the US shale gas revolution.

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 θ. Producers have the option to shut down production, so the minimum production in each region is zero.

The remaining model setup is 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 provided in Appendix A1, while a summary of the model with transportation costs is shown in Appendix A5.

The first result to emerge from the theoretical framework is that regional cost shocks have a weaker effect on market prices than global shocks.

Proposition 1. *The pass-through of a regional cost shock is weakly lower than that of a global cost shock; that is,*

$$\frac{dP}{d\Delta} \leq \frac{dP}{dc}. \tag{1}$$

The result is intuitive. In the case where the solution is interior, the Cournot price is a weighted 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 between regional and global cost shocks,

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[2]Transportation costs affect the value of trade between the markets, but do not alter the key insights from the model discussed below.

a point that has recently also been highlighted by Muehlegger and Sweeney (2021).[3]

The distinction between local and global shocks also has consequences for the role of capacity constraints. In our framework, 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 different from the situation with global cost shocks, where quantities in each region move in the same direction and quantity reactions of individual regions are hence smaller.

A key objective of this paper is to investigate cases in which capacity constraints bind. For arbitrarily large values of θ, spare capacity would be so large that no possible regional cost shock could cause this constraint to bind. We thus make the mild assumption that there is a regional cost shock Δ, such that the capacity constraint becomes binding.

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

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

We can now characterize the short-run pass-through of a regional cost shock. Our central result is that 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 follows:*

1. *If $\Delta < \underline{\Delta}_A^C$, region A has a large cost advantage and produces at its capacity constraint; there is no pass-through of local cost shocks:*

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

2. *If $\underline{\Delta}_A^C < \Delta < \overline{\Delta}_B^C$, both regions produce positive quantities and neither region A's nor region B's capacity constraints bind. There is a intermediate level of pass-through:*

   $$dP/d\Delta = s_A \times n/(n+1).$$

3. *If $\overline{\Delta}_B^C < \Delta < \overline{\Delta}_A^S$, region B is capacity constrained, so marginal quantities can only be*

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[3]In Section 5.3, we discuss the implications for standard pass-through regressions in detail.

produced by region A. Accordingly, pass-through increases to

$$dP/d\Delta = ns_A/(ns_A + 1).$$

4. If $\overline{\Delta}_A^S < \Delta$, region A shuts down production and there is no pass-through:

$$dP/d\Delta = 0.$$

These results are shown in Figure 1. When the regional cost shock is small ($\underline{\Delta}_A^C < \Delta < \overline{\Delta}_B^C$, represented by the mid-section of Figure 1), production in both regions is unconstrained. Producers respond to price changes by adjusting production levels and the global price is determined by world-average marginal cost. This is the interior solution of the Cournot model corresponding to standard econometric models.

However, as the cost advantage of region A rises—that is, Δ becomes more negative and falls below $\underline{\Delta}_A^C$—firms in region A will eventually produce at full capacity. Once full capacity is reached, any further reductions in cost cannot stimulate production. This lack of quantity response implies that there is no cost pass-though for any further change in local production costs. Thus, when the local cost advantage is sufficiently large, global prices are fully determined by the marginal costs of producers not affected by the shock.

Non-linearities in the cost pass-through of a local shock also arise in the case of large shocks increasing regional costs (positive Δ). Consider the situation of a large cost disadvantage for region A. As Δ increases, region A reduces production while region B increases production. At some point, rival region B will produce at full capacity, shown in the figure as the section $\overline{\Delta}_B^C$. For further cost increases, A will continue to reduce output, but at a slower rate since competitors in B do not increase their production anymore. Hence, the cost pass-through is increased in this segment.

Finally, with sufficiently strong cost disadvantage, production in a region may cease entirely, which again sets the local cost pass-through to zero. 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 and the empirical chal-

lenge is to estimate the slope coefficient. However, with regional shocks, corner solutions of the model are much more likely to be reached. The slope coefficient capturing the effect of local shocks varies depending on market conditions, in particular on whether the solution to the market equilibrium is an interior (slack capacity) or a corner solution (capacity constrained).

An interesting corollary from the results on the short-run pass-trough is that regional cost shocks may have a stronger impact on firm profitability and valuation than on market prices. For example, in the case of a large cost advantage, additional changes in marginal cost do not affect output and market prices (i.e., the pass-through is zero). Unit profitability, however, is still affected one-for-one by cost shocks. This implies that valuations of firms might still respond to such shocks, in particular if investors expect them to be persistent. In our empirical section, we provide direct evidence for this effect.

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. As the higher-cost region eventually loses all production capacity, there can be no cost pass-through of a local cost increase. By contrast, the lower-cost region eventually attracts all firms, so the pass-through of a negative regional cost shock exactly coincides with that of a global shock in the long run.[4]

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

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

Taken together, our theoretical results highlight two important points. First, for regional shocks to affect market prices, a reallocation of production is necessary. However, in the short run, such a reallocation might not be possible as capacity constraints are likely to bind. These constraints introduce a non-linearity in the pass-through by modifying the short-run price impact of local cost shocks.

Second, the short- and long-run effects of local cost shocks are very different. A regional

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[4]In the long run, one might also expect that the input prices adjust to close the gap in marginal cost between the regions. However, examples from many segmented input markets, such as labor, show that such adjustment takes place at a very slow rate. The long-run predictions of our model continue to hold as long as either of the adjustments takes place sufficiently slowly.

cost decrease has a stronger pass-through effect in the long run than in the short run. This makes it difficult to extrapolate long-run effects from estimates based on short-run data. In our application to the ammonia market, we provide empirical evidence both for the non-linearity of the short-run pass-through induced by capacity constraints and for the long-run reallocation of production.

3. Application to the Ammonia Market

We apply our theoretical model to the market for ammonia, a synthetic gaseous compound produced mainly from natural gas. Ammonia is the basic building block for all nitrogen products, including fertilizer, and hence is the foundation of the nitrogen industry. It plays a particularly crucial role in global food production as there are currently no suitable substitutes for nitrogen fertilizers.[5] The importance of ammonia is likely to grow in the future, as it is an efficient carrier of zero-emissions energy and potential fuel, especially for the maritime industry.

The ammonia market is well-suited for our empirical application for several reasons. First, it is one of the markets that has been most strongly affected by the relative decline of US natural gas prices, which allows us to study the effect of large regional cost shocks. Second, most of ammonia is produced with a common, fixed technology across regions, which facilitates the comparison of differences in regional marginal costs. Third, by the standard emission-intensive trade-exposed criteria, the ammonia industry is one of the most exposed industries to region-specific climate policy. Hence the case of the ammonia industry is particularly relevant for the evaluation of such policies. This section further describes the ammonia industry and how it relates to our theoretical setup.

3.1. Ammonia Market Background

Ammonia is a synthetic gaseous compound made up of the elements nitrogen and hydrogen. It is one of the largest-volume synthetic chemicals produced globally. In 2021, total world ammonia production was about 183 million metric tonnes (USGS, 2022). The largest share of this output is used as fertilizer, either in direct field application or after upgrading it into

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[5]Other key nutrients—potassium and phosphorus—are complements in plant growth.

other fertilizer compounds, especially urea.[6] In fact, ammonia plays a critical role in global food production. Nitrogen fertilizer products make up more than 80% of global fertilizer consumption (Yara, 2017), and it is estimated that more than 40% of world grain production is enabled by fertilizers (Roberts et al., 2009).

Most ammonia is produced through the synthesis of hydrogen obtained through the reforming of natural gas using the Haber-Bosch process, an energy-intensive process that allows for the fixation of nitrogen from the atmosphere through a reaction with hydrogen. Ammonia can be also produced through gasification of other feedstock carbohydrates, such as coal and naphtha, or by using hydrogen produced through electrolysis of water. The latter production process allows for the production of zero emissions ammonia if renewable energy is used. As of 2022, no large-scale production facilities exist based on water electrolysis, however such facilities are scheduled to start production in the coming years.

Ammonia synthesis occurs in designated plants under very high temperatures and pressure. Natural gas costs account for up to 90% of total ammonia production costs (Boulamanti and Moya, 2017), making this industry particularly suitable for studying the pass-through of energy prices. The ammonia industry is a process industry with roughly constant marginal costs up to capacity constraints. This feature greatly simplifies our empirical analysis, as it allows us to approximate marginal costs by the local price of natural gas.

Production in multiple regions: Ammonia production is fragmented in a large number of firms. This is facilitated by the fact that the production inputs—air, fossil fuels, and capital—are available in many locations. Moreover, economies of scale are limited. Globally, the ten-firm concentration ratio in the ammonia market is 19% (PotashCorp, 2014). [7]

High capital and transportation costs and the strategic importance of nitrogen for food security ensure that ammonia production is geographically spread, and less than 10% of ammonia production is traded internationally. Nevertheless, as Figure 2 (a) shows, the market remains tightly integrated, resulting in synchronized international ammonia prices.[8] As of

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[6]About 20% of ammonia production is consumed in the chemical industry to produce products such as pharmaceuticals, plastics, textiles, or explosives.

[7]According to USGS capacity data for US ammonia producers, the Herfindahl-Hirschman Index over our sample period is below 2100 for any year, indicating only a moderate market concentration.

[8]However, this low trade share has lead the existing literature on nitrogen prices to essentially neglect trade

2013, Europe and North America held 15% and 10% of global ammonia production capacity respectively (International Fertilizer Association, 2021). Since the late 1990s, the regions have become major importers of ammonia and account for approximately 60% of global ammonia imports.[9] Since those large producers are also the main importers, economic theory suggests that the global ammonia price is set on those markets.[10] This view is also shared by market participants (see, e.g., Yara, 2017, 2012; Huang, 2007).[11]

Segmented input markets: While the market for ammonia is integrated, natural gas markets are geographically segmented as non-pipeline shipments of natural gas are costly and very limited over our sample period.[12] Particularly relevant for our empirical setting, there are no US non-pipeline exports of natural gas prior to 2014. Reflecting this market segmentation, North American natural gas prices are up to five times lower than European prices in the wake of the shale gas revolution.

Common technology: The production technology is provided by external engineering and construction companies that offer proprietary designs for ammonia synthesis plants. The differences in the energy efficiency between the technologies are small, implying that the many ammonia producers around the globe essentially share a common technology. This is similar to oil refining, where a barrel of crude oil yields a similar quantity of gasoline, diesel, or jet fuel.

Constant marginal cost: As is typical for a process industry, ammonia production lines tend to operate continuously at a constant rate, stopping only once a year for a few days for maintenance. The output rate is defined by the plant design. In theory, the output can be

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(see, e.g., Beckman and Riche, 2015; Etienne et al., 2016; Bushnell and Humber, 2017).

[9]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 ranges between 20% and 30%.

[10]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, which specializes in ammonia production and processes most of its natural gas into that commodity, all the largest net ammonia exporters are also among the largest net natural gas exporters (Gaulier and Zignago, 2010). This allows us to treat the EU and the US as the price-setting regions.

[11]For example, Yara, a leading ammonia producer, writes in their handbook that "[i]n general [...] there tends to be a 'supply-driven' fertilizer market in which the established 'price floor' indirectly determines fertilizer prices. This price floor is set by the producing region with the highest natural gas prices. Historically the highest gas prices have been in the US and in Western Europe" (Yara, 2012).

[12]Although LNG trade tripled between 2000 and 2018, LNG trade still amounted to just above 1% of the global natural gas consumption in 2018. Over two-thirds of the global LNG trade is delivered to South-East Asia.

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 and re-opening rather than through changes in the process parameters.

Fixed capacity: Construction of a new ammonia plant is costly, in the range of $1000–$2000 per ton of annual capacity, and completion of a greenfield project takes a minimum of three years. Upon completion, plants remain in operation with minor upgrades for as long as 50 years or more. Thus, short-run capacity adjustments are practically impossible.

Energy efficiency: Energy efficiency is a crucial determinant of marginal cost. Since producers around the world use a common technology, there are relatively small differences in efficiency between 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 for by lower natural gas prices.

Transportation costs: Ammonia transportation costs are generally non-negligible and transatlantic freight rates typically stay above 50 USD/t. However, as there is virtually no direct ammonia trade between the US and Europe, what matters from a modeling perspective is the difference in freight costs from the low-cost ammonia exporting regions to Europe and the US. Data from market intelligence firms confirms that this difference remains very small and the cost ranges provided frequently overlap.[13] This justifies the assumption of zero transportation costs in the baseline model.

Other inputs: Although natural gas is by far the main input, the production of ammonia also requires electricity, cooling water, chemicals, catalysts, and labor. Furthermore, the Haber-Bosch process generates excess carbon dioxide (CO_2), which brings co-product revenues. We do not account individually for those marginal cost components. Instead, we rely on a detailed micro-costing study (Boulamanti and Moya, 2017) of 116 ammonia production

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[13]For example, Argus (2018) reports freight rates from Point Lisas (Trinidad and Tobago) to the US Gulf in the range of 37–47 USD/t and to NW Europe in the range of 44–56 USD/t.

facilities around the world. The study reveals that those costs are similar around the world. In 2013, these costs were estimated to be \$59.8 per ton in the US and \$68.1 per ton in Europe.[14]

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

Although the producers have been allocated free permits, firms have an opportunity cost reflected by the price at which permits can be sold in secondary markets.[15] 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 January 1, 2013. After that date, EU emission costs are calculated based on the carbon content of natural gas, which is 53 kg per MMBtu, and emissions prices. With the estimated technology, the production of one short ton of ammonia requires surrendering 30.1 * 0.053 = 1.595 permits.

Marginal costs: The particular nature of the ammonia industry described in this section justifies the use of a linear marginal cost function. Unit marginal cost is a sum of three components: feedstock cost, determined by 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. We therefore calculate regional marginal production costs of a short ton of ammonia via[16]

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[14]We convert values reported in (Boulamanti and Moya, 2017) from euro to US dollars using the average exchange rate in 2013.

[15]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.

[16]The calculations assume that firms are homogeneous within a region. In reality, ammonia producers differ with respect to their efficiency even within regions. As a consequence, individual firms might react differently to a shock and regional weighted average marginal cost does not necessarily change linearly with natural cost. This effect could introduce a certain degree of bias in our results.

$$MC^{EU} = \begin{cases} \$68.1 + 30.1 * \text{Natural Gas}^{EU} & \text{before 2013} \\[2em] \$68.1 + \underbrace{30.1 * \text{Natural Gas}^{EU}}_{\text{Feedstock Costs}} + \underbrace{1.595 * \text{CO2}^{EU}}_{\text{Emissions Costs}} & \text{since 2013} \end{cases}$$

where natural gas is the price of natural gas per MMBtu, CO2 represents the unit costs of European Emission Allowances, and the superscripts EU and NA stand for Europe and North America, respectively.

3.2. Data

Our empirical applications focus on the role of capacity constraints in explaining the pass-through from natural gas prices around the US shale gas revolution. The sample period runs from January 1996 through to December 2017. We combine data from various sources, as detailed here.[17]

Ammonia prices: We obtain monthly spot prices of ammonia for different locations through Green Markets (Bloomberg). The series includes the major import markets, in particular US and Western Europe, as well as the ammonia export market, such as the Caribbean and the Middle East.

Natural gas prices: US natural gas prices are measured by Henry Hub (Louisiana) spot prices, as nearly 50% of the North American ammonia production is concentrated in the hub's proximity (i.e., in Louisiana, Oklahoma, and Texas). Since the European natural gas market is dominated by contract rather than spot prices during our sample period, we use long-term contract prices based on Platt's formula to measure European prices.[18]

Production quantities: Annual data on ammonia production for North America and Europe is

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[17]Unfortunately, no data on the marginal costs and production for individual North American and EU firms or plants exists for our sample period. However, the nature of ammonia production, in particular the crucial role of natural gas costs for marginal costs, allows us to test the key implications of our theoretical model from readily available market prices for natural gas and ammonia.

[18]According to the International Gas Union, only 15% of the natural gas purchased in Europe in 2005 on the wholesale market was determined by spot prices, while 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.

obtained from USGS.

Capacity utilization rates: Aggregate utilization rates for North America are obtained from USGS. For Europe, we combine USGS country-level production data with data from market intelligence reports on production capacity in Europe. Moreover, we have also gathered plant-level data on utilization rates for North American ammonia plants collected from annual company reports and Sec Form 10-K filings for publicly traded ammonia producers.[19][20]

3.3. Shale Gas Revolution, Capacity Constraints, and Market Regimes

Shale gas revolution: The shale gas revolution has had an drastic impact on the nitrogen industry in North America. According to the US Energy Information Administration, US shale gas production started to increase in 2006, augmenting production from around 60,000 MMcf per day in 2005 to near 90,000 MMcf per day in 2017. As a result, the Henry Hub natural gas price fell over the period, from a yearly average of $8.7 per MMBtu in 2005 to below $3 MMBtu in 2017. This caused an important shift in marginal production costs of ammonia between average Northern American and European producers. Figure A1 shows that prior to 2006, the cost of producing a ton of ammonia was around $60–$70 higher in North America. By August 2008, the relative costs of North American producers were approximately $100 lower and remained below that level until early 2016. Structural break tests for the series of marginal cost differences based on the Bai (1994) procedure confirms the existence of a structural break in the series around 2008.

Capacity constraints: The key mechanism highlighted in this paper relies on the idea that large enough cost shocks can push producers to their capacity constraints. This is indeed the case for North American producers over our sample period. Prior to 2007, producers had substantial slack and produced well below their capacity constraints. Figure A1 presents the evolution of production capacity and capacity utilization for the US and Europe. It shows that while capacity in both regions evolved very smoothly, USGS-reported capacity utilization in the US changed from a rate of about 60% in the early 2000s to a constant high utilization rate

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[19]Since the vast majority of European ammonia producers are privately owned, it was not possible to collect similar data for Europe.

[20]The reporting only comprises a sub-sample of plants held by publicly traded companies and is not consistent across companies. We therefore use the data only to provide descriptive evidence on changes in North American utilization rates but not in the formal econometric analysis.

of over 80% after the shale gas revolution. Meanwhile, European utilization rates remained at lower levels of about 70% throughout the sample period. Figure A3 presents further evidence for substantial changes in North American capacity utilization from corporate reports on publicly traded companies. It shows that prior to 2007, fewer than 70% of plants for which we obtained this information produced near capacity.[21] After the beginning of the shale gas revolution, almost all plants produce at full capacity and there is no systematic excess capacity. Moreover, the existence of excess capacity can also be gauged by the closure of plants, which reduced the number of operating plants from 37 in 2001 to 22 in 2007. This trend reversed with the shale gas revolution, with a gradual reactivation of idled plants. The information on capacity utilization obtained from various sources thus supports the idea that North American ammonia producers have operated at capacity after about 2007. It is also consistent with the substantial cost advantage that North American producers have over their European competitors.

Market regimes: The early period of the shale gas revolution coincided with the period of the global commodity boom and bust that was primarily driven by demand. US ammonia prices nearly tripled from \$292 in November 2007 to \$844 in September 2008, falling to \$113 just four months later, to about half of the marginal cost at that time. Periods of economic boom are important for producers to recover their capital expenditure; however, they are not captured in the standard Cournot model in which the parameters of the demand function are kept constant and may also adversely affect estimates of pass-through coefficients (Bushnell and Humber, 2017). In the main specification, we therefore include dummy variables for the period between January 2007 and July 2009. We also show that the timing assumption is not crucial, as our results are robust to alternative definitions of the boom-and-bust period. Taken together, we distinguish between the following three market regimes: slack capacity (January 1997–December 2006), commodity boom and bust (January 2007–June 2009), and full capacity (July 2009–December 2017).

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[21]Due to maintenance and other production outages, total reported production can be below nameplate capacity even when plants operate at full capacity. The figure assumes a threshold of 80% nameplate capacity to define full capacity.

3.4. Empirical Strategy

Our main empirical strategy focuses on the short-run predictions of the theoretical model.[22] Following the theoretical setting, we break down the pass-through in a component reflecting global costs, (c_t), and a component reflecting local costs, (Δ_t). To obtain the pass-through during the various regimes identified in the previous section, we estimate the equation

$$P_t = \sum_{i=S,B,F} D_t^i \times (\alpha^i + \beta_1^i \cdot c_t + \beta_2^i \cdot \Delta_t) + \epsilon_t, \tag{2}$$

where D_t^i is a dummy variable taking on the value 1 in each of the following regimes: $D_t^S = 1$ before January 2007 (slack capacity), $D_t^F = 1$ after June 2009 (full capacity), and $D_t^B = 1$ between January 2007 and June 2009 (boom-and-bust period).[23] Consistent with our theoretical model, our baseline specification restricts $\beta_1^S = \beta_1^F$; that is, we maintain the same pass-through coefficient for global cost shocks for the slack and the full-capacity period, while allowing the coefficients on the local shock to vary with the market regime.

The theoretical model from Section 2 makes several predictions regarding the pass-through coefficients in Equation 3. First, according to Proposition 1, we expect the coefficient on local cost shocks in the unconstrained regime, β_2^S, to be smaller than the coefficient on the global shock, β_1. Second, from Proposition 2, we expect the marginal effects from local cost shocks in the constraint regime, given by β_2^F, to be close to zero. Third, the linkages between international ammonia prices imply that the pass-through is similar for different ammonia price benchmarks. Finally, existing evidence suggests that the pass-through of global cost shocks in most industries is close to unity, which would imply that β_1 is roughly equal to one.

For the empirical implementation, we define

$$c_t = MC_t^{EUR} - \overline{MC^{EUR}},$$

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[22]Because the long-run adjustments to regional cost shocks can play out over several decades, they are more difficult to evaluate with limited historical data. Still, the subsequent sections provide additional evidence from plant closures and openings, as well as firm valuations, that are consistent with the long-run implications of our theoretical framework.

[23]As discussed in the previous section, including a dummy for the 2007–2009 commodity boom-and-bust period is important to avoid contaminating the coefficient estimates with observations from a period that was primarily demand-driven and characterized by outliers (Bushnell and Humber, 2017). We show in Appendix Table A3 that the results are robust to alternative dates defining the different regimes.

where MC_t^{EUR} stands for marginal cost of an average marginal producer in period t, while $\overline{MC_t^{EUR}}$ is the average marginal cost over the analyzed period. In a similar fashion, we define the local shock as the difference between the US and European marginal cost in period t:

$$\Delta_t = MC_t^{US} - MC_t^{EUR}.$$

This definition, which uses European marginal costs as a proxy for the global cost shock, is justified because European natural gas prices are consistently based on long-term oil-linked contracts throughout our sample period.

4. Empirical Results

4.1. Cost Pass-Through

The main empirical results are shown in Table 1. The first column displays the estimates for the pass-through to US ammonia prices. The point estimate pertaining to global cost shocks is close to unity, suggesting that changes in marginal costs that are common to both regions are fully passed on to ammonia prices. Consistent with our theoretical framework, we find that the pass-through of local cost shocks varies depending on whether or not producers are capacity constrained. For the period with slack capacity, we obtain a statistically significant estimate of 0.41. It indicates that prior to the shale gas revolution, about 40% of idiosyncratic changes in North American natural gas costs were passed on to ammonia prices. For the period following the US shale gas revolution, the point estimate drops to -0.16 and is not significantly different from zero. This suggests that there is no further pass-through of idiosyncratic changes in North American natural gas costs once producers are operating at full capacity. Taken together, these results corroborate the key insights of our theoretical model. They show that the pass-through of local cost shocks is generally different from that of global costs and depends crucially on producers' ability to adjust output.

Columns 2–4 show the impact of the global shock and the shock to North American producers on ammonia prices at an import hub in Europe and two export hubs located in the Middle East and the Caribbean, respectively. Although the point estimates differ slightly across specifications, the overall results closely mimic those obtained for US ammonia prices. For all specifications, the r-squared is 80% or larger, indicating good explanatory power of our

model for all ammonia price benchmarks. The robustness to the location is intuitive since international ammonia prices are tightly linked through trade. It reflects the fact than when the law of one price holds, the pass-through is similar for all price benchmarks.

TABLE 1

Cost pass-through of local shocks under slack and full capacity

| Dep. Var | Regional Ammonia Price | | | |
	USA	Europe	Middle East	Caribbean
	(1)	(2)	(3)	(4)
Coefficient Estimates				
Global Shock (c_t)	1.02***	0.97***	0.88***	0.99***
	(0.07)	(0.05)	(0.07)	(0.07)
Local Shock (Δ_t, Slack Capacity)	0.41***	0.25***	0.33***	0.47***
	(0.06)	(0.05)	(0.06)	(0.07)
Local Shock (Δ_t, Full Capacity)	−0.16	−0.09	−0.17	−0.20
	(0.11)	(0.09)	(0.12)	(0.11)
R^2	0.84	0.85	0.80	0.82
Num. obs.	264	264	264	264

Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. Dependent variable: Ammonia spot price in a given region in \$/ short ton. Slack Capacity is defined as period 1996.1-2006.12, Full Capacity as period 2009.07-2017.12. Values for coefficients in period 2007.01-2009.06 are not reported.
Source: Bloomberg/ Green Markets and authors' calculations. Monthly data 1996.1 - 2017.12.

4.2. Robustness

The results obtained from our baseline estimation are robust to different regression specifications, to alternative definitions of the various regimes, and to the addition of demand shifters. Our first set of robustness exercises, displayed in Appendix Table A2, considers different regression specifications. In contrast to the baseline model, we allow the coefficient on the global shock to vary between the periods in which the North American producers were operating at full capacity or had some slack capacity. As shown in columns 1 and 3, this affects the point estimates for the pass-through of global shocks during the slack regimes, but not the qualitative conclusions. Moreover, when we restrict the coefficient on the local cost shocks to zero during the full capacity regime (columns 2 and 4), the pass-through coefficient on the global coefficient is near unity again.

In a second set of exercises, shown in Appendix Table A3, we allow for various definitions (timing) of the commodity boom, testing various combinations of commodity boom start and end dates. The results show that this only affects the pass-through coefficients during the commodity boom periods, but hardly affects the point estimates and significance of the pass-through coefficients during the slack- and full-capacity period.

Finally, we control for various demand shifters such as food price index, regional GDP growth, regional food production growth, and regional population growth, as well as lagged values of those variables. Except for the food price index, all variables are on a regional level (separately for Europe and North America) and in annual frequency. The food price index is a monthly global variable. In the specification with lags, we use 12th lag for the annual variables and 4th and 12th lag for the monthly variables. The results are presented in Appendix Table A4. Again, these robustness tests do not qualitatively change our key result. In all specifications, the pass-through of the local costs shock is significant in the period before the shale gas revolution. Once producers are at their capacity limit, the point estimate becomes zero or even negative, indicating that there is no cost pass-through from local shocks during the full-capacity regime.

4.3. Response of Quantities to Cost Shocks

Our results so far confirm the theoretical prediction that the pass-through of cost shocks decreases as producers operate at full capacity. In the Cournot model with capacity constraints, the non-linearity arises because producers operating at full capacity are unable to bring output to the desired level. This section provides further evidence for this mechanism by investigating the response of quantities to cost shocks.

Appendix Figure A4 presents the regional production levels in North America and Europe against the size of the local shock in North America. It shows that before 2006, both North American and European production decreases with approximately a linear trend. However, in that period, adverse costs shocks in North America in 2000 and 2005, in line with the Cournot model, are associated with some production relocation from North America to Europe. In the period after 2006, once the permanent cost gap between the region opens sharply, North American production increases by nearly 20% and remains at this level until the end of our

sample, seemingly not responding to changes in the cost gap between North America and Europe.

We estimate the effect of marginal cost changes on quantities via the the panel regression

$$\text{Production}_{t,r} = \sum_{i=S,B,F} D_t^i \times (\rho^i \cdot MC_{t,r}) + \gamma_t + \delta_r + \epsilon_{t,r}, \tag{3}$$

where r indicates the region (North America or Europe), $i = S, B, F$ indicates the three different regimes previously identified, and δ_r and γ_t are region and time fixed effects, respectively. In a two-region panel setting, the ρ coefficients can be interpreted as the quantity impact of regional cost differences (i.e., the local cost shock).

TABLE 2
Ammonia Production Quantities: Panel Regressions

Dep. Var	Ammonia Production (in '000 tonnes)	
	(1)	(2)
Marginal Cost	−7.44**	
	(2.14)	
Marginal Cost (Slack Capacity)		−32.40***
		(7.30)
Marginal Cost (Full Capacity)		−2.70
		(2.18)
Region FE	✓	✓
Time FE	✓	✓
R^2	0.39	0.65
N	42	42

Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.
A two-region panel regression with annual regional production in North America and Europe as the dependent variable and region specific marginal cost as explanatory variables. Slack Capacity is defined as the period 1996.1-2006.12, Full Capacity as the period 2009.07-2017.12. Values for coefficients in period 2007.01-2009.06 are not reported.
Source: Bloomberg/ Green Markets, IFA and authors' calculations. Annual data 1996 - 2016.

The results from the regression are presented in Table 2. The full sample regression without dummy variables, column 1, suggests that production is relatively elastic. The point estimates imply that a 10$ increase in local production costs shifts nearly 70,000 tonnes of production to the other region. However, the specification masks an important time variation,

as shown in column 2. Once we allow for different coefficients in the periods of slack (before 2007) and full capacity (since July 2009), we see that quantity adjustments occur only in the first period. Our estimates suggest that in the period with slack capacity, a 10$ increase in marginal cost in one region shifts over 320,000 tonnes of production from one region to another. Once the North American producers reach their full capacity, such adjustments are not possible, as confirmed by the coefficient being close to zero and statistically insignificant. These results further support the theoretical Cournot model with capacity constraints.

5. Implications

5.1. Market Valuation

Our results so far show that after the shale gas revolution, there is only limited pass-through of the reduction in North American natural gas prices into ammonia prices. The natural gas price differential between North American and the marginal EU producers implies that US ammonia producers earned windfall profits after the shale gas revolution. This section tests whether this is indeed the case by examining relative stock market valuations of North American producers.

For this purpose, we construct two separate stock portfolios for the listed ammonia producers in North America and in Europe. The portfolios include all firms for which ammonia production is a core activity and that concentrate their production in a single region.[24] Portfolios are weighted by the firms' ammonia production capacity and are normalized to take on a value of 1 on January 1, 2005.[25] The North American portfolio includes all publicly traded ammonia-producing companies operating in North America. The EU portfolio includes all public European ammonia producers that concentrate their ammonia facilities in the EU.

Figure 3 presents the cumulative returns on stocks of the North American ammonia producers relative to those of European ammonia producers. As seen by the dashed line, the evolution of the relative valuation closely follows the marginal cost gap between the regions. Initially, the relative stock market valuation of the US-based ammonia producers increases

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[24]We include only firms for which ammonia revenues exceed 5% of total revenues. Appendix A2 describes the construction of the portfolios in detail.

[25]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.

as the gap in the natural gas prices between the two regions increases. After 2015, the cost differential begins to decrease, and so do the "abnormal returns" of the American stocks. This visual intuition is confirmed by statistical tests indicating that the two series are cointegrated.

5.2. Long-Run Effects on Ammonia Production

Our analysis so far has mainly focused on the short-run implications of our model, which are easier to test empirically. However, with a few additional assumptions, the model also makes long-run predictions regarding the location of quantities.

Conjecture 1. *New investments occur only in the region for which* $\Delta << 0$. *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. Even with non-negligible lump sum investment costs, if production plants have a finite lifetime, new investments required to maintain the capacity will always occur in the low-cost region.[26] Once all producers are located in one region, costs in the other region no longer affect prices. The long-run model predictions are thus in stark contrast to pass-through in the short run.

To test the conjecture empirically, we collect information on all investment announcements and all disinvestment decisions in North America and Europe between 1996 and 2016 as reported by the USGS and other industry sources. As presented in Figure 4, the investment flows over our sample period follow the predicted pattern.

The upper left panel of Figure 4a shows that in the late 1990s and early 2000s, production capacity decreased in both North America and Europe. In that period, ammonia producers in both regions had high costs relative to the rest of the world. Since natural gas prices were, on average, higher in North America 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 4 mln tonnes, or nearly 25%, in that region. During the same period, Europe lost only 0.9 mln tonnes of capacity (1.4 mln tonnes were closed and 0.5 mln tonnes added). The shale gas revolution changed this picture. The bottom right panel

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[26]Fixed-capacity costs further complicate the theoretical model, thus we refrain from formal analysis. See Borenstein (2000) for an excellent discussion of the implications of fixed costs on competitive pricing.

of the figure shows that North America experienced a large inflow of new investments. Over 6 mln tonnes of capacity were commissioned between 2009 and 2018, and not a single plant was closed. During the same period, only one plant was built in Europe, in landlocked Slovakia, while one plant of similar size was closed.

To further shed light on the role of the regional cost advantage on investment, Figure 4b plots the exact timing of decision announcements against the marginal cost gap between North American and European producers. It shows that the cost disadvantage of North American producers prior to the shale discoveries is associated with multiple plant closures. New plants are only commissioned once unit profit margins exceed \$200/t, but cease when the marginal cost gap decreases towards the end of the sample period. The pattern reflects the high capital intensity of ammonia production and the long adjustment times of capacity in this industry. It suggests that short-run capacity constraints can remain binding for many years or possibly even decades.

5.3. Capacity Constraints, Market Linkages, and the Predictive Failure of Standard Pass-Through Models

Our results so far suggest that international linkages and capacity constraints are important to explain the observed price impact of large regional cost shocks. This section examines the consequences of ignoring these features in standard pass-through models.[27] Although the models discussed in this section are generally useful in their original setting, we show that their predictions can fail in the context of large regional cost shocks and capacity constraints, such as those observed during the shale gas revolution.

First, we consider an average cost model, in which a regional ammonia price is regressed on marginal costs in the key producing regions—Europe and North America. The estimated equation for this model reads

$$\text{P}_{r,t}^{Ammonia} = \alpha_r + \beta_r^{EUR}\text{MC}_t^{EUR} + \beta_r^{NA}\text{MC}_t^{NA} + \eta_{r,t}, \tag{4}$$

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[27]Until now, we have expressed the market price as a function of a global shock and a local shock. Those were obtained through decomposition of the regional marginal costs, allowing us to make a direct link to the key propositions of our theoretical framework. A more standard approach is to present global price as a function of marginal costs of producers active on the market. The relation between the two representations is shown in the last paragraph of Appendix Section A1.

where $P_{r,t}^{Ammonia}$ is the price of ammonia in region r and $\eta_{r,t}$ represents the error term.

The results for the average cost model are shown for the North American (Tampa, US) ammonia price, $r = NA$ (North America), in panel (a) of Table 3. The full sample estimates, displayed in column 1, indicate significant pass-through, both from European marginal costs slightly larger than 1 and from North American marginal costs around 0.2. However, these estimates mask considerable differences between the slack-capacity regime (column 2), with a relatively high North American marginal cost pass-through and the capacity-constraint regime (column 3), where the pass-through is statistically indistinguishable from zero. The differences in coefficients across columns are not surprising, as equation 4 represents a reparameterization of the baseline model from the previous section and coefficients are estimated separately for each period. The exercise shows that linear average cost models with constant coefficients are generally unsuitable to make predictions about the effects of large cost shocks that push producers to their capacity constraints.

Second, we consider a regional cost model in which we regress the regional ammonia price against a regional marginal cost. This model has been estimated by Bushnell and Humber (2017), among others. The estimated equation in this setting is

$$P_t^{Ammonia} = \alpha + \beta MC_{r,t} + \eta_t. \tag{5}$$

The results from this model are presented in panel (b) of Table 3, with US ammonia prices as the dependent variable and North American (odd columns) and European (even columns) marginal cost as the independent variables. Columns (5) and (6), in which we present the results for only the full-capacity regime, clearly highlight the importance of choosing the correct independent variable. Regressing the US ammonia prices against the European marginal cost (column 6) yields plausible results, with a coefficient slightly above unity and strong evidence for cointegration between the two series. However, a regression of the US ammonia price against the costs of the capacity-constrained North American producers (column 5) results in a spurious correlation. Although the coefficient of 0.88 is plausible, we fail to find any cointegration and the model explains only 4% of the variation, implying that the estimate should be interpreted with caution. Similarly, over the whole sample period, the model that explains

TABLE 3

Regression Results; Standard Pass-through Models

(a) Average Cost Model

Dep. Var	Ammonia Price (US)		
Sample Period	Whole	Slack Capacity	Full Capacity
	(1)	(2)	(3)
Coefficient Estimates			
MC_{NA}	0.22***	0.39***	−0.42
	(0.05)	(0.06)	(0.26)
MC_{EUR}	1.12***	0.71***	1.19***
	(0.05)	(0.09)	(0.07)
Cointegration Test			
ADF Stat	−5.76**	−4.71**	−5.48**
ADF Lags (BIC)	2	1	1
R^2	0.79	0.75	0.78
Num. obs.	264	132	102

(b) Regional Cost Model

Dep. Var	Ammonia Price (US)					
Sample Period	Whole		Slack Capacity		Full Capacity	
	(1)	(2)	(3)	(4)	(5)	(6)
Coefficient Estimates						
MC_{NA}	0.52***		0.71***		0.88*	
	(0.11)		(0.06)		(0.39)	
MC_{EUR}		1.14***		1.21***		1.15***
		(0.05)		(0.08)		(0.06)
Cointegration Test						
ADF Stat	−1.83	−5.54**	−3.75*	−2.73*	−1.86	−5.39**
ADF Lags (BIC)	3	2	1	2	2	1
R^2	0.06	0.78	0.65	0.67	0.04	0.77
Num. obs.	264	264	132	132	102	102

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_{EUR} and MC_{NA} are the regional average marginal costs for Europe and North America (in $/ short ton) respectively.
Source: Bloomberg/ Green Markets and authors' calculations. Monthly data 1996.1 - 2017.12 (Whole) with sub-samples 1996.1-2006.12 (Slack Capacity) and 2009.07-2017.12 (Full Capacity).

US ammonia prices with North American marginal costs performs poorly (column 1). There is no evidence for cointegration between prices and costs, again suggesting the regression is spurious. Moreover, the estimated coefficient implies an implausibly low pass-through of 50%.

Conversely, explaining US ammonia prices with European marginal cost yields a better fit. There is evidence in favor of cointegration in all periods. Based on available evidence and our theory, the model is likely to be misspecified as it does not account for the contribution of North American marginal costs during the slack-capacity regime. However, since the cost gap between North America and Europe is rather small prior to the shale oil revolution, it still provides a good approximation for the dynamics of ammonia prices. Indeed, for the period when both regions operate with slack capacity (columns 3 and 4), both European and North American marginal cost models perform relatively well.

Third, we consider one-way fixed effects models with region fixed effects (see, e.g., Miller et al., 2017). The model allows for a region-specific fixed effect, but otherwise assumes that price in each region is determined by regional marginal cost alone. Contrary to the previous approaches, which rely on separate regressions for different regions, the model estimates a single coefficient β in a joint estimation

$$\mathrm{P}_{r,t}^{Ammonia} = \alpha + \beta \mathrm{MC}_{r,t} + \delta_r + \eta_{r,t}, \tag{6}$$

where δ_r represents the region fixed effect.

Such an approach may be justified in the absence of market linkages and capacity constraints, which is possibly the case for the cement industry studied in Miller et al. (2017). However, the approach is unsuitable for the ammonia industry and other industries for which the product markets are integrated. In our two-region setting, the estimate of β is just a weighted average of coefficients in regressions of regional ammonia price against regional marginal cost. As discussed for the local cost model, this average includes a potentially spurious relationship between output prices and local costs in the constraint region.

The results are shown in columns (1)–(3) of Table 4a. The coefficient on the marginal cost in specification (1) in the table is a weighted average of coefficients in regressions of regional ammonia price against regional marginal cost, which are 0.52 for North America and 1.12

for Europe, respectively.[28] The weights are determined purely by the relative variation of marginal costs in the two regions.[29] Although the point estimate of 0.97 seems very plausible, this is just a coincidence driven by the fact that the variation in North American marginal cost is just one-third of the variation in EU gas prices throughout the analyzed period.[30] A similar logic holds for column (3) since the variation in marginal costs in North America is even lower after the onset of the shale gas revolution. In general, however, marginal costs in the region producing at full capacity could be volatile relative to costs in the other region. In this case, the pass-through estimates obtained through the fixed effects model would be lower, indicating that they lack a meaningful interpretation.

Finally, we consider two-way fixed effect panel models that rely on differences-in-differences by including region and time fixed effects. The specification reads

$$P_{r,t}^{Ammonia} = \alpha + \beta MC_{r,t} + \delta_r + \gamma_t + \eta_{r,t}, \tag{7}$$

where δ_r and γ_t represent the region and time fixed effects, respectively. This model has been used to analyze the pass-through by Ganapati et al. (2020) and Stolper (2016), among others. In the theoretical setting considered in this paper, the model creates particularly stark issues.

For example, market linkages constitute a clear violation of the Stable Unit Treatment Value Assumption (SUTVA), a critical assumption for causal inference. For our setting, the SUTVA assumes that the change in regional price of the final good depends only on the change in regional marginal costs, and is unaffected by changes in the marginal cost in the other regions. As shown by our theoretical and empirical analysis, this assumption is clearly violated.

Another consequence of the law of one price is the fact that price differences between regions are negligible. For the case of ammonia, for example, price spreads between Europe and the US stay small even as marginal cost gaps widen considerably. As Table 4a, column (4), shows, the two-way fixed effects regressions explain essentially no variation in prices. More-

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[28]See Table 3(b), column (1), and Appendix Table A5(b), column (1), respectively.

[29]Table A1 in the appendix provides a detailed description of the marginal costs.

[30]The pass-through coefficient in column (1) is thus calculated as 0.5220 * (5238.551/ (5238.551 + 14674.123)) + 1.1234* (14674.123/ (5238.551 + 14674.123)), where the expression in brackets is the sum of the variance of marginal cost in the US and and Europe, as shown in Appendix Table A1.

TABLE 4
Panel Analysis

(a) Regressions

Dep. Var	(1)	(2)	(3)	(4)	(5)	(6)
			Ammonia Price			
Method		One-way Panel			Two-ways Panel	
Period	Whole	Slack Capacity	Full Capacity	Whole	Slack Capacity	Full Capacity
Region FE	✓	✓	✓	✓	✓	✓
Time FE				✓	✓	✓
Marginal	0.97***	0.81***	1.02***	0.00	0.17***	−0.13***
Cost	(0.05)	(0.04)	(0.09)	(0.01)	(0.03)	(0.02)
R^2	0.39	0.64	0.37	0.00	0.26	0.26
N	528	264	204	528	264	204

Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.
A two region (North America, Europe) panel regression with ammonia spot price in $/ short ton in US (Tampa) and Europe (Western Europe CFR) as the dependent variable and region specific marginal cost as explanatory variables.
Source: Bloomberg/ Green Markets and authors' calculations. Monthly data 1996.1 - 2017.12 (Whole) with sub-samples 1996.1-2006.12 (Slack Capacity) and 2009.07-2017.12 (Full Capacity).

(b) Variance Decomposition

Price Series	Time FE	Region FE	Residual
Ammonia	99.32%	0.07%	0.61%
Natural Gas	51.90%	9.54%	38.56%
Crude Oil	98.99%	0.08%	0.93%

Note: Variance decomposition table shows the proportion of the variation of the regional commodity prices (1996.1 - 2017.12) explained by the fixed effects. In the analysis we included Northern American and European prices for each commodity. For Ammonia Tampa CFR and Western Europe CFR prices, for natural gas Henry Hub spot prices and oil linked contract prices, for crude oil WTI and Brent spot prices.
Source: Authors and Bloomberg

over, the negative coefficient is not economically meaningful. When the model is estimated separately for the slack and the constraint period, the sign on the marginal cost coefficient changes, while the r-squared remains low. All of these are indications that the model is a poor fit for a market with international linkages.

To understand the problems with panel models with time fixed effects, it is useful to con-

sider the variance decomposition of ammonia and natural gas prices. As shown in Table 4b, the overwhelming share of variation in ammonia prices is explained by a common time effect. In a difference-in-difference setting, the common time and region variation is removed by fixed effects. Only the residual variation, constituting less than 1% of the total variation in ammonia prices, remains to be used in the estimation of β. A similar picture is obtained for crude oil prices, indicating that these issues are not unique to the nitrogen market. In Appendix Table A6, we present variance decomposition separately for the slack- and full-capacity regimes.

Table 4b also shows that common time effects explain only about 50% of the variation in natural gas prices. Since gas markets are not as tightly linked, the residual variation in gas prices is much higher, suggesting that regional cost spreads are much larger than regional price spreads. Consistent with our setup and previous results, these cost spreads should be used to explain the *level* of prices rather than *differences* in prices across regions.

Taken together, the various exercises highlight the importance of non-linearities induced by capacity constraints and by the law of one price in explaining the price pass-through of natural gas prices after the shale gas revolution. These features are particularly relevant for the ex-ante evaluation of regional climate policies, as historical pass-through estimates from models ignoring capacity constraints and the law of one price can be misleading about the expected impact of policies.

5.4. Implications for Carbon Policy

Decarbonization potential: Understanding market linkages is crucial for designing carbon taxation. Our model makes clear predictions about the impact of such a policy. One implication is that with international linkages and large cost differences, decarbonization in the short run (through a decrease in quantity demanded rather than changes in technology) can only be achieved by the high-cost producer. In the short run, an increase in carbon tax on the highest cost producer is passed through into global prices, creating additional rents for producers in the lower cost region. In the case of ammonia, the incidence will fall on farmers or food consumers worldwide.

Suppose instead that a low-cost region introduces a decarbonization policy, as analyzed for example by Bushnell and Humber (2017) for US nitrogen producers. Our results show that

as long as the emissions costs created by the carbon tax are much lower than the difference in marginal cost between the US and Europe, we expect no pass-through into ammonia prices. The carbon tax would be fully paid by US producers, but would have no effect on quantities and hence emissions. From that perspective, the leading role of the EU in implementing carbon taxation is easy to understand. Since Europe already has high energy costs, further increases will more likely be passed through into prices and reduce emissions, even though the effectiveness of such a policy depends mostly on the price elasticity of demand.

A policy that could potentially mitigate the local impact of regional carbon taxation is carbon border adjustment mechanisms. While this has been a feature of every major US national bill that would price or cap carbon, carbon border adjustments for the EU are only foreseen for 2026 onward. Our results provide strong evidence that such policies are indeed effective in reducing leakage in the affected region.

The results also have interesting political economy consequences. With drastic cost differences, a further cost increase on the high-cost producer does not reduce profits further and hence limits the incentive to lobby against decarbonization policy. By contrast, carbon taxes in the low-cost region would destroy producer rents. This might explain why climate change policy is more difficult to pass in the US, especially since the shale gas boom.

Emissions-Intensive Trade-Exposed (EITE) definitions: 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 emissions-intensive trade-exposed (EITE) industries. In the EU, the emissions-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 includes the industry if the sector's trade intensity with non-EU countries is above 10%.

Our analysis shows that such criteria do not provide a sufficient metric to identify the exposed industries. Under the current EU definition, both the EU and North American ammonia industry are deemed to be exposed to carbon leakage. However, the impact of a carbon tax differs between the regions. In particular, a modest carbon tax in the US would leave

ammonia prices largely unaffected and not induce leakage. Our results suggest that the cost pass-through of region-specific cost shocks is more informative about the price impact and leakage than the standard trade criterion.

6. Conclusion

We have presented a pass-through model of local cost shocks in an integrated market with capacity constraints. When local shocks are small, the impact of a local cost shock is mitigated relative to global shocks due to production reallocation. Once the shock is large enough such that the producers in the region with cost advantage reach their capacity constraints, the pass-through of a cost decrease becomes zero. Our empirical application to the ammonia market confirms this prediction. The mechanism explains why the drastic decrease in input costs of North American producers in the wake of the shale gas revolution did not translate into lower nitrogen fertilizer prices or higher output levels in North America.

Our model has several implications for regional carbon taxation. For example, we find that carbon taxation in the low-cost region is likely to be ineffective in increasing output prices and in curbing demand for energy-intensive goods in the short run. We also highlight that it is not the commonly used degree of trade exposure, but rather profit margins, that define an industry's response to carbon taxation. Taking these effects into account is crucial for designing appropriate regional climate policies and industry exemptions.

Finally, we provide evidence for the predictive failure of popular pass-through regressions under linked output markets and capacity constraints. We demonstrate that the pass-through of local cost shocks is time-varying, depending on whether or not capacity constraints bind. This effect is not captured by constant coefficient models. We also show that the existence of output market linkages invalidates the standard SUTVA assumptions of difference-in-difference-type estimations of the pass-through, such as panel models with region and time fixed effects. Taken together, these results provide a cautionary tale for extrapolating evidence from standard pass-through models and from small regional cost shocks to evaluate the potential impact of local carbon policies.

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FIGURE 1

Cost Pass-Through: Regional vs. Global Cost Shocks
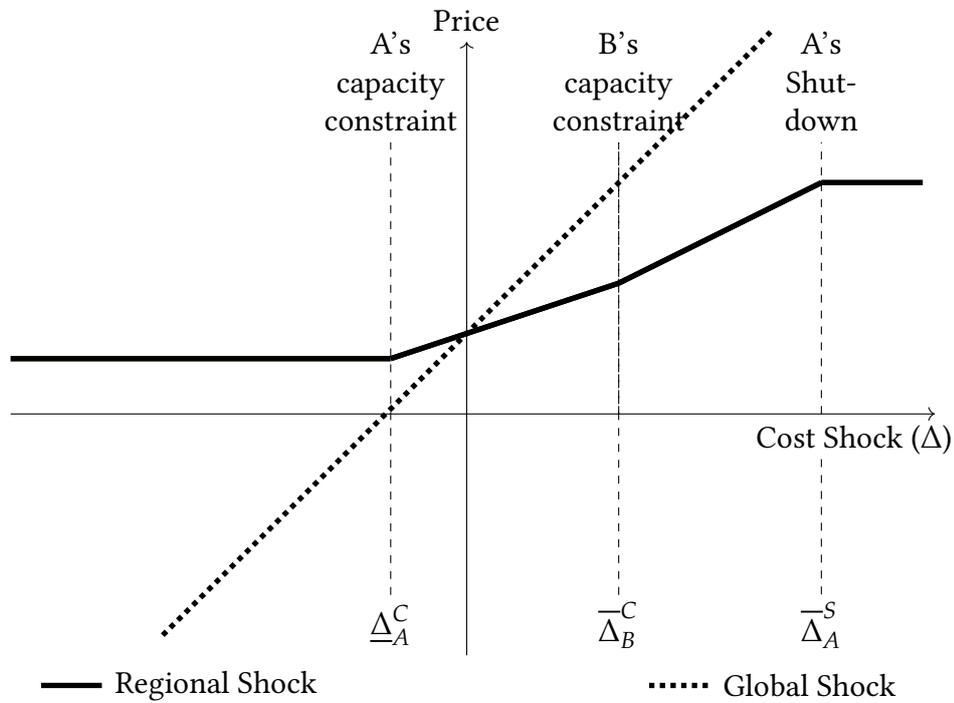
Notes: Theoretical pass-through of regional and of global cost shocks following Propositions 1 and 2.

FIGURE 2
Ammonia and Natural Gas Prices

(a) Ammonia Prices
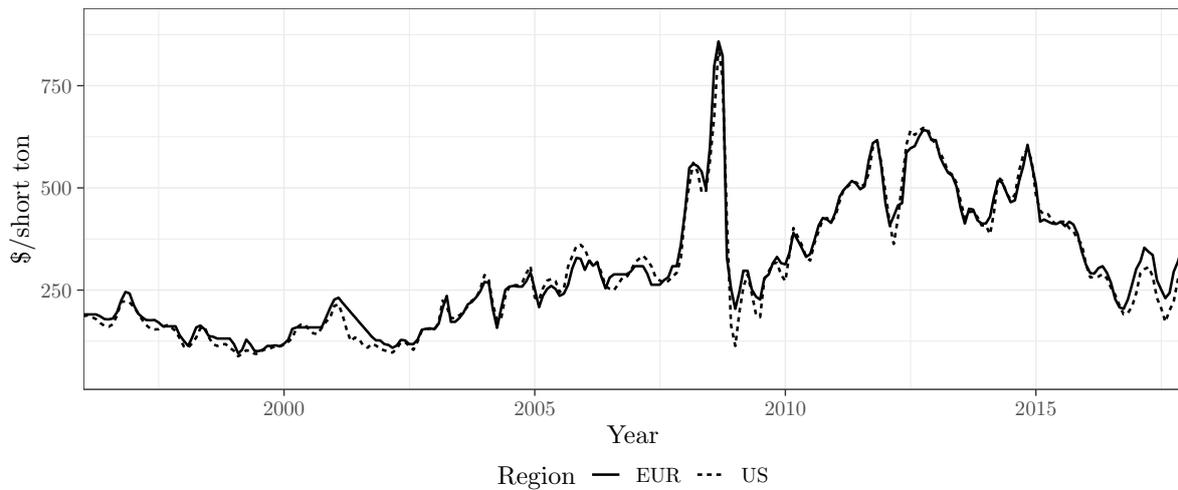
(b) Natural Gas Prices
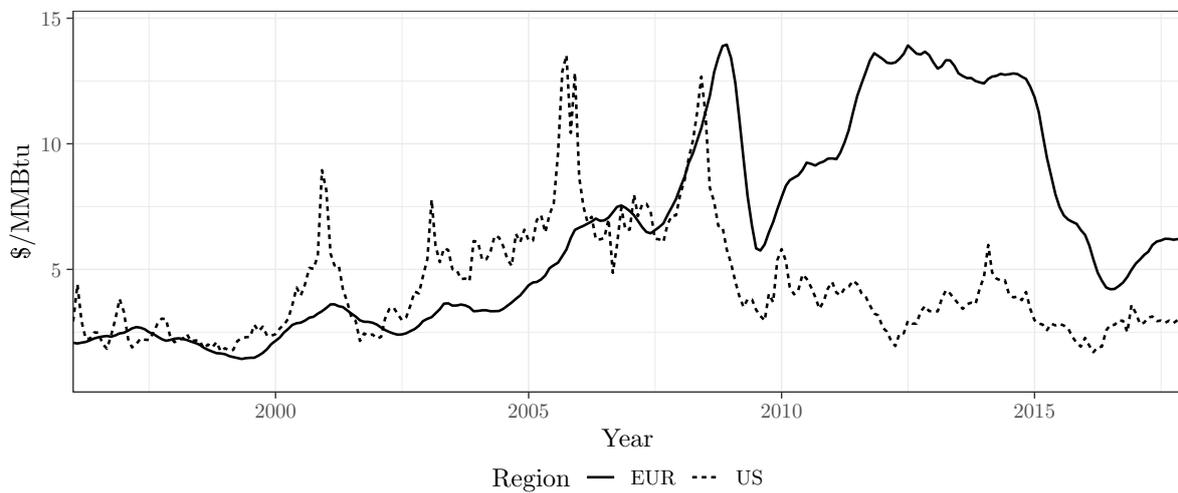
Notes: Ammonia spot prices in Tampa and Western Europe CFR. Natural gas prices are Henry Hub spot price for the US, contract prices for Europe.

FIGURE 3

North American vs. European Ammonia Producers' Stock Price Ratio and Marginal Cost Gap
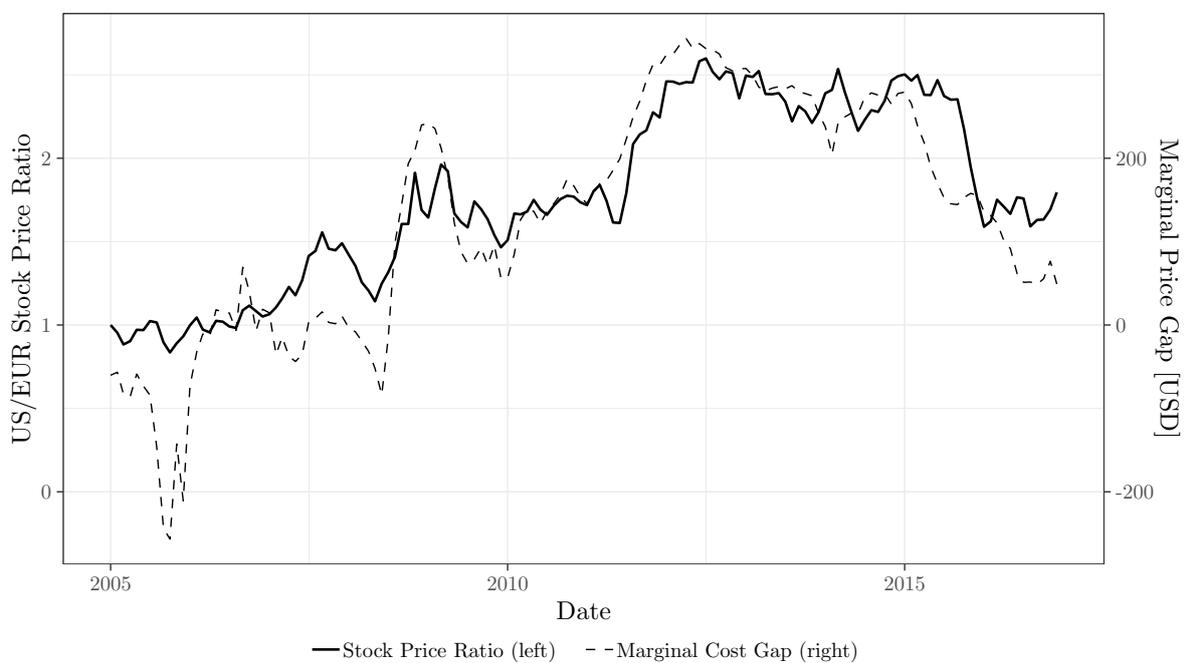
Notes: Stock Price Ratio is the ratio of regional ammonia producer indices (Northern American Producers Index/European Producers Index) as described in the appendix. Marginal Price Gap is the difference between regional marginal costs in USD per short ton of ammonia.

FIGURE 4
(Dis)Investments in the Ammonia Industry

(a) Plant Expansions and Closures
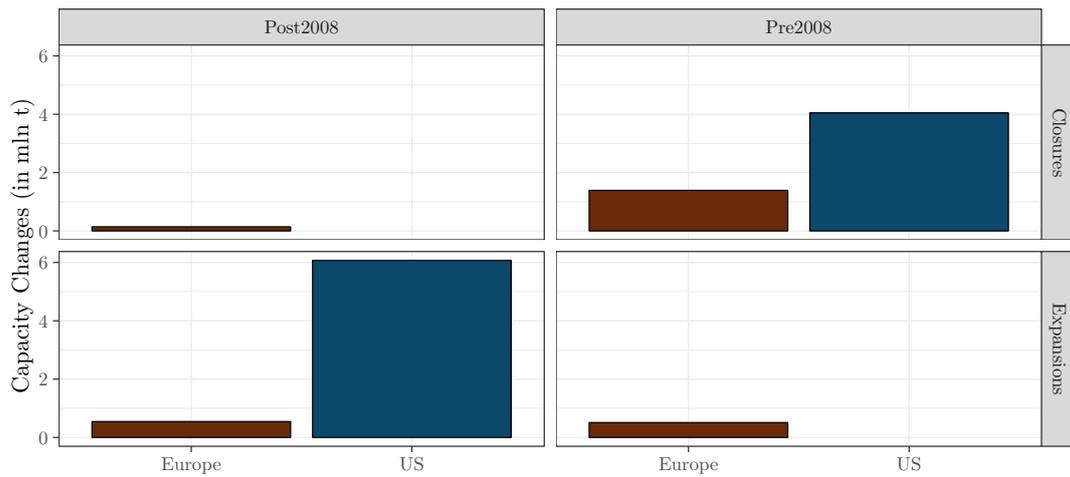
(b) Marginal Cost Gap and (Dis)Investment decisions
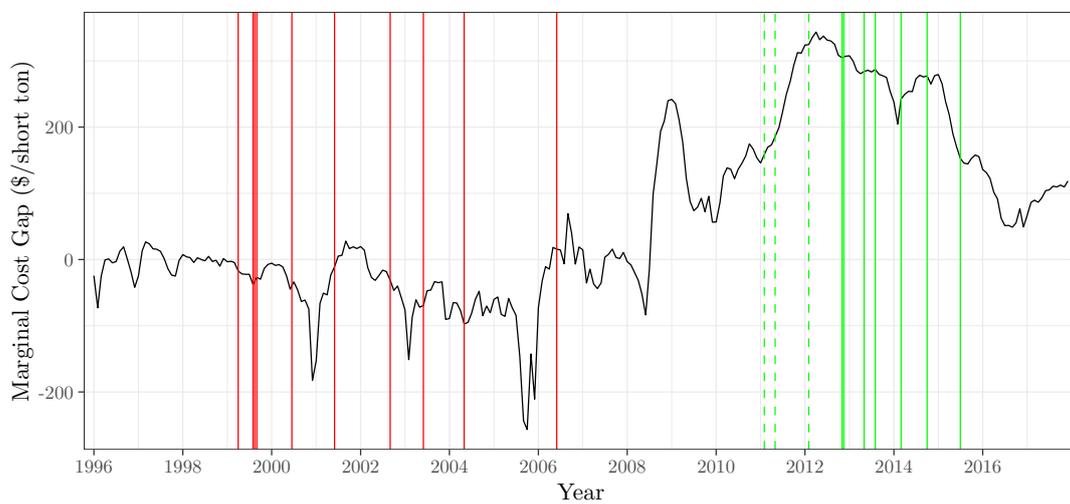
Notes: Red lines: disinvestments (plant closures); Green lines: investments (announcement dates for completed/advanced projects; dashed for plant restarts/expansions, solid greenfield/brownfield projects) in the US ammonia industry. Each line represents a single event. A detailed list of all expansion and closure decisions are provided in the online appendix.

Appendix

A1. Appendix: Derivation of Model Results

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

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 $P = a - b * Q$. A 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 to differ by firm. As long as the difference is sufficiently small that capacity constraints (shut down or maximal capacity) do not bind for any firm, this would not affect the results.

Marginal cost in region A is denoted 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 Δ 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., $\Delta = 0$), that is, $k_i = q_i^*(1 + \theta)$, where q_i^* is the equilibrium production quantity when $\Delta = 0$ and θ is the scaling factor.

For each individual firm, we have a profit function that 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 π_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 $Q_{-i,A} = (n * s_A - 1) * q_{i,A}$ and $Q_{-i,B} = (n * (1 - s_A) - 1) * q_{i,B}$ into the first order conditions) gives the first order necessary conditions:

$$q_{i,A} = \frac{\left(a - bQ_B^* - \Delta - c\right)}{b\,(ns_A + 1)}, \tag{8}$$

$$q_{i,B} = \frac{\left(a - bQ_A^* - c\right)}{b\,(n(1 - s_A) + 1)} \tag{9}$$

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:

$$q_{i,A}^* = \frac{a - c - \Delta(n\,(1 - s_A) + 1)}{b\,(n + 1)} \tag{10}$$

$$q_{i,B}^* = \frac{a - c + \Delta n s_A}{b\,(n + 1)} \tag{11}$$

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 ($q_i \le k_i$) and shutdown ($q_i \ge 0$) constraints. Equations 10 and 11 imply that the full capacity constraints are equal in each region and given by:

$$k_i = \frac{a - c}{b\,(n + 1)}\,(1 + \theta) \tag{12}$$

The constraints are slack for the following values of Δ:

$$q_{i,A} \ge 0 \quad \rightarrow \quad \Delta \le \overline{\Delta}_A = \frac{a - c}{n\,(1 - s_A) + 1} \tag{13}$$

$$q_{i,A} \le k_i \quad \rightarrow \quad \Delta \ge \underline{\Delta}_A = -\frac{\theta(a - c)}{n\,(1 - s_A) + 1} \tag{14}$$

$$q_{i,B} \ge 0 \quad \rightarrow \quad \Delta \ge \underline{\Delta}_B = -\frac{a - c}{n s_A} \tag{15}$$

$$q_{i,B} \le k_i \quad \rightarrow \quad \Delta \le \overline{\Delta}_B = \frac{\theta\,(a - c)}{n s_A} \tag{16}$$

The notation reads the following way: If region A's cost disadvantage exceeds $\overline{\Delta}_A$, then production in region A is shut down. Likewise, if A's cost disadvantage exceeds $\overline{\Delta}_B$, producers in region B are at full capacity and cannot increase their output further. Thus, we have to first address the question of whether their own shutdown constraint or the rival's full-capacity constraint binds first.

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 10 and 11.

By comparing constraints defined in equations 13–16, we get the general conditions for the order in which constraints bind as Δ changes:

$$\overline{\Delta}_B < \overline{\Delta}_A \,\&\, \underline{\Delta}_A > \underline{\Delta}_B \quad \text{if} \quad \theta < \min\left(\frac{ns_A}{(1-s_A)*n+1}, \frac{(1-s_A)n+1}{ns_A}\right)$$

$$\overline{\Delta}_B > \overline{\Delta}_A \,\&\, \underline{\Delta}_A > \underline{\Delta}_B \quad \text{if} \quad \frac{ns_A}{(1-s_A)*n+1} < \theta < \frac{(1-s_A)n+1}{ns_A}$$

$$\overline{\Delta}_B < \overline{\Delta}_A \,\&\, \underline{\Delta}_A < \underline{\Delta}_B \quad \text{if} \quad \frac{(1-s_A)n+1}{ns_A} < \theta < \frac{ns_A}{(1-s_A)*n+1}$$

$$\overline{\Delta}_B > \overline{\Delta}_A \,\&\, \underline{\Delta}_A < \underline{\Delta}_B \quad \text{if} \quad \theta > \max\left(\frac{ns_A}{(1-s_A)*n+1}, \frac{(1-s_A)n+1}{ns_A}\right)$$

We can read the conditions in the following way: $\overline{\Delta}_B < \overline{\Delta}_A$ implies that B's capacity constraint binds for lower cost increase (Δ) at A than A's shutdown constraint. $\underline{\Delta}_A > \underline{\Delta}_B$ means that A's capacity constraint binds for a smaller cost decrease than B's shutdown constraint.

When $\overline{\Delta}_B < \overline{\Delta}_A$ and $\Delta > \frac{\theta(a-c)}{ns_A}$ (see equation 16), B produces at full capacity and the region cannot increase production for further increases in Δ. 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 Δ that leads to complete shutdown changes to $\Delta = a - bK_B - c = \overline{\Delta}_A^S = \frac{(a-c)(n(s_A\theta+s_A-\theta)+1)}{n+1}$.

Similarly, when $\underline{\Delta}_A < \underline{\Delta}_B$ and $\Delta < -\frac{a-c}{ns_A}$ (see equation 15), B shuts down, while a further decrease in costs in A leads to an 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 Δ at which A reaches its capacity constraint is given by $\Delta = \underline{\Delta}_A^C = -\frac{(a-c)(n\theta s_A+ns_A+\theta-n)}{n+1}$.

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.

$$P = \frac{a + \Delta n s_A + cn}{n + 1} \quad \text{if} \quad \max\left(\underline{\Delta}_A, \underline{\Delta}_B\right) < \Delta < \min\left(\overline{\Delta}_A, \overline{\Delta}_B\right) \tag{17}$$

$$P = \frac{a + cn(1 - s_A)}{n(1 - sA) + 1} \quad \text{if} \quad \overline{\Delta}_A < \Delta \& \overline{\Delta}_A < \overline{\Delta}_B \tag{18}$$

$$P = \frac{a + n s_A(c + \Delta) - bn(1 - s_A)K_B}{n s_A + 1} \quad \text{if} \quad \overline{\Delta}_B > \Delta > \overline{\Delta}_A^S \tag{19}$$

$$P = a - b(n(1 - s_A)K_B) \quad \text{if} \quad \overline{\Delta}_B < \overline{\Delta}_A^S < \Delta \tag{20}$$

$$P = \frac{a + n s_A(c + \Delta)}{n s_A + 1} \quad \text{if} \quad \underline{\Delta}_A^C < \underline{\Delta}_B \& \underline{\Delta}_A^C < \Delta < \underline{\Delta}_B \tag{21}$$

$$P = a - b(n s_A k_i) \quad \text{if} \quad \Delta < \underline{\Delta}_A^C < \underline{\Delta}_B \tag{22}$$

$$P = \frac{a + cn(1 - s_A) - bn s_A K_A}{n(1 - sA) + 1} \quad \text{if} \quad \Delta < \underline{\Delta}_A \& \underline{\Delta}_A > \underline{\Delta}_B \tag{23}$$

When cost shocks are such that none of the regions is constrained, the price is as in equation 17. As cost shock increases, if s_A and θ are such that $\overline{\Delta}_B > \overline{\Delta}_A$, region A shuts down before region B reaches its capacity constraint and for $\Delta > \overline{\Delta}_A$ price is given by equation 18. When capacity constraints are tighter, such that $\overline{\Delta}_B < \overline{\Delta}_A$, $\overline{\Delta}_B > \Delta > \overline{\Delta}_A^S$ implies that B produces at full capacity, while A is still in the market, the price is given by equation 19. Further increase in Δ makes firms in region A shut down, and price is given by equation 20.

For negative shocks, when s_A and θ are such that $\underline{\Delta}_A^C < \Delta < \underline{\Delta}_B$, B's shutdown constraint binds before A reaches its capacity constraint, thus for $\underline{\Delta}_A^C < \Delta < \underline{\Delta}_B$ price is given by equation 21. Further decrease in Δ makes A reach its capacity constraint, which happens for $\Delta = \underline{\Delta}_A^C$. For such a case, the price is given by equation 22. When, A's capacity constraints are tighter, such that $\underline{\Delta}_A > \underline{\Delta}_B$, for cost decreases high enough for A to reach its capacity constraint, the price is given by equation 23.

Given the price equations presented in equations 17 - 23, 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 $\frac{n s_A}{n+1}$; when A's production is unconstrained and B's is at 0 or k_i, the pass-through increases to $\frac{n s_A}{n s_A + 1}$.

Equations 17 - 23 can also be expressed in terms of marginal costs in each region instead of global and regional shock. 17 is equivalent to $P = \frac{a + n s_A \mathrm{MC}^A + n(1 - s_A)\mathrm{MC}^B}{n+1}$, where MC^r stands

for marginal cost in a region r. 19 is equivalent to $P = \frac{a + n s_A \text{MC}^A - b n (1 - s_A) K_B}{n s_A + 1}$. The remaining equations are not relevant for the empirical results presented in this paper.

A2. Appendix: Construction of Stock Return Series

Stock return ratios from Figure 3 have be created in the following way.

First, we collect 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 comprehensive public data is not available for Europe, for which we rely on two sources. From the EU Emissions Trading System Operator Holding Accounts[31] we collect 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[32]. Although the latter is also incomplete, covering roughly 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 for Europe does not provide ownership data at the annual frequency for the entire period. We determine historical ownership and match plant owners to stock tickers via a manual search.

Next, we collect financial statements of the listed ammonia producers to identify plant owners for which ammonia production is a "core" activity. Since we do not 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 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

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[31]http://ec.europa.eu/environment/ets/oha.do?languageCode=en
[32]https://www.globalsyngas.org/resources/map-of-gasification-facilities

results are robust to alternative choices of the threshold level.

For each stock in the list, we compute monthly returns. 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. We thus 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 identify 28 listed ammonia producers in the two regions; we exclude 17 according to the criteria above, leaving 8 in the 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. A complete list of producers, with the number of years in which they are included in the sample and average weight, is presented in Table A7. It shows 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

Descriptive Statistics

	Mean	SD	Min	Max
AMMONIA$_{EUR}$				
Full Sample	301.90	152.57	95.25	858.20
Slack Capacity	189.81	61.01	95.25	328.85
Full Capacity	419.34	114.11	204.12	641.38
AMMONIA$_{US}$				
Full Sample	294.03	156.01	88.00	844.59
Slack Capacity	183.70	68.99	88.00	360.76
Full Capacity	411.94	127.31	172.37	646.82
MC$_{EUR}$				
Full Sample	263.17	121.15	111.23	487.91
Slack Capacity	167.16	46.57	111.23	295.16
Full Capacity	362.66	97.61	201.59	486.95
MC$_{NA}$				
Full Sample	200.58	72.38	115.11	499.29
Slack Capacity	202.24	78.19	116.35	499.29
Full Capacity	171.36	28.63	115.11	253.93
NGAS$_{EUR}$				
Full Sample	6.42	3.98	1.43	13.95
Slack Capacity	3.29	1.55	1.43	7.54
Full Capacity	9.63	3.24	4.21	13.92
NGAS$_{US}$				
Full Sample	4.33	2.23	1.70	13.52
Slack Capacity	4.38	2.41	1.74	13.52
Full Capacity	3.43	0.88	1.70	5.97
EUA ($/st)				
Full Sample	5.27	7.99	0.00	40.71
Slack Capacity	0.00	0.00	0.00	0.00
Full Capacity	9.32	5.78	0.00	21.14

Note: Slack Capacity is defined as period 1996.1-2006.12, Full Capacity as period 2009.07-2017.12. Ammonia US and EUR are Tampa and Western Europe CFR prices in USD/short ton. Natural gas prices (NGAS) are Henry Hub (US) and contract prices (EUR) in $/MMBtu, Marginal Costs (MC) in Europe and North America are calculated according to formula described in the main text. EUA stands for EU Carbon Emission Allowances.
Source: Bloomberg/ Green Markets and authors' calculations. *Source:* Authors and Bloomberg/Green Markets. Monthly data 1996.1 - 2017.12.

TABLE A2

Regression results: Model with varying coefficient on global shock

Dep. Var	Ammonia Price (US)		Ammonia Price (EUR)	
	(1)	(2)	(3)	(4)
Coefficient Estimates: Normal Times				
Global Shock (c_t, Slack Capacity)	1.10***	1.10***	0.81***	0.81***
	(0.05)	(0.05)	(0.04)	(0.04)
Global Shock (c_t, Full Capacity)	0.77***	1.15***	0.76***	1.03***
	(0.22)	(0.06)	(0.17)	(0.05)
Local Shock (Δ_t, Slack Capacity)	0.39***	0.39***	0.23***	0.23***
	(0.06)	(0.06)	(0.05)	(0.05)
Local Shock (Δ_t, Full Capacity)	−0.42		−0.29	
	(0.26)		(0.20)	
R^2	0.84	0.85	0.85	0.84
Num. obs.	264	264	264	264

Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. Dependent variables: Ammonia spot price US - Tampa CFR, Europe - Western Europe CFR in $/ short ton. Slack Capacity is defined as period 1996.1-2006.12, Full Capacity as period 2009.07-2017.12. Values for coefficients in period 2007.01-2009.06 are not reported.
Source: Bloomberg/ Green Markets and authors' calculations. Monthly data 1996.1 - 2017.12.

TABLE A3

Regression results - robustness to timing of commodity crises

Dep. Var	Ammonia Price (US)			Ammonia Price (EUR)		
Timing of commodity crisis	2007.1-2008.12	2008.1-2008.12	2008.1-2009.6	2007.1-2008.12	2008.1-2008.12	2008.1-2009.6
	(1)	(2)	(3)			
Coefficient Estimates: Normal Times						
Global Shock (c_t)	0.91***	0.98***	1.06***	0.88***	0.92***	0.98***
	(0.10)	(0.07)	(0.05)	(0.08)	(0.06)	(0.04)
Local Shock (Δ_t, Slack Capacity)	0.43***	0.41***	0.40***	0.27***	0.24***	0.24***
	(0.06)	(0.06)	(0.06)	(0.05)	(0.05)	(0.05)
Local Shock (Δ_t, Full Capacity)	−0.25*	−0.18	−0.13	−0.16	−0.12	−0.07
	(0.12)	(0.10)	(0.10)	(0.09)	(0.08)	(0.08)
Coefficient Estimates: Commodity Crisis						
Global Shock (commodity crisis)	2.18***	0.77	1.82**	2.44***	0.79	1.90**
	(0.38)	(0.67)	(0.59)	(0.42)	(0.81)	(0.61)
Local Shock (commodity crisis)	0.99	0.41	1.39***	1.04	0.39	1.34***
	(0.60)	(0.64)	(0.31)	(0.64)	(0.61)	(0.30)
R^2	0.81	0.82	0.84	0.83	0.83	0.85
Num. obs.	264	264	264	264	264	264

Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. Dependent variable: US ammonia spot price (Tampa) in $/ short ton. Slack Capacity is defined as period 1996.1-2006.12, Full Capacity as period 2009.07-2017.12. Values for coefficients in period 2007.01-2009.06 are not reported.
Source: Bloomberg/ Green Markets and authors' calculations. Monthly data 1996.1 - 2017.12.

TABLE A4
Cost pass-through of local shocks under slack and full capacity with demand shifters

| Dep. Var | Regional Ammonia Price | | | |
| | USA | | Europe | |
	(1)	(2)	(3)	(4)
Coefficient Estimates				
Global Shock (c_t)	1.15***	0.86***	0.94***	0.73***
	(0.09)	(0.13)	(0.11)	(0.12)
US Local Shock (Δ_t, Slack Capacity)	0.46***	0.42***	0.24***	0.25***
	(0.07)	(0.07)	(0.05)	(0.05)
US Local Shock (Δ_t, Full Capacity)	0.01	−0.37*	−0.06	−0.34*
	(0.14)	(0.17)	(0.14)	(0.16)
Controls				
Demand Shifters	X	X	X	X
Lagged Demand Shifters		X		X
R^2	0.85	0.86	0.86	0.87
Num. obs.	264	252	264	252

Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. Dependent variable: Ammonia spot prices Tampa CFR (USA) and Western Europe CFR in \$/ short ton.Slack Capacity is defined as period 1996.1-2006.12, Full Capacity as period 2009.07-2017.12. Values for coefficients in period 2007.01-2009.06 are not reported. Demand shifters include food price index, regional GDP growth, regional food production growth and regional population growth. Except for the food price index all variables are on a regional level (separately for Europe and Northern America) and in annual frequency. Food price index is a global variable in monthly frequency. In the specification with lags we use the 12th lag for the variables in annual frequency and the 4th and 12th lag for the variables in monthly frequency.
Source: Bloomberg/ Green Markets and authors' calculations. Monthly data 1996.1 - 2017.12.

TABLE A5
Average and Regional Cost Models: European Ammonia Price

(a) Average Cost Model

Dep. Var	Ammonia Price (Europe)		
Sample Period	Whole Sample	Slack Capacity	Full Capacity
	(1)	(2)	(3)
Coefficient Estimates			
(Intercept)	−22.44	9.69	86.76**
	(16.31)	(8.13)	(29.08)
MC_{US}	0.16*	0.23***	−0.29
	(0.06)	(0.05)	(0.25)
MC_{EUR}	1.11***	0.79***	1.06***
	(0.05)	(0.07)	(0.06)
Cointegration Test			
ADF Stat	−5.46**	−3.48**	−4.98**
ADF Lags (BIC)	3	2	1
R^2	0.80	0.74	0.78
Num. obs.	264	144	108

(b) Regional Cost Model

Dep. Var	Ammonia Price (Europe)					
Sample Period	Whole Sample		Slack Capacity		Full Capacity	
	(1)	(2)	(3)	(4)	(5)	(6)
Coefficient Estimates						
(Intercept)	208.10***	6.26	69.40***	6.88	271.58***	46.35*
	(26.72)	(10.01)	(10.72)	(9.96)	(61.32)	(18.54)
MC_{US}	0.47***		0.60***		0.86*	
	(0.13)		(0.06)		(0.35)	
MC_{EUR}		1.12***		1.09***		1.03***
		(0.05)		(0.06)		(0.06)
Cointegration Test						
ADF Stat	−1.94	−5.45**	−2.72	−3.12*	−2.51	−4.88**
ADF Lags (BIC)	3	3	2	2	2	1
R^2	0.05	0.79	0.58	0.70	0.04	0.77
Num. obs.	264	264	132	132	102	102

Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. Engle-Granger Critical Values for ADF Test.
Dependent variable: European ammonia spot price (Western Europe CFR) in $/ short ton. MC_{EUR} and MC_{US} are the regional average marginal costs for Europe and Norther America (in $/ short ton) respectively.
Source: Bloomberg/ Green Markets and authors' calculations. Monthly data 1996.1 - 2017.12 (Whole) with sub-samples 1996.1-2006.12 (Slack Capacity) and 2009.07-2017.12 (Full Capacity).

TABLE A6
Variance Decomposition

Variable	Time FE	Region FE	Residual	Sample Period
NGAS	78.93%	6.84%	14.23%	Slack Capacity
AMMONIA	97.95%	0.22%	1.83%	Slack Capacity
NGAS	21.47%	63.2%	15.34%	Full Capacity
AMMONIA	98.94%	0.09%	0.97%	Full Capacity

Source: Authors and Bloomberg/Green Markets. Monthly data with subsamples 1996.1-2006.12 (Slack Capacity) and 2009.07-2017.12 (Full Capacity).

TABLE A7
Listed Ammonia Producers

Ticker	Region	Start Date	End Date	Average Capacity
3NB.BG	EUR	2005-01	2016-12	550
YAR.OL	EUR	2005-01	2016-12	4900
ZAP.PL	EUR	2005-11	2016-12	1100
AGU	US	2005-01	2016-12	3453
ASIX	US	2016-09	2016-12	530
CF	US	2005-08	2016-12	4610
LXU	US	2005-01	2016-12	344
OCIP	US	2013-10	2016-12	323
POT	US	2005-01	2016-12	1874
RTK	US	2006-01	2015-12	290
TNH	US	2005-01	2016-12	970

Note: Capacity is average annual capacity in thousand metric tonnes. Tickers: 3NB:BG - Neochim AD, YAR.OL - Yara AS, ZAP.PL - Grupa Azoty Puławy 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

FIGURE A1

Gap in Marginal Cost between North America and Europe
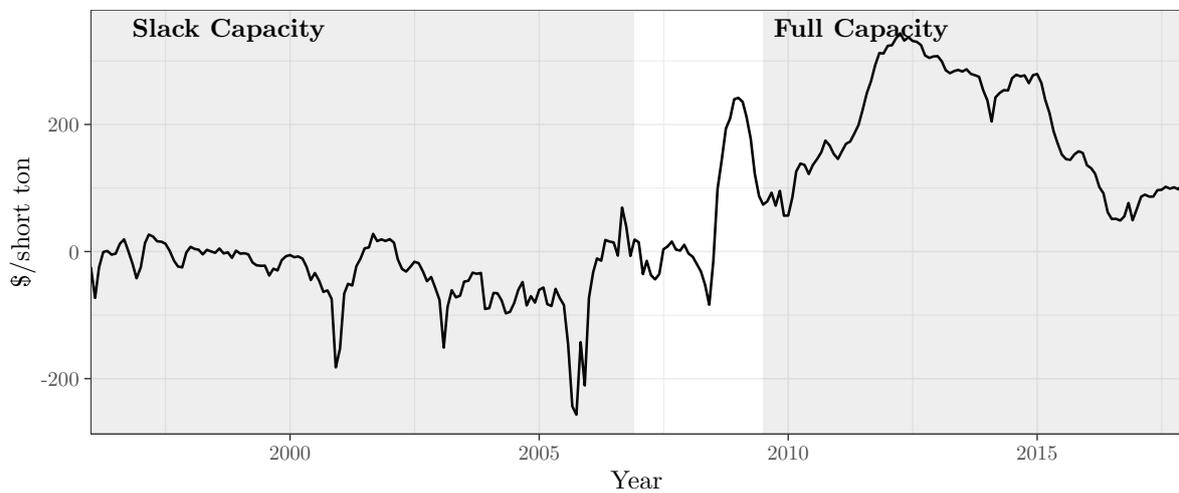
Note: Plot shows gap in ammonia marginal cost between North American and European producers. Areas marked gray represent period with slack and full capacity. Area in white represents the period of commodity boom.
*Source:* Authors and Bloomberg/Green Markets

FIGURE A2
Capacity and Capacity Utilisation in US and Europe
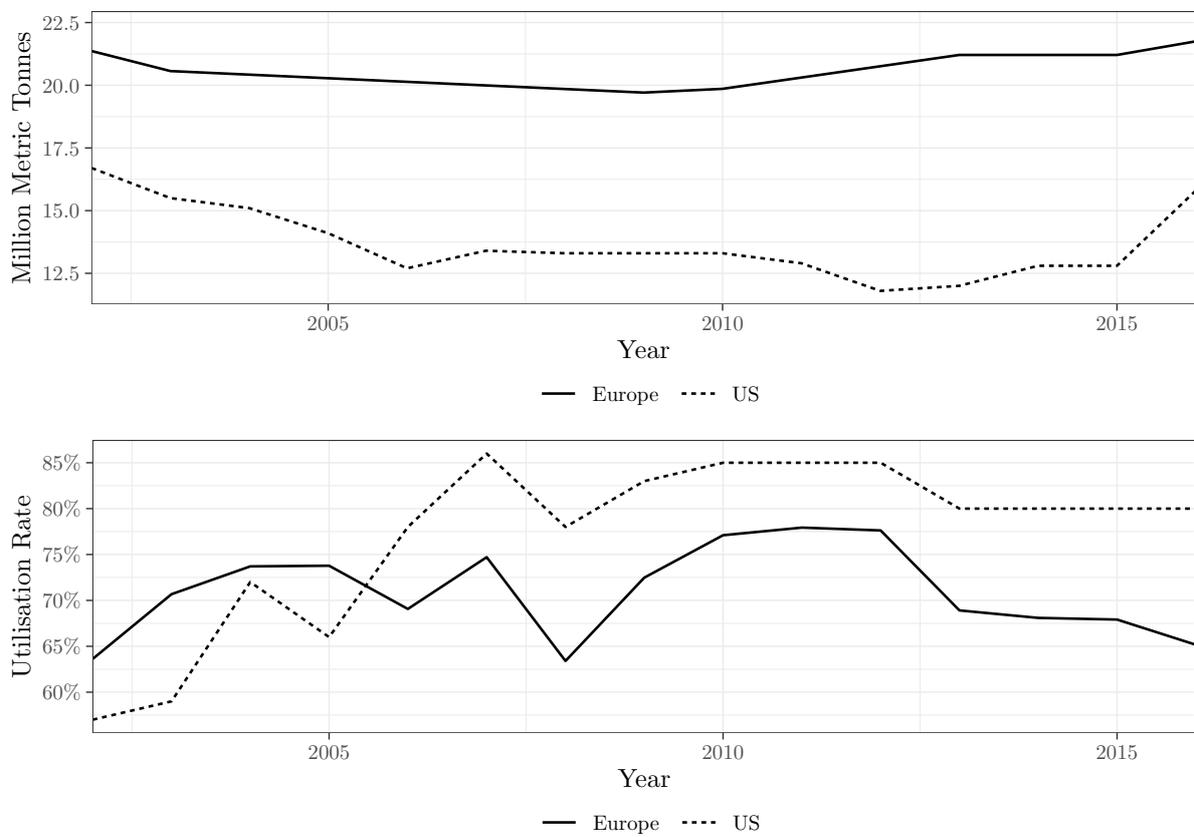

Source: Authors and USGS.

Number of Active Plants and US Capacity Utilisation from Corporate Reports
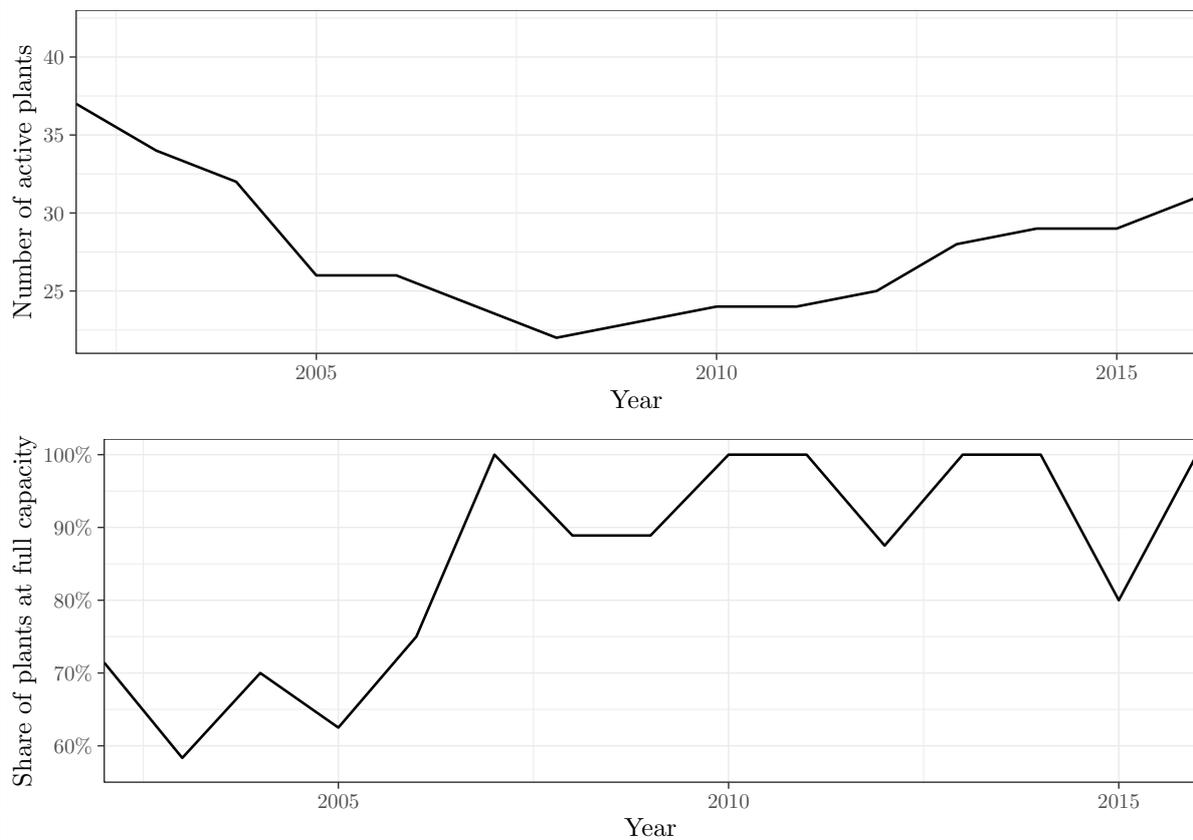

Note: The top panel plots the number of active plants per year in the US as reported by the USGS. The bottom panel plots the share of plants operating close to full capacity, as estimated from corporate reports and 10-K forms for publicly traded companies. Full capacity is defined as more than 80% of reported nameplate capacity. *Source:* Authors and USGS.

FIGURE A4
Production and Marginal Cost Gap

(a) Regional Annual Ammonia Production
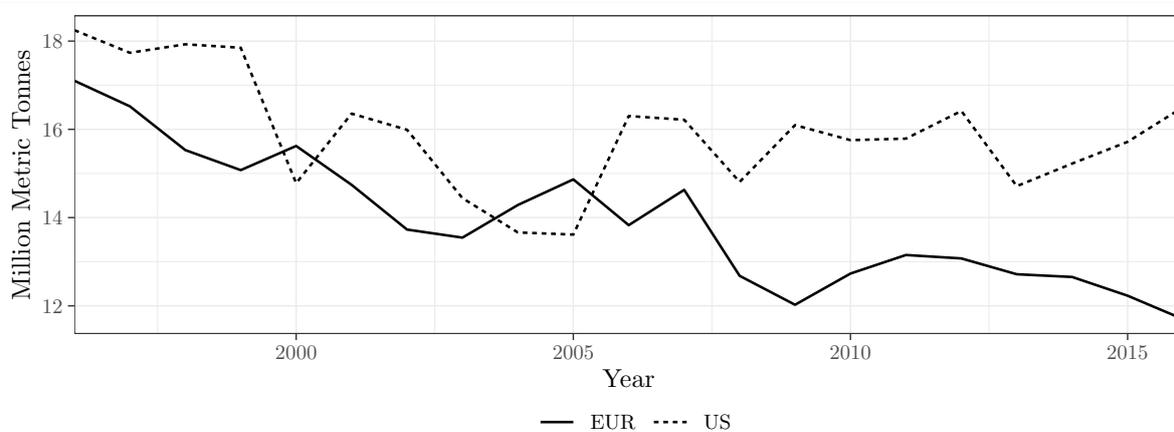
(b) Marginal Cost Gap
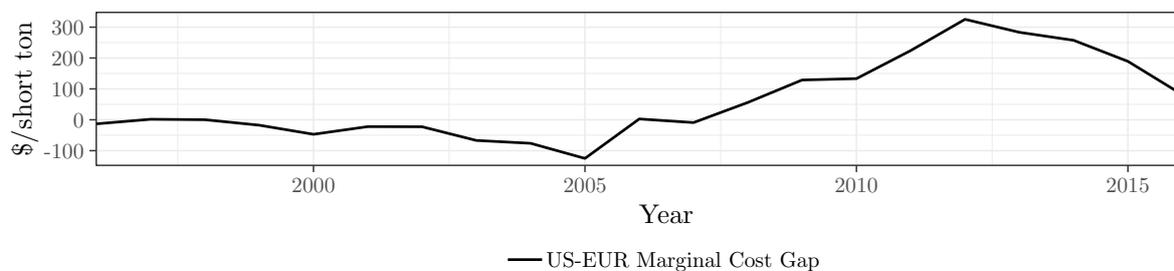
Note: In panel (a), ammonia production has been calculated adjusting regional nitrogen production data according to ammonia's 82% nitrogen content. Under the label US we also include production data for Canada. EUR represents Western and Central Europe.
Source: Authors, Bloomberg/Green Markets and IFA

Online Appendix

A5. Model Extension: Transportation Costs

In the baseline model we assume that there are no transportation costs. We now release this assumption in line with a classical model of (Brander, 1981).

However, since we focus our analysis on the price impact of local cost shocks, we do not set the transportation costs in a fixed proportion to the product price as in the classical model. Instead, we just set it to a constant per unit price t.

The introduction of transportation costs extends the producer problem. Now each producer needs to decide independently how much to produce for a local market and how much for the export market. The cost of producing for the local market is the marginal cost of production c, while the marginal cost for the export market is the sum of the marginal production cost and transportation cost $(c + t)$.

Thus, we define $q_{i,A,A}$ as the production of a producer i located in region A for the domestic market, $q_{i,A,B}$ as the production of a producer i located in region A for the export market, $q_{i,B,B}$ as the production of a producer i located in region B for the domestic market, and $q_{i,B,A}$ as the production of a producer i located in region B for the export market.

To make the total market size identical to the baseline case, we assume that the demand function on each of the markets is equal to the half of the global demand show earlier, thus $P_r = a - 2*b*Q$.

The assumption on the capacity constraints remains unchanged, however now we have to consider production for markets such that $q_{i,r,r} + q_{i,r,-r} \leq q_i^*(1 + \theta)$, where q_i^* is the equilibrium production quantity when $\Delta = 0$ and transportation costs are t, while θ is the scaling factor. For $t = 0$, the capacity constraint is at the same level as in the baseline model. Our assumption implies, however, that the capacity constraints become tighter as the transportation costs increase, but this does not qualitatively affect our results.

Similarly, as in the case without transportation costs, for each individual firm, we have a profit function that we can solve to get $q_{i,r,r}^*$ $q_{i,r,-r}^*$, the optimal quantities for the local and

export markets. This yields the profit functions for each region:

$$\pi_{i,A,A} \;=\; q_{i,A,A}\left(a - 2*b(Q_{B,A} + Q_{-i,A,A} + q_{i,A,A}) - (c + \Delta)\right),$$

$$\pi_{i,A,B} \;=\; q_{i,A,B}\left(a - 2*b(Q_{B,B} + Q_{-i,A,B} + q_{i,A,B}) - (c + \Delta + t)\right),$$

$$\pi_{i,B,B} \;=\; q_{i,A,A}\left(a - 2*b(Q_{A,B} + Q_{-i,B,B} + q_{i,B,B}) - (c)\right),$$

$$\pi_{i,B,A} \;=\; q_{i,B,A}\left(a - 2*b(Q_{A,A} + Q_{-i,B,A} + q_{i,B,A}) - (c + t)\right)$$

$$,$$

where $Q_{r1,r2}$ represents total output of producers in region $r1$ for market $r2$. $Q_{-i,r1,r2}$ is production of all producers in region $r1$ for market $r2$ other than firm i.

Interior solution. Following the steps presented in the description of the base model, we can calculate optimal quantities in an unconstrained case with the optimal quantities shown in the equation below.

$$q^*_{i,A,A} \;=\; \frac{a - c - \Delta - (\Delta - t)(n\,(1 - s_A))}{2b\,(n + 1)} \tag{24}$$

$$q^*_{i,A,B} \;=\; \frac{a - c - \Delta - t - (\Delta + t)(n\,(1 - s_A))}{2b\,(n + 1)} \tag{25}$$

$$q^*_{i,B,B} \;=\; \frac{a - c + (n\,(s_A)\,(\Delta + t))}{2b\,(n + 1)} \tag{26}$$

$$q^*_{i,B,A} \;=\; \frac{a - c - t + (n\,(s_A)\,(\Delta - t))}{2b\,(n + 1)} \tag{27}$$

$$\tag{28}$$

The higher the transportation costs, the higher the share of production sold locally.

The necessary condition for the interior solution to hold is a sufficiently low shock. The case-by-case analysis is made more complicated with transportation costs as we need to check if these costs are sufficiently low such that the export production is not negative. This substantially increases the number of conditions to analyze. In particular, we identify the following possibilities.

Starting with values of Δ close to zero, we have the interior solution and producers in A and B produce both for local and foreign markets (**Case 1**). As the value of Δ increases, pro-

ducers in A decrease production for both export and local markets, while producers in region B increase production for both markets. Depending on the level of capacity constraints, we consider two paths. If capacity is sufficiently slack at B, A decreases export production until it drops to 0, focusing on the local market only (**Case 2**). Further increase in Δ makes the producer in A drop production completely (**Case 3**), while B continues production for both local and foreign market. However, if the level of spare capacity is not sufficiently high, we also need to consider the case that as Δ increases, producers at B reach full capacity while producers at A produce both for local and for export market (**Case 4**), or that producers at B reach full capacity only when producers in A stop exporting (**Case 5**). In such a case, producers in B need to change their allocation strategy, equating marginal revenues from export and domestic production given the capacity constraint, rather then setting it to marginal cost as in the unconstrained case.

As Δ decreases, symmetrically, a further four cases are to be considered in which producers in A increase production and producers in B decrease production in response to the shock. If capacity is sufficiently slack at A, producers in B may drop exports, producing only for local markets (**Case 6**). Further decrease in Δ makes the producer in B drop production completely (**Case 7**). However, if the level of spare capacity is not sufficiently high, we also need to consider the case that as Δ decreases, producers at A reach full capacity while producers at B still produce both for local and for export markets (**Case 8**), producers at A reach full capacity only when producers in B stop exporting (**Case 9**). In contrast to cases 4 and 5, changes in Δ to not affect the production decisions of the unconstrained producer, thus the allocation between domestic and export markets remains unchanged for all lower values of Δ after A's capacity constraint is reached.

The large number of cases to consider makes describing the full equilibrium a tedious process that may not be worth the reader's time. We will instead focus on a single example, in which we assume $A = 2$, $B = 2$, $c = 1$, $s_A = 0.5$, $n = 2$, and $t = 7/16$. In other words, a symmetric case in which in each region there are two producers and transportation costs amount to 7/16 of production cost.

With those parameters, for values of Δ close to zero, both regions produce for domestic

and export markets (Case 1). For a positive shock, as Δ increases, producers in region A reduce their production both domestically and for export, until their export production reaches zero (Case 2). A further increase of Δ makes producers at B reach their capacity constraints. Now with capacity constraints binding, the producers in B need to make sure the marginal revenues from export and domestic sales are equal (Case 4). Thus, a further increase in Δ, which leads to further reduction of A's domestic production, implies that producers in B shift part of their domestic production for export—producers in B reduce domestic production in order to enjoy higher prices at the export market. We therefore observe non-monotonicity of B's domestic and export production levels (though, not in the total production). Further increase in Δ leads to shutting down production A's domestic production.

For a negative delta, as Δ decreases, producers at A reach capacity constraint before producers at B cease production (Case 8) and production remains on the same level also for lower values of Δ.

Those observations are summarized in Figure A5, in which production decisions of producers in A and B (for both domestic market and export) as well as prices in each market are presented. As we can see, as long as Δ is not too high, predictions from the model without the transportation hold. For higher values of Δ, however, we observe a deviation from the original model. Once producers in region A stop exporting to B, price in B settles, while price in A continues to increase with Δ, as local producers keep decreasing production in response to higher production costs. The cost pass-through of a local shock increases once producers in B reach capacity constraint. For higher values of Δ, as producers in A keep reducing domestic output, foreign producers start relocating part of their production from domestic to foreign market. Prices in both regions increase. Finally, the price stabilizes once Δ is so high that producers in B cease production.

The model can be extended further, for example by adding additional regions, but it quickly becomes intractable. For a numerical solution to a multiregional model with capacity constraints, we refer the reader to Alsabah et al. (2021).

Impact of local shocks on regional production and prices in a model with transportation costs

Quantity, Producers in A

Cost Shock (Δ)

— Domestic   -- Export

Quantity, Producers in B

Cost Shock (Δ)

— Domestic   -- Export

Market Price

Cost Shock (Δ)

— Region A   -- Region B
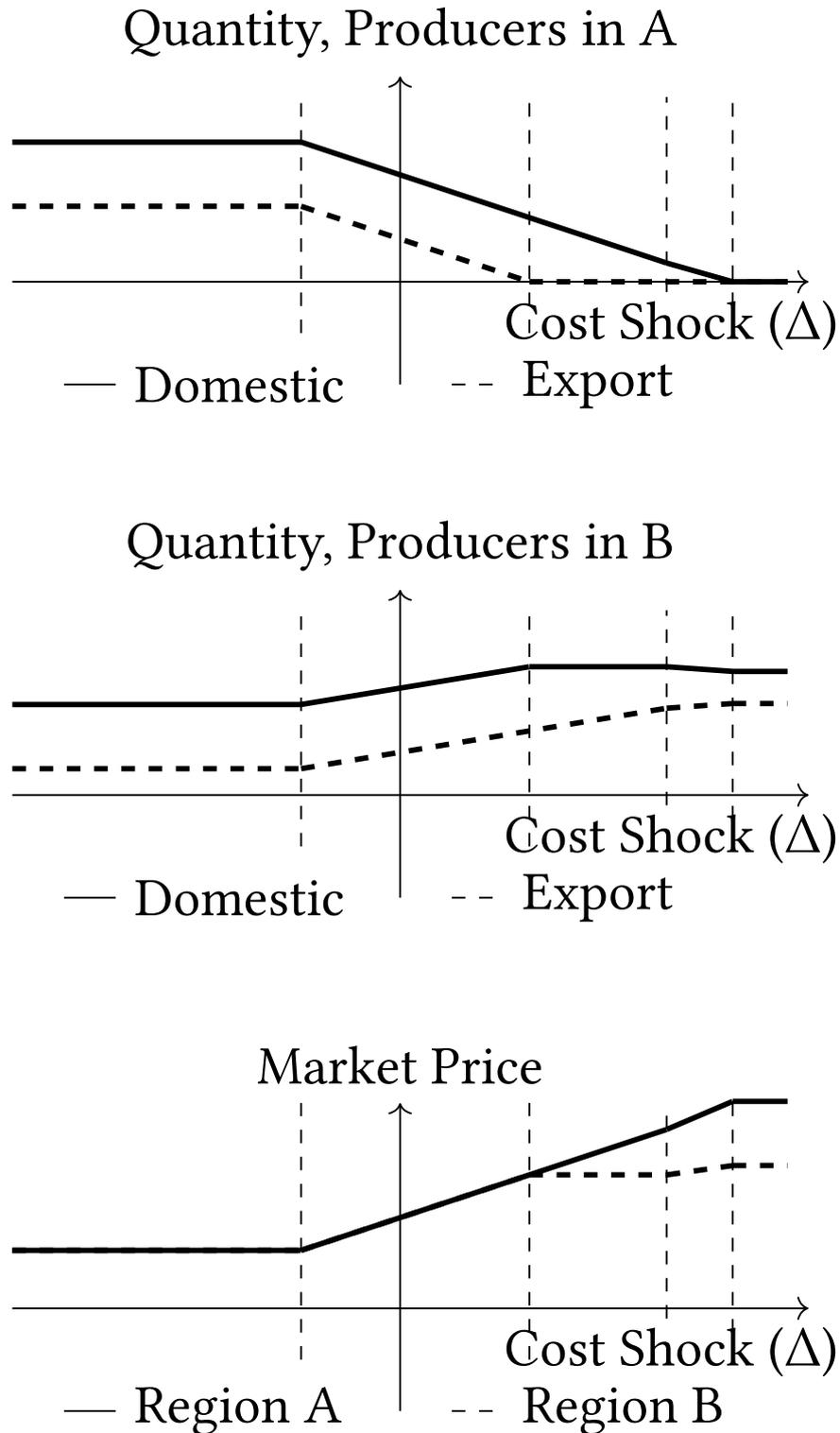
Source: Authors. *Note:* In the figure, the following values of parameters were assumed: $A = 2$, $B = 2$, $c = 1$, $s_A = 0.5$, $n = 2$, $t = 7/16$. Dashed vertical lines represent threshold at which various constraints bind.