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Experience curve for natural gas production by hydraulic fracturing

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ABSTRACT

From 2007 to 2012 shale gas production in the US expanded at an astounding average growth rate of over 50%/yr, and thereby increased nearly tenfold over this short time period alone. Hydraulic fracturing technology, or "fracking", as well as new directional drilling techniques, played key roles in this shale gas revolution, by allowing for extraction of natural gas from previously unviable shale resources. Although hydraulic fracturing technology had been around for decades, it only recently became commercially attractive for large-scale implementation. As the production of shale gas rapidly increased in the US over the past decade, the wellhead price of natural gas dropped substantially. In this paper we express the relationship between wellhead price and cumulative natural gas output in terms of an experience curve, and obtain a learning rate of 13% for the industry using hydraulic fracturing technology. This learning rate represents a measure for the know-how and skills accumulated thus far by the US shale gas industry. The use of experience curves for renewable energy options such as solar and wind power has allowed analysts, practitioners, and policy makers to assess potential price reductions, and underlying cost decreases, for these technologies in the future. The reasons for price reductions of hydraulic fracturing are fundamentally different from those behind renewable energy technologies – hence they cannot be directly compared – and hydraulic fracturing may soon reach, or maybe has already attained, a lower bound for further price reductions, for instance as a result of its water requirements or environmental footprint. Yet, understanding learning-by-doing phenomena as expressed by an industry-wide experience curve for shale gas production can be useful for strategic planning in the gas sector, as well as assist environmental policy design, and serve more broadly as input for projections of energy system developments.

1. Introduction

Hydraulic fracturing is the process of drilling into a rock formation and injecting at high pressure a mixture of sand, water, and chemicals with the goal of extracting gas or oil from known fossil fuel reserves. This technique, combined with advancements in horizontal drilling technologies, spurred the massive increase of shale gas production in the US over the past 10 years. Beginning around 2005, the shale gas revolution has helped the US reach unprecedented levels of natural gas production. Between 2007 and 2012 shale gas production in the US expanded at an average growth rate of more than 50%/yr (EIA, 2015b).[1] Shale gas production through hydraulic fracturing grew nearly tenfold over this time frame, and the fraction of total natural gas produced through fracturing technology (today around 50%) has increased dramatically.

Unsurprisingly, the increase of unconventional gas production impacted the US natural gas market, causing a sharp decline in the wellhead price (Mazur, 2012). As hydraulic fracturing techniques and drilling technology continue to develop, resulting in additional production increases, further price declines are possible. Both the private and public sectors value analysis regarding the potential effects on market prices of continued growth in unconventional gas production. In this article, based on an inspection of progress achieved in the field of hydraulic fracturing technology so far, we provide an indicator for potential future gas price reductions.

While plenty of literature exists on price and manufacturing cost reductions, as well as on learning-by-doing phenomena, for a large range of energy technologies (see e.g. McDonald and Schrattenholzer, 2000; Nemet, 2006; Greaker and Sagen, 2008; van Benthem et al., 2008; Neij, 2008; Schoots et al., 2010), comprehensive research on price reductions for the use of hydraulic fracturing technology has not yet been undertaken. As production of unconventional natural gas continues to grow, it is insightful to investigate past and prospective

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[1] Although extraction of natural gas in the US rapidly increased from around 2007, commercial hydraulic fracturing began to take hold about two years earlier, initiating exponential growth of production. We therefore use 2005 as marker for the start of the shale gas revolution

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gas price developments. This article presents an experience curve for the US natural gas industry from the start of the shale gas revolution. We examine the impact of increased shale gas production on the wellhead price of natural gas, and show that a learning-by-doing trend exists that reflects past achievements deriving from the accumulation of experience. This trend may be indicative for future price developments, or even for the prospects of the gas industry as a whole. We present an experience curve that may provide insight into one of the factors determining future gas price levels and that, complemented with other price development indicators as well as ancillary knowledge on limitations to its extrapolation, could possibly be used as empirical information for strategic considerations in industry, as background material for public policy planning, or as input for climate change mitigation research. For instance, in principle this experience curve could be implemented in integrated assessment models as used for low-carbon energy technology diffusion studies such as by the Intergovernmental Panel on Climate Change (IPCC, 2014), although such models normally require cost-data rather than price-based information as input. We end our article by reflecting on whether a price floor for natural gas production could soon be reached, and by listing some of the factors that may slow down future price declines or, inversely, contribute to price increases. We hereby connect to recent literature on this subject matter (see notably IEA, 2015, as well as Aleklett, 2015).

2. Experience curve

Experience curve analysis is a method for expressing the relationship between *price* reductions and cumulative production of a good or technology. The experience curve is related to the learning curve, which is a way of illustrating the relationship between *cost* reductions and cumulative production (see Wene, 2000), for details on the distinction between these two concepts). Based on the correlation between price and production observed for the past, experience curves yield information for potential price reductions in the future. The steepness of the experience curve, expressed by the value of the learning rate, identifies the rapidity of structural market, manufacturing, or industry change for in principle any technology. The experience curve methodology stipulates that every doubling of cumulative production of a certain commodity or technology generates a constant relative reduction (in %) of its price, which is the learning rate.

Both engineers and economists have developed and used experience curves to assist the formulation of public policy as well as the design of investment strategies. They have, for instance, done so for renewable energy technologies, the price of which – partly in response to private sector initiatives and public policies stimulating their deployment – has fallen steadily in recent times, as producers and users exercise economies-of-scale and gain experience from learning-by-doing and other mechanisms. Analyzed over extended periods of time, technological learning involves stable long-term price declines, while studies over short-term time scales give evidence of price evolutions with sometimes great variability that occasionally yields much higher or substantially lower learning rates for brief intervals than the long-term average. Manufacturing processes or entire industries for energy technologies, like for technologies in many other sectors, can be characterized by a median learning rate of typically around 20% (McDonald and Schrattenholzer, 2000).

For many technologies, experience curves have been developed from a perspective of industry-wide learning (see, for example, Ferioli et al., 2009). This is the approach we also adopt here. In order to determine an experience curve for hydraulic fracturing in the natural gas industry, we gathered historical shale gas production data and price level data from the US Energy Information Administration (EIA, 2014). In Fig. 1 we reproduce the cumulative shale gas production and wellhead price data that we retrieved for the US between 1997 and 2015. We converted these data into SI units and expressed prices in constant US(2009)$ terms. Since the publication of US natural gas wellhead prices ceased in 2012, we had to deduce the wellhead price data for 2013–2015: in the Appendix we explain how we did this. Natural gas prices may be subject to a variety of factors that are undesirable from an experience curve analysis point of view, including market fluctuations and manipulations, supply constraints and demand uncertainties, but for our purpose – determining an industry-wide learning rate – these are the most representative data that we could possibly retrieve.

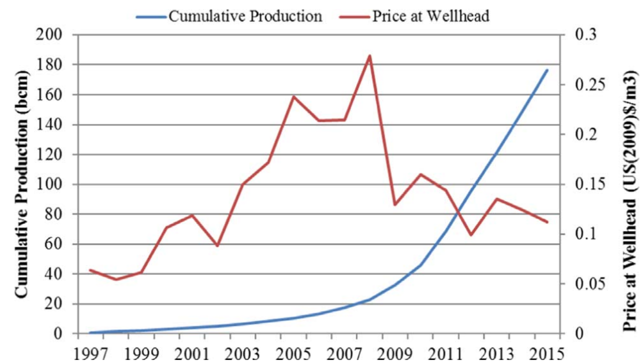

Fig. 1. Cumulative Production of Shale Gas and Price of Natural Gas. (Data from 1997 to 2015).

Two clear trends can be detected in Fig. 1: (1) cumulative production of shale gas has increased exponentially over the past decade, and (2) the wellhead price of natural gas has significantly decreased since about 2007, roughly by a factor of two.[2] This observation inspired us to create an experience curve for the industry using hydraulic fracturing technology, by expressing the recently achieved reductions in natural gas prices as function of the cumulative production of shale gas in this industrial sector. The starting point for our experience curve analysis is 2005, since this year represents the beginning of the shale gas revolution. The equation below is used to determine the experience curve, the slope of which is the learning rate, which constitutes a measure for the progress recently attained by the natural gas industry.

$$P(x) = P(x_0)\left(\frac{x}{x_0}\right)^{-L}$$

x: Cumulative output
$P(x)$: Price at cumulative output
L: Learning parameter
$LR = 1-2^{-L}$: Learning rate

Through a regression of our data on the basis of this equation it is easy to visualize the experience curve and calculate the learning rate as the relative reduction of natural gas prices (in %) with every doubling of cumulative production of shale gas. The experience curve we constructed is shown in Fig. 2, which clearly illustrates the learning effect. As is common practice for this methodology, our data are plotted on a double-logarithmic scale, since this allows for the direct calculation of the learning rate based on the steepness of the downward sloping straight line. Due to a lack of publicly available data on specific production costs, the data used in this graph are the wellhead prices

[2] Note that during the early years of the decade prior to 2005 natural gas prices also were particularly low. An explanation for this early price dip falls beyond the scope of this paper.

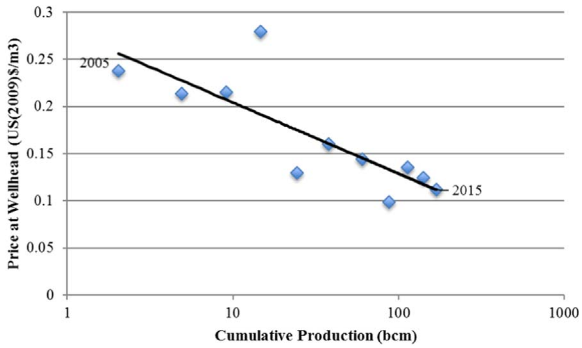

Fig. 2. Experience Curve for Natural Gas Production by Hydraulic Fracturing. (Data reported by the EIA, converted from real US$ per thousand cubic feet to constant US(2009)$ per cubic meter (EIA, 2014). This experience curve therefore represents learning-by-doing by the entire shale gas industry, and not by individual companies creating or using hydraulic fracturing technology.

The experience curve depicted in Fig. 2 captures the shale gas revolution from a perspective of industrial production and price data in the period 2005–2015. The learning rate of this curve is 13%, that is, a doubling of shale gas output results on average in a 13% fall in constant US(2009)$ terms of the price of natural gas. The R^2 of this regression is 0.66, hence the fit is reasonable but implies by no means a conclusive statistical reliability. In order to derive a statistically more significant experience curve, future analysis should incorporate a larger data set, ideally covering at least two orders of magnitude of expansion of cumulative production of shale gas, as pointed out in Ferioli et al. (2009). The 13% steepness of our learning curve is an indicator for the speed of experience gained by the industry from new hydraulic fracturing technologies and drilling techniques.

Technologies themselves do not learn, but systems of human interactions producing and/or using these technologies. The experience curve (or learning curve) therefore measures the improving performance of the learning system (see e.g. Wene, 2000, pp. 27–30, figure 2.1). For any experience curve analysis, the basis of investigation is formed by the nature, extent, and boundaries of the learning system. Given the type of data that we used, our learning rate represents a measure for the know-how and skills accumulated thus far in the US shale gas industry, and thus not for the experience gathered by individual entities manufacturing or employing hydraulic fracturing technology. In other words, the learning system in our case is represented by the ensemble of project teams developing, generating, applying, operating and maintaining hydraulic fracturing technology, as well as the exploration teams in search of viable shale gas plays, and possibly still other parts of the natural gas industry including e.g. organizational, logistical, and infrastructural components of it. Our analysis does not allow for exposing learning phenomena within sub-systems of the shale gas industry. Such analysis could perhaps be undertaken in the future, for which other approaches – and especially data – are needed than the ones we adopted for this paper.

Identifying membership and boundaries of the shale gas learning system, for which the industry-wide experience curve is depicted in Fig. 2, is necessary to provide new insights for industrial strategies and public policy. Yet it is complex, possibly considerably more so than for e.g. photovoltaic (PV) modules. Likewise intricate, but equally important, is defining the input and output of the learning system. The input to our learning system is knowledge and human drive for industrial discovery and progress that create new experience with innovative fracking technology. Output of the system is the price of natural gas, and especially the reduction thereof through shale gas production. Wellhead prices seem a reasonable proxy for the performance of the learning system, since they determine to a large extent how natural gas competes in the market place. For sub-systems of the natural gas industry better proxys may exist. For example, production costs may be a good proxy for the fracking technology development process. But this is not the focus of our present work – one of the reasons being that production costs are intrinsically hard to obtain, for industrial confidentiality and competitivity reasons.

3. Discussion

There is significant empirical support for the existence of experience-curve relationships between price and cumulative capacity from all fields of industrial activity (Wene, 2000). For example, the price of PV technology has experienced a decline by a factor of nearly 100 since the 1950s in a way that neatly matches an experience curve with a learning rate of around 20%. 'True' learning-by-doing, however, is only one of several possible contributing explanations for technology price reductions, as mechanisms such as economies-of-scale, automation, and R & D may also play a substantial role (see e.g. Nemet, 2006, for the case of PV). Moreover, demand variabilities, policy interventions, and knowledge spillovers also may have a sizeable effect on experience curve behavior. Market dynamics therefore need to be taken into consideration when developing an experience curve for any technology, and when extrapolating it if the technology is at an early stage of development. The more orders of magnitude of cumulative capacity the experience curve is established on, the more reliable the associated learning rate usually is. Even then, however, extrapolating it may be unwarranted: experience curves eventually tend to plateau when technologies mature, involving a reduction in the learning rate, which implies that less price reductions materialize per doubling of cumulative production (see e.g. Ferioli et al., 2009). If our hydraulic fracturing experience curve is used for assessing future natural gas production prices, these issues definitely need to be accounted for.

For well-established markets and technologies, the remaining available doublings of cumulative capacity may limit the scope for learning in the future. For example, for coal power plants based on conventional technology the global volume required to double cumulative sales to date is close to 2000 GW. This shows that even when the technology is still subject to learning, there is minimal room left for additional price reductions as not much more experience can be acquired in the relatively stable coal market (Wene, 2000). But for nascent markets and technologies, such as shale gas production, the extrapolation of the experience curve may bear more relevance, as the many possible usages of natural gas proffer ample opportunity for continued growth. We here inspect more closely the extent to which the experience curve for hydraulic fracturing implies opportunity for further price reductions in the future.

There are a number of factors that can limit the further production of unconventional gas. Correspondingly, there are factors affecting the stability of the experience curve, both internal (or endogenous) and external (or exogenous) to the learning system defined above. The distinction between these two types of factors is policy relevant, because internal disturbances may threaten the survival of the learning system, while the learning system may have mechanisms to handle external disturbances (see, e.g., Wene, 2015). We here discuss a number of external disturbances, i.e. factors potentially affecting the learning rate available in the learning system's environment. External factors, such as more severe environmental constraints or regulation, or lack of water resources, will most likely increase the cost of the technology or process involved, and may show up – at least temporarily – as a reduction in the learning rate. It has been argued, however, that such an apparent reduction in the learning rate does not necessarily mean that the system stops learning altogether, that is, that the system ceases to improve its performance (Wene, 2015). Some analysts therefore contest the existence of a "price floor" for learning technologies or industries, such as in our case for shale gas production through hydraulic fracturing. They point out that a lack of price reductions does not per se imply a failure of the experience curve; a lack of price reductions in diminishing markets, for example, may actually confirm rather than disprove the experience curve. Despite the absence of overall discernable learning, learning phenomena may still be at work e.g. at the sub-system or technology component level, but these may be out-shadowed by other developments (see Ferioli et al., 2009).

Exogenous limitations to the deployment of hydraulic fracturing technology include the use of chemicals, fugitive emissions, water scarcity, and public opinion. These factors are important to consider when assessing the correlation between output and price reductions. In Europe, public opposition to hydraulic fracturing continues to act as a major limiting factor to unconventional gas development, whilst concerns regarding subsurface and surface environmental impacts are carefully weighed against uncertain social and economic benefits. Drinking water contamination from chemicals used in the hydraulic fracturing process is one of the chief public health fears of European citizens. Governments in the EU also worry that the development of domestic unconventional gas production would be irreconcilable with climate change commitments, due to the possibility of methane leakage during the extraction process and because emissions of greenhouse gases need to be precluded altogether during the 2nd half of the century. Given the lack of comprehensive and conclusive studies into the effects of the hydraulic fracturing process, an understandable level of uncertainty exists surrounding some of these exogenous factors or environmental externalities. As these reflections indicate, the learning observed in recent years for the US shale gas industry may not directly translate (or 'spill over') into similar learning in other parts of the world, such as in Europe: regional learning variations may be sizeable.

With regards to water usage in the extraction process, a scientific consensus already seems to exist regarding the potential harmful effects of hydraulic fracturing on groundwater levels. Large amounts of water are needed in the hydraulic fracturing process. While volumes differ depending on the geology and location of the play, the average well to be hydraulically fractured requires some 14,5 million liters of water (Jackson et al., 2014). In many water-scarce areas, the hydraulic fracturing process contributes to the depletion of groundwater levels and, in some cases, competes with other industries that rely on water. Unconventional gas production through hydraulic fracturing can have an adverse impact on the subsistence of aquifers and can directly interfere with water allocation for municipalities, livestock, and irrigation purposes.[3] The externality of local water depletion may hinder further development of hydraulic fracturing in many places in the world. Consequently, an exogenous limitation may exist that could soon imply a lower bound to the experience curve for hydraulic fracturing, in line with the method suggested by Ferioli et al. (2009).

Likewise, policy developments can influence the experience curve for hydraulic fracturing. Regulation of chemicals, fugitive emissions, and water usage may increase the price of this technology. Inversely, such regulation could also yield learning-by-doing for new technological developments, involving e.g. the use of more efficient or less chemicals, recycling hydraulic fracturing water, and sourcing brackish and municipal wastewater. How these respective upward and downward drivers for price changes will play out is hard to predict. Certain high-cost producers may initially find it difficult to compete in a new regulatory environment. Switching to water-free hydraulic fracturing could add about 25% onto production costs (Kiger, 2014), which could yield a floor to the hydraulic fracturing experience curve under conditions of water scarcity.

[3] While water requirements for hydraulic fracturing are significant, in comparison to water usage for hydropower, biofuel production, and other water-intensive sources of energy, hydraulic fracturing may remain the more efficient option in some cases.

It is particularly pertinent to examine the role that international oil markets may play on unconventional gas production, in the US and elsewhere, when the effects of policy developments on the hydraulic fracturing experience curve are investigated.[4] Increased unconventional oil production in the US, reduced demand from Europe, and a constant output maintained by OPEC, led to an oil supply glut in December 2014. Oil prices experienced a 40% drop in comparison to June that year, reaching a level below US$60/barrel. In an effort to maintain its market share, OPEC – led by Saudi Arabia – continued to keep output constant as more US oil entered the market. As a result, in January 2016 the international benchmark oil price briefly dipped under US$30/barrel. While the outlook for oil prices remains uncertain, it is important to consider the effects of a low oil price when analyzing the future of shale gas production in the US.

In the short-term, low oil prices will probably not significantly affect unconventional gas output in the US, essentially for two reasons: (1) investors have already incurred fixed production costs, therefore producers of shale gas will maintain output so long as variable costs are met; and (2) low oil prices squeeze out the least-efficient older shale gas rigs, allowing the more efficient ones to continue production. While rig count has been the traditional proxy for production estimates, gains in rig efficiency mean that a declining rig count will not necessarily be followed by a decline in production.

In the medium- to long-term a persistently low oil price could have a greater effect on shale gas production. Cuts in capital expenditures can influence the hydraulic fracturing experience curve. US oil and gas producers are expected to slash their budgets by 51% between 2014 and 2016 (WSJ, 2016). A producer's capital structure determines its ability to finance future projects. Companies that take on large amounts of debt to fund hydraulic fracturing projects have little choice but to keep producing in a low-price environment in order to generate cash for interest payments. If oil prices continue to stay low, producers will be forced to restructure, sell assets, or even in some cases declare bankruptcy.

Financial distress of producers may put pressure on the experience curve if output declines in the future. Since 2015, over 50 North American oil and gas producers have filed for bankruptcy (Haynes and Boone, 2016). If producers' assets are found to be less valuable than their outstanding debt, raising future debt for new projects may be difficult. This will limit access to capital and hinder developments of new wells. The experience being gained in some shale gas plays may slow down or even stop. Producers with assets in low-cost dry-gas formations (such as the Marcellus play in the eastern US) are more likely to sustain production and thus contribute positively to the hydraulic fracturing experience curve. Producers in high-cost wet-gas plays, however, may need to let output levels drop or cease their activity.

In addition to the factors listed above, which all can influence the future of US shale gas production, the adoption of hydraulic fracturing technologies outside the US should also be considered. If exogenous limitations to pursuing hydraulic fracturing in the US cannot be appropriately addressed and hinder a continued decrease of shale gas prices following the experience curve, there may still be potential for price reductions through reverse technology transfer. Applying the US unconventional gas revolution to other parts of the world with shale reserves, such as in China, may result in further technology development and improvement for hydraulic fracturing. These technological advances can then be reapplied to the hydraulic fracturing industry in the US and hence induce further price reductions.

[4] Oil and gas production streams are still linked by common drilling hardware and, in some cases, even produced from the same wells (with natural gas sometimes produced as 'by-product' of oil production). More generally, oil and gas markets and prices are still intimately related to each other. Although it is difficult to formulate a correlation between oil prices and natural gas production, the effect of the former on the latter is important to consider, e.g. for investment purposes.

If production continues to increase, natural gas prices will ultimately reach a lower bound. Eventually wellhead prices will hit a floor at some given output level. The timing of such a price floor will depend on a number of factors, including the price itself, and the floor price may actually have been reached already. At the start of the US shale gas revolution producers benefited from high oil and gas prices, which allowed investments to flow into unconventional gas projects. The high price environment brought many hydraulic fracturing projects online, which resulted in greater efficiency measures and lower costs, as expressed in the experience curve for hydraulic fracturing gas prices. If today an end to the experience curve for hydraulic fracturing has already been reached, will the current low price environment continue to hold in the future? Not necessarily.

In the 2015 Annual Energy Outlook, the EIA projected that natural gas prices in the US would continue to decline in 2016 (EIA, 2015a). For the next couple of decades, it thinks gas prices will rebound and may follow a steady increase. The projected climb in prices is based on the assumption that domestic and international demand for natural gas will increase. Growing demand for US pipeline and LNG exports is projected to put upward pressure on the Henry Hub spot price. Also, lower-cost shale gas reserves are expected to be extracted first, leaving more expensive production to take place later. The projected price increase over the next several decades may itself in fact push back further learning-by-doing and associated gas extraction cost reductions.

Benefits from additional learning for hydraulic fracturing are not necessarily confined to the hydrocarbon industry. Efficiencies gained from shale gas production may also be applied to other uses. Geothermal energy production, for example, currently uses a technique similar to hydraulic fracturing to release searing water trapped in the Earth's crust. In “Enhanced Geothermal Systems” (EGS), fracture networks are created in rocks by injecting under high pressure a mixture of water and chemicals into vertically driven wells. Underground hot water can thus be released and surface water pumped underground, heated and sent back to the surface to generate electricity (TEM, 2014). EGS can extend the size and life of existing geothermal fields, but are currently hampered by a lack of commercialization. Applying the hydraulic fracturing experience curve to geothermal energy generation is one way to show possible price reductions in this domain, as a result of an increase in production through the use of advanced techniques. Applications in other sectors can motivate the calculation of experience curves such as in our case for hydraulic fracturing.

4. Conclusion and policy implications

Since 2005 shale gas production in the US through hydraulic fracturing has grown exponentially, and today has reached unprecedented levels. This large shale gas supply increase has forced wellhead prices down. Indeed, the shale gas revolution in the US has shown the impact hydraulic fracturing technology has had on increasing natural gas production and associated price reductions. In this paper we have presented an experience curve with a learning rate of 13% for shale gas production through hydraulic fracturing as observed over the past decade in the US. This experience curve may be helpful for industry planners and policy makers in efforts to estimate the trajectory of future shale gas prices, both within and outside the US, and to assess opportunities for applying hydraulic fracturing technologies in other countries around the world. The price reduction trend illustrated by our hydraulic fracturing experience curve provides insight into future shale gas price levels at given levels of output.

While this experience curve may help illustrating the “learning-by-doing” effect for hydraulic fracturing in the US, it must be handled appropriately in order to offer robust and reliable considerations for energy policy making and strategic purposes. In particular due attention needs to be given to the fact that experience curves eventually level off. The important question that still needs to be answered is when and at what total cumulative capacity this leveling off will occur for hydraulic fracturing (see Ferioli et al., 2009). Also, experience curves themselves offer little explanation with regards to the underlying technological change, reasons for learning, and causality between cumulative output and price reductions of production (Yeh and Rubin, 2012). In our case, much still needs to be understood with regard to why precisely learning occurred in the US shale gas industry: was it due to an increased number of wells drilled, or maybe the number of wells completed per square kilometer, or perhaps the number of fracture stages, or possibly higher production volumes per well drilled? These are the sorts of questions that further research could potentially answer. In order to better place our experience curve and corresponding price-production relationship into perspective, we have discussed some of the main factors that may affect the experience curve for hydraulic fracturing into the future.

As the US transitions to the world's top natural gas producer, there are a number of factors to consider that may advance or hinder further unconventional gas production. Tighter regulations for the use of chemicals and water may on the one hand obstruct further gas price declines, while on the other hand encouraging further technological development of hydraulic fracturing as producers are forced to become more efficient in the production process. At the same time, stricter policy measures to regulate where and how a well may be hydraulically fractured can potentially result in reduced production. Such exogenous factors can affect the shape and slope of the hydraulic fracturing experience curve. Continued increases in output will eventually lead to a point at which the wellhead price of natural gas no longer falls. Such a price floor, hotly debated by specialists in the industry, implies a flattening of the experience curve. Further research is needed to assess the potential effects of low gas prices. Too low a spot price may limit unconventional production, while too low a wholesale price may create an oversupply problem. More analysis is also required on R&D investment trends and on the application of hydraulic fracturing technology outside the US and in other (energy) sectors.

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Appendix: post-2012 data

Since 2012 the EIA discontinued its estimates of well-head prices, due to conceptual issues associated with the data series obtained until then. In order to obtain price points for 2013 and 2014, we used the average natural gas prices for those years for the lower-48 US states from EIA's 2015 Annual Energy Outlook (EIA, 2015a). In order to obtain the price point for 2015, we used the lower-48 average natural gas price for that year from EIA's (2016) Annual Energy Outlook (EIA, 2016). Note that EIA (2016) did not include lower-48 average prices prior to 2014. We converted all price data into constant US(2009)$ terms using historical GDP deflators provided by the US Bureau of Economic Analysis (BEA). Both wellhead price data and lower-48 average prices were initially expressed in terms per thousands of cubic feet (ft^3). These data were converted into cubic meters (m^3) terms on the basis of a conversion factor of 28.32. The ensuing data set for the period 2005–2015 yielded a learning rate of 13% with R^2=0.66 statistical reliability.

In an earlier version of our analysis (with data points only up to 2014), we adopted a slightly different approach to retrieving post-2012 data. In order to obtain price points for 2013 and 2014, we used a cross-plot linear regression for historical wellhead prices and Henry Hub (HH) prices to achieve a best fit (with as outcome $y=1.18x-0.01$ (R^2=0.98). From this equation we extrapolated the 2013 and 2014 wellhead prices. The HH spot price for 2014 was not given as annual average, hence we obtained it by averaging the monthly EIA HH spot price for that year. Wellhead price data were converted from thousands ft^3 to billion cubic meters (bcm, or billion m^3) by applying a factor of 0.02832. The ensuing data set for the period 2005–2014 yielded a learning rate of 10% with R^2=0.67 statistical reliability, hence largely consistent with the result obtained above through our alternative method for obtaining post-2012 data. This sensitivity test demonstrates the robustness of our analysis with regard to the time period chosen and the way in which we obtained and/or deduced our data.

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