Citation: Massol, O. & Rifaat, O. (2018). Phasing out the U.S. Federal Helium Reserve: Policy insights from a world helium model. Resource and Energy Economics, 54, pp. 186-211. doi: 10.1016/j.reseneeco.2018.08.003

Phasing out the U.S. Federal Helium Reserve:
Policy Insights from a World Helium Model ☆

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July 2018

☆ This paper has greatly benefited from the judicious comments of Albert Banal-Estañol, Rachid Boularas, Samuel Burton, Richard Clarke, Jeremy Eckhause, Florian Fizaine, Robert Jolley, Florian Perrotton, Arthur Thomas and an anonymous referee from the French Association of Environmental and Resource Economists (FAERE) for insightful suggestions. Remaining errors are, of course, our responsibility. This work was supported by the Chair "The Economics of Natural Gas". The views expressed herein are strictly those of the authors and should not be construed to reflect the opinions of IFP Énergies Nouvelles, IFP School or City, University of London.

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Phasing out the U.S. Federal Helium Reserve: Policy insights from a world helium model ☆

Abstract

This paper develops a detailed partial equilibrium model of the global helium market to study the effects of the recently decided rapid phase out of the U.S. Federal Helium Reserve (FHR), a vast strategic stockpile accumulated during the 1960s. The model incorporates a detailed representation of that industry and treats both helium producers and the FHR as players in a dynamic non-cooperative game. The goal of each player is assumed to be the maximization of discounted profit, subject to technical and resource constraints. We consider two alternative policies aimed at organizing the phase out of the FHR: the currently implemented one and a less stringent one whereby the FHR would be allowed to operate as a profit-maximizing agent during an extended period of time. Evidences gained from a series of market simulations indicate that, compared to the current policy, a less stringent policy mandate systematically increases the financial return to the U.S. federal budget, always enhances environmental outcomes as it lowers helium venting into the atmosphere, and also augments global welfare in three out of the four scenarios considered in the paper.

Keywords: Helium economics; Strategic reserve; Resource conservation; Imperfect competition; Partial equilibrium modeling.

JEL Codes: Q38; Q31; L72; L78; Q02.

1. Introduction

The worldwide consumption of helium, a noble gas that combines a number of remarkable properties,[1] is growing rapidly. This natural element is used in a number of advanced technologies (e.g., leak detection, chromatography, welding under inert conditions) and is a nearly non-substitutable input in a disparate set of activities including fiber-optic technology, electronic manufacturing (e.g., semiconductors, flat panels), rocket launching (to purge the fuel tanks), and cryogenics. Helium is also critically needed to cool magnetic resonance imaging (MRI) scanners, a now essential diagnostic tool for the medical community. During the years 2007–2013, that historically stable market experienced a series of noticeable supply shortages and unusually high prices.[2] Given the critical importance of that commodity for our modern societies, helium suddenly emerged as a source of political concern (NRC, 2010; Nuttall et al., 2012a; Glowacki et al., 2013) and the future availability of helium resources subsequently became the topic of a burgeoning literature authored by science and technology experts.[3] The present paper provides a complementary perspective as it details an economic analysis of the world helium market and examines the rationale of a U.S. government policy: the 2013 Helium Stewardship Act (HSA).

Helium is an exhaustible finite resource. Though helium is naturally present in the atmosphere, its concentration is so low that the cost of separating it from the air is prohibitive. Commercial helium is thus obtained as an optional by-product of a second exhaustible resource: natural gas. Helium can be separated from the gas streams extracted from a limited number of helium-rich natural gas deposits. If not separated, the helium in fuel gas is typically wasted as it dissipates in the atmosphere when the gas is burned without significantly increasing the atmospheric concentration of helium.

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[1] *Helium has the lowest boiling point of any substance, is the second-best gaseous conductor of heat and electricity, and is the second lightest element.*

[2] *"The price of helium, Inflated," The Economist, May 3, 2007.*

[3] *For example, Cai et al. (2010) report a joint research effort by scientists and industrial experts at Cambridge (UK) that culminated in the development of a detailed system dynamics model of the world helium industry. Another example is the analysis in Mohr and Ward (2014) which has its methodological roots in the geoscience literature.*

To conserve helium resources, a vast strategic stockpile – the Federal Helium Reserve (FHR) – was accumulated by the U.S. government as part of the country's cold war efforts during the 1960s. It was then expected that the revenues obtained from the sales of the stored helium during the 1970s would permit a recovery of the cost of the FHR by 1980 (Epple and Lave, 1982). However, that plan failed and the U.S. government had to wait until 1996 before being able to start reselling its reserve (NRC, 2000). In 2013, the U.S. Treasury debt accumulated through the helium program was finally paid back, yet nearly a third of the original stockpile still remained. As a result, that long-awaited debt repayment convinced the U.S. Congress to pass the 2013 HSA instructing the federal government to: (i) rapidly deplete the remaining inventory – the Act imposes the sale of a flow of helium, equal to the amount the FHR can produce, each year – and (ii) subsequently cease its commercial operations. Accordingly, the federal government's commercial operations are expected to cease in 2022.

The purpose of this paper is to examine the economics of this rapid phase out of the FHR. Deciding how much helium to extract from the remainder of the Federal Reserve requires answering more general questions about the allocation of helium resources over time, the potential future demand by helium-dependent technologies, the potential new sources that may become available in the future, and the nature of the strategic interactions among helium producers. To the best of our knowledge, such a methodologically sound analysis was not conducted to guide the provisions in the 2013 Act. The two main informal arguments that motivated the 2013 Act can be summarized as follows. First, because of the progressive depletion of the underground reservoir, the annual production capacity of the FHR is expected to gradually fall in the coming years, thereby providing an opportunity for a smooth phase out of the FHR. Second, new sources of helium, both foreign and domestic, will shortly become available, thereby limiting the need for FHR supplies in the near future. Nevertheless, it is not certain that the proposed extraction trajectory maximizes the present discounted value of the profits from federal sales nor that this is a socially desirable policy. As the federal sales represented approximately 30 percent of the global helium supplies in 2013 (USGS, 2015), one may wonder whether the rapid resource extraction pattern stipulated in the 2013 Act could artificially generate low prices, thereby blurring the functioning of the helium market and distorting the firms' decisions.

To investigate the extraction trajectory that should be considered by the U.S. federal government, we propose a computerized dynamic model of the international wholesale helium market aimed at evaluating helium production and investment strategies. This deterministic, discrete-time, finite-horizon oligopoly model is formulated as an open-loop, Nash non-cooperative dynamic game that is solved numerically. Using this model, a series of simulations under markedly different scenarios are conducted to determine the optimal resource extraction patterns for the FHR and quantify their economic impact on both the world helium market and the U.S. federal treasury. Overall, we believe that this multi-period model is a valuable tool for public decision makers, professionals, and scholars interested in the politically sensitive issues observed in the helium sector.

Our analysis highlights that the rapid resource extraction path falls short of the policy objective to maximize the "returns to the American taxpayers". Implementing a slower extraction pattern has the potential to bring about sizeable gains to the U.S. Treasury. Depending on the scenario, we found that the present discounted value of its future stream of net revenues would rise by between +25.5 percent and +61.0 percent. Another important finding is that such an augmentation is not necessarily obtained at the expense of the consumer surplus and is welfare-enhancing in three out of the four scenarios examined in this paper. Lastly, we observe that the rapid phase out of the FHR occasions a net waste of helium which is estimated to be on the order of 122.8–533.2 MMcf.

From a methodological perspective, the rich literature on dynamic-games (e.g., Dasgupta and Heal, 1979; Dockner et al., 2000; Long, 2011) typically focuses on parsimonious continuous-time models that are analytically tractable. In the present paper, we examine the market equilibrium of a detailed model for which an analytical solution is virtually out of reach but, following Mathiesen (1985) and Rutherford (1995), a numerical one can be obtained by reformulating the market equilibrium problem as an instance of a mixed complementarity problem (MCP).[4] In recent years, a growing literature has applied that methodology to investigate a variety of issues including: the impact of a CO_2 regulation on power investment and electricity prices (Fan et al., 2010; Lise et al., 2010); the effects of

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[4] *An MCP is a square system of nonlinear inequalities that represent the economic equilibrium through zero marginal profit and market balance conditions determining equilibrium quantities and prices (Cottle et al., 1992; Gabriel et al., 2012a; Murphy et al., 2016).*

renewable energy penetration in Europe for gains from trade and carbon dioxide emissions in the power sector (Abrell and Rausch, 2016) or the strategic behavior of producers in either power (Bushnell, 2003; Pineau et al., 2011), natural gas (Gabriel et al., 2005; Egging et al., 2008; Holz et al., 2008; Gabriel et al., 2012b; Abada et al., 2013), oil (Huppmann and Holz, 2012) or coal industries (Haftendorn and Holz, 2010; Trüby and Paulus, 2012; Trüby, 2013). This paper represents the very first application of that method to model the helium industry.

At an empirical level, this paper contributes to the small, and very much needed, literature attempting to shed a light on helium economics. It should be noted that there is a dearth of recent economic analyses of the world helium market. The existing economics literature on that inert gas is limited to the U.S. market and predominantly dates back to the 1980s when the U.S. dominated the world helium market . At that time, the discussion chiefly revolved around the issue of the rationale for U.S. governmental stockpiles. In one of the very first articles analyzing the economics of helium, Epple and Lave (1980) present an early numerical model of the U.S. helium industry. Drawing upon the operations research literature, they formulate a mathematical programming problem aimed at determining the optimal rate of helium production and storage (private and public) over time that would maximize the discounted social welfare. In this model, the rate of natural gas production is assumed to be exogenous. The model is solved numerically under a series of alternative scenarios, combining two possible demand projections and three possible values for the discount rate. The results do not provide any justification for government intervention in the helium industry.

Other related works, though more loosely connected to ours from a methodological perspective, are the empirical studies in Liu (1983) and Uri (1986, 1987). In these articles, a structural econometric model of the helium market is specified and estimated to either build supply and demand projections (Liu, 1983; Uri, 1987) or empirically confirm that demand and industry supply respond to normal market forces (Uri, 1986). The case of helium extraction has also motivated a handful of contributions in the theoretical literature on natural resources economics. For example, the analytical model in Pindyck (1982) considers the joint extraction of two finite exhaustible resources forming a composite ore and examines how the price trajectory of each resource depends on its demand, and the demands and storage costs of the other resource. The article uses a continuous time formulation and shows that the competitive market will extract, produce, and store at socially optimal rates if firms are risk-neutral and the average cost of storage is constant. The results provide little economic justification for government programs aimed at stockpiling helium. Further extensions of that analytical framework are given in Hughey (1989) where the role of helium demand in the market equilibria for both natural gas and helium is investigated, and in Hughey (1991) which assesses the economics of three subsidy policies that could be implemented in the helium sector.

The paper is organized as follows. In the next section, we clarify the background. The third section presents the framework of our analysis and details the conceptual structure of a computerized model of the global helium market. Section 4 contains our simulation results and the last section offers a summary and some concluding remarks. For the sake of clarity, Appendix A summarizes the nomenclature and Appendix B presents the calibration of the demand function. The cost and geological parameters used in our market simulations are detailed in Appendix C.

2. Background and motivation

This section briefly reviews the history of the U.S. strategic helium reserve and the recent trends observed in the global helium market with the aim to clarify both the background and the motivation of our analysis.

2.1 The build-up of the Federal Helium Reserve

From 1917 to 1961, the U.S. government had a monopolistic position in the global production of helium, and government agencies and their contractors were its primary consumers. In the early 1960s, a conjunction of factors—including the depletion of the government’s helium-rich deposits and the perceived strategic importance of helium for both defense and space exploration—convinced Congress to authorize an ambitious conservation policy: the creation of a strategic stockpile of helium at an underground reservoir at the Cliffside gas field near Amarillo, Texas. Under this Helium Program, the U.S. Bureau of Mines was instructed to: (i) invest in a helium pipeline infrastructure connecting the helium-rich gas deposits in Kansas, Oklahoma, and Texas to that storage site; and (ii) buy almost all the helium that these natural gas producers could produce under negotiated long-term contracts, thereby encouraging them to invest in helium separation capabilities.

On the premise that helium demand would rise exponentially, the aim of the program was to store volumes in the 1960s that would be needed in the 1970s. Sales of the stored helium in the 1970s were to take place at a price calculated to recover the costs incurred by the federal government by 1980. However, in the early 1970s, it became evident that lower-than-expected demand levels would materialize during this decade. In 1973, the U.S. government ceased accumulating helium and canceled the purchase agreements. The sudden suspension of these purchases caused a considerable resource waste as private helium separation plants were mothballed and an annual volume of 2.2 billion cubic feet (Bcf) of unsold helium resources were again vented into the atmosphere (Sears, 2012). To conserve helium, in 1975 the U.S. Bureau of Mines decided to allow those private companies with separation plants connected to the federal gathering system to store privately-owned helium in the Cliffside reservoir. Since then, this storage service has been offered at cost and has enabled diminished helium venting in the U.S. One should note that even today this is still the unique facility in the world, allowing private storage of helium.

2.2 The long-awaited repayment of the helium-related federal debt

During the 1970s and 1980s, the helium market experienced an enduring oversupply situation and private firms were selling helium at a lower price than the posted price for governmental helium. This posted price was administratively determined on the basis of the historical cost of the helium program. As there was no demand for federal helium at that price, the federal inventory remained unchanged (Epple and Lave, 1982). Over the years, the growing cost of the helium-related federal debt recurrently questioned the economic rationale of government intervention in that industry. In his presidential address to the American Economic Association, T.C. Koopmans deplored that economic reasoning played no role in the decision to build the strategic helium reserve: it was motivated solely by arguments over future demand projections anticipating the effective deployment of radically new technologies without assessing the costs and benefits of that policy (Koopmans, 1979).

During the late 1980s, a growing global consumption of helium was observed and helium prices gradually increased to approach parity with the posted price of the U.S. Bureau of Mines (Sears, 2012). This situation opened a policy debate on how to optimally clear the federal helium inventory. In 1995, the responsibility for operating the helium program was transferred to the U.S. Bureau of Land Management (BLM).

In 1996, the Congress passed the Helium Privatization Act that instructed the BLM to privatize its helium-purifying facilities, sell the helium reserve in the Cliffside reservoir by 2015 and organize the cessation of the FHR operations by no later than 2015. The main policy objective pursued in the 1996 Act was to organize the repayment of the $1.4 billion debt accumulated by the helium program. The provisions in the 1996 Act were thus aimed at ensuring that the revenues derived from these sales would be sufficient to repay the federal government for its helium-related spending, including the historical purchasing cost, the investment cost in the supporting infrastructure, and the interest. This was done using a minimum price formula based on historical cost figures that stipulated, for each year, the minimum price above which federally-owned helium could be sold.

2.3 An optimal phase out of the Federal Helium Reserve?

By October 2013, the debt had surprisingly been paid off ahead of schedule and yet a third of the original federal stockpile (i.e., approximately 10.8 Bcf) still remained. As the provisions in the 1996 Act did not envisage the continued operation of the helium program after the repayment of the federal debt (U.S. Government Accountability Office, 2013), this sooner-than-expected reimbursement generated anxiety among market participants as some feared it could end with a brutal shutdown of the FHR, causing an immediate shortage of helium.[5] The Congress thus enacted the ‘Helium Stewardship Act’ of 2013 that allocates a volume of 3 Bcf to future noncommercial uses (e.g., national security uses, federally-funded scientific research) and secures the continued commercial operation of the reserve until the remaining volume of federally-owned helium in the reserve attains that 3 Bcf threshold. The BLM’s commercial operations (i.e., the federal helium sales and the provision of private storage service

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[5] *“Helium, inflation warning,” The Economist, September 28, 2013.*

to helium producers connected to the BLM's helium pipeline infrastructure) are compelled to cease afterwards.

From a practical perspective, the 2013 legislation introduces a radical change in the pricing mechanism used for disposing of the federal helium sales as it instructs the BLM to implement an auction mechanism. The move toward a market-oriented pricing mechanism for the federal sales of helium represents a policy response to the preceding BLM's pricing policy that was judged inadequate and may have delayed the industry's efforts to develop alternative helium sources (NRC, 2010).[6] In the present paper, we do not explicitly model the BLM auction but rather consider that the federal helium is sold at the market clearing price in the world helium market.

The 2013 Act also instructs the BLM to offer for sale in each year a quantity of helium set at the maximum total production capacity of the Federal Helium System. The technical staff at the BLM thus conducted a series of detailed reservoir engineering studies to identify the maximum production capacity that could be attained by the FHR in each year. Figure 1 summarizes the outcome of these engineering studies and presents the 2014–2029 time-path that gives the maximum amount of helium that can be extracted in each year from the FHR as a function of the remaining reserve that year. If this "as-fast-as-technically-possible" extraction trajectory is effectively implemented by the BLM, there will be annual sales of diminishing volumes until 2022 (i.e., over nine years), at which point the 3 Bcf threshold triggering the cessation of the BLM's commercial activities will be attained.

Figure 1. The time-path of the FHR's planned production trajectory

[PLEASE INSERT FIGURE 1 HERE]

Given the relative sizes of the FHR and the world helium market, one may wonder whether this rapid extraction trajectory could have a negative impact on helium prices. Surprisingly, to the best of our knowledge, economic considerations played no role in the determination of that extraction

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[6] *One of the unintended consequences of the 1996 Act was that the BLM's posted price gradually became a market benchmark for the global price of helium in the contracts signed by private industrial gas companies. During 2007–2013, there was a global shortage of helium but the posted price of federal helium remained close to the minimum price established in the 1996 Act and was thus predominantly based on historical cost figures with little or no consideration for the actual value of helium.*

trajectory which was solely derived from technological concerns. The purpose of the present analysis is thus to examine the economic rationale for such a rapid depletion strategy for the FHR. In particular, we aim at comparing the market outcomes obtained under the 2013 Act with those obtained with a hypothetical policy that allows the BLM to conduct commercial operations during an enlarged period of either 13, 18 or 23 years.

2.4 A changing world helium scene

The global helium market has recently undergone a series of fundamental changes and taking them into account is critical when attempting to analyze the impacts of the proposed closure of the FHR.

First, from a global perspective, helium supply has long been dominated by the U.S. but most new sources are developing elsewhere. Between 2008 and 2013, the U.S. share of worldwide helium extraction capacity declined from 75.5 percent to 66.1 percent (IHS, 2014). The other helium-producing nations are: Poland (1.6% of the 2013 global capacity), Russia (2.6%), Algeria (11.9%), Qatar (15.5%), China (0.1%), and Australia (2.2%). Further capacity expansions are scheduled to start up in the coming five years in Algeria and Qatar. In addition, Russia is endowed with substantial helium reserves in the remote, undeveloped gas fields in East Siberia and could also soon emerge as a major producer in the world helium market. The state company Gazprom is currently developing these fields to export natural gas to China and has also unveiled ambitious plans to install large-scale helium separation facilities there. Helium production could commence after 2020 and, if fully developed, that project could make Russia the world's largest helium producer. Nevertheless, it is believed that this project will have to be phased because of both the size of the project and the lack of infrastructure in this remote area (Gasworld, 2016). The exact timing and magnitude of this phased development are still unknown but, given its size, this Russian project is likely to have an important impact on future helium prices.

Second, within the U.S., the industry structure is also expected to radically change as helium production will severely decline owing to the accelerating net depletion of the natural gas fields in Texas, Oklahoma, and Kansas, and the associated decline in extraction capacity. New projects are currently being developed in other areas not connected to the BLM pipeline infrastructures (e.g., in Wyoming, Colorado) but production at these new sites will not be sufficient to compensate that decline.

Because of the coming depletion of the private sources in the mid-continent region and the planned termination of federal sales, the country is expected to become a net importer in the near future (NRC, 2010).

Lastly, the global helium industry exhibits a concentrated market structure as supply depends on a small number of separation plants worldwide. Though competition exists in the U.S. industry, this is not the case in other countries where all the local plants are controlled by the national oil company (e.g., Algeria, Qatar, Russia). The degree of industry concentration is thus expected to increase as global helium production shifts outside the U.S. The three largest players together controlled 42.9 percent of the global helium separation capacity in 2013 and will control up to 47.5 percent in 2018 (IHS, 2014). This cumulative share could possibly increase to 63 percent after 2020 if the Russian project is developed at full capacity. Therefore, any partial equilibrium model of the world helium market should capture the oligopolistic nature of that industry.

3. Model

In this section, we first present an overview of our modeling framework. Then, we present a detailed description of the market participants and their associated optimization problems. Lastly, a final subsection discusses the solution strategy.

3.1 Overview

The present analysis is based on the World Helium Model (WHM), a detailed partial equilibrium model that applies principles from game theory and optimization to simulate the global helium marketplace. The WHM is formulated as a deterministic, discrete-time, finite-horizon oligopoly model that explicitly takes into account the imperfectly competitive structure of the world helium industry. It portrays the strategic interactions between two main types of suppliers: the U.S. federal government – represented by the BLM – that operates the federal helium reserve, and the private firms separating helium from natural gas. To account for the heterogeneous nature of the constraints and decisions problems observed in the private sector, the private sector is further disaggregated using a typology of three mutually exclusive groups of firms: (i) the existing companies processing helium from neighboring gas fields where future production cannot increase, (ii) the U.S. firms with plants connected to the BLM's storage system, and (iii) the firms that can invest in new helium processing equipment.

In the WHM, all individual suppliers are depicted as profit-maximizers under certain constraints, with a distinctive revenue and cost structure for each supplier type. Consistent with the industrial organization observed in the helium markets, the WHM assumes that some of these agents can behave à la Cournot and exert market power (by withholding supplies to force up prices for larger profits) whereas the others are price-takers. The behavior and strategy sets of these agents are further detailed in the next subsection. The market equilibrium modeled in the WHM emerges from the joint solution of the separate optimization problems faced by the suppliers taken together with market-clearing conditions.

3.2 Formulation of the World Helium Model[7]

We consider a discrete time model with periods $t \in \{0,1,...,T_H\}$ that have a standard duration of one year and aim at modeling the decisions to be taken in years $t \in \mathrm{T} := \{1,...,T_H\}$ where T_H is the time horizon. We also let $\{1,...,T_{BLM}\}$ denote the first periods during which the BLM is allowed to conduct commercial operations (i.e., these operations cease at the end of the year T_{BLM}, with $T_{BLM} < T_H$). Hereafter, we assume that the time horizon T_H is large.

We let J denote the set of all the suppliers. This set is decomposed into mutually exclusive subsets $J := \{BLM\} \cup J_1 \cup J_2 \cup J_3$ where the subsets J_1, J_2 and J_3 respectively denote: the subgroup of the private companies processing helium from neighboring gas fields where future production cannot increase, the U.S. firms with plants connected to the BLM's storage system, and the private suppliers that are capable of expanding their future annual production of helium. We let q_t^j denote the quantity of helium supplied by agent j in year t.

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[7] *Please note that, to ease readability, a nomenclature summarizing the notation is detailed presented in Appendix A.*

In the remainder of this subsection, we explicitly write out the market-clearing conditions and the optimization problem for each individual market participant, including the objective function and constraints. We use the following convention: if in the optimization problem of an agent j, a variable has an asterisk, this indicates that this variable is exogenous to the agent's problem but endogenous to the market model. For example, a price-taking agent naïvely views the price variable as fixed even though the full market model equilibrates price to equate supply with demand.

a – The demand side

The world demand is modeled using a linear demand function. We assume that d_t the total quantity of helium demanded in year t for all uses (e.g., cryogenics; pressurizing and purging; controlled atmospheres; welding cover gas; leak detection; breathing mixtures) is a strictly decreasing function of the helium price p_t, an increasing function of the lagged consumption, and is parameterized by an exogenous term y_t representing the aggregate real income:

$$d_t = \alpha y_t - \gamma p_t + \lambda d_{t-1}, \qquad \forall t \in \mathrm{T},\ d_0 \text{ given.} \tag{1}$$

where the income coefficient α, the price coefficient γ and the lagged coefficient λ are empirically-determined parameters (with $\alpha > 0$, $\gamma > 0$ and $0 \le \lambda < 1$).

From that definition, it is straightforward to define the linear inverse demand functions that gives, in each year t, the willingness-to-pay the price p_t as a function of both the present and lagged consumption levels: $p_t = P_t\left(d_t, d_{t-1}\right)$.

b – The market clearing conditions

The market-clearing conditions tie the separate helium producers' optimization problems defined hereafter to the simplified representation of the demand side. The market clearing condition at time t ensures balance between global supply and demand by forcing demand and supply to equilibrate:

$$\sum_{j \in J} q_t^j = d_t, \qquad \forall t \in \mathrm{T}. \tag{2}$$

c – The BLM

This agent controls the extraction operations conducted at the FHR. We let q_t^{BLM} denote the non-negative quantity extracted and sold to commercial users by the BLM in each year t. We use the convention that the BLM's remaining reserve R_t is measured at the end of year t (i.e., once the quantity q_t^{BLM} has been extracted and sold). At the end of 2013 (year 0), the BLM is endowed with the initial reserve R_0.

We assume that the BLM is allowed to conduct commercial operations during T_{BLM} years after which its reserve level must be equal to $\underline{R}$ (i.e., the 3 Bcf allocated to non-commercial uses stipulated in the 2013 Act).

In this paper, we consider two alternative extraction behaviors for the BLM. The first one follows the rapid extraction path stipulated in the 2013 Act whereas the second one is derived from the solution of on an optimization problem.

The rapid extraction trajectory in the 2013 Act (BLM – Model I)

Recall that the 2013 Act imposes a predetermined and rapid extraction trajectory: it instructs the BLM to offer for sale in each year a quantity of helium set at the maximum total production capacity of the federal helium system until the 3 Bcf reserve threshold is attained. With that rapid extraction path, the desired reserve threshold is attained in year 9 (see Figure 1). So, we set $T_{BLM} = 9$ years and consider the following extraction trajectory:

BLM – Model I ($T_{BLM} = 9$)

$$q_t^{BLM} = \overline{Q_t^{BLM}}, \qquad \forall t \in \{1,...,T_{BLM} - 1\}, \qquad \text{(BLM I–1)}$$

$$q_t^{BLM} = R_0 - \underline{R} - \sum_{t'=1}^{(\overline{T_{BLM}} - 1)} \overline{Q_{t'}^{BLM}}, \qquad \text{for } t = T_{BLM}, \qquad \text{(BLM I–2)}$$

$$q_t^{BLM} = 0, \qquad \forall t \in \{T_{BLM} + 1,...,T_H\}. \qquad \text{(BLM I–3)}$$

where $\overline{Q_t^{BLM}}$ is the annual production ceiling of the federal helium system in year t indicated in Figure 1. Equation (BLM I–1) compels the BLM to offer for sale in each year a quantity of helium set at the maximum production capacity during the period 2024-2021 (i.e., in years 1 to 8). In year 9, equation (BLM I–2) imposes the BLM to extract the residual quantity allocated to commercial operations (i.e., the difference between the total amount allocated to commercial operations $\left(R_0 - \underline{R}\right)$ and the cumulated volumes extracted during the previous years). The BLM is then compelled to cease its supplies in subsequent years (equation (BLM I–3)).

The case of a possibly slower extraction trajectory with Cournot behavior (BLM – Model II)

As one can question the rationality of that imposed "as-fast-as-technically-possible" extraction trajectory, we explore the economics of an alternative policy prescription that would allow the BLM to operate over a possibly longer horizon of T_{BLM} years, with $T_{BLM} \geq 9$. Under that alternative mandate, the BLM is no longer compelled to adopt the fastest extraction path and can consider possibly slower trajectories. One has thus to clarify: (i) how the geological considerations at the Cliffside reservoir restrict the player's decisions and (ii) the behavior of that player.

Regarding the former, the trajectory in Figure 1 suggests that, in each year t, the production ceiling at the Cliffside reservoir can be approximated by an empirically-determined linear function of R_{t-1} the reserve available when year t begins: $\eta R_{t-1} + \mu$ where η and μ are two positive parameters.[8] We thus proceed, assuming that in each year t the quantity extracted by the BLM cannot exceed the value determined by that linear function.

Regarding the latter, the policy objectives mentioned in the 2013 Act explicitly stipulate that the BLM's sales must be conducted so as to "*maximize the total financial return to the taxpayer*" (Helium Stewardship Act, 2013) which suggests that the BLM can be modeled as a profit-maximizing agent. Furthermore, even if the BLM's market share in the international market is compelled to diminish in the future because of the depletion of its reserve, the BLM is likely to remain a significant player during the

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[8] *The assumption of a linear relation between the annual production capacity of an underground reservoir and the remaining reserve at the beginning of the year is frequently retained in models of the oil industry (e.g., Griffin and Teece, 1982).*

early years of the planning horizon. Therefore, we assume that this agent is able to behave à la Cournot and thus to assess how the agents' extraction decisions are modifying equilibrium prices.

We thus consider the following optimization problem.

BLM – Model II ($T_{BLM} \geq 9$)

$$\underset{q_t^{BLM}}{\text{Max}} \quad \Pi_{BLM} = \sum_{t=1}^{T_{BLM}} \beta_{BLM}{}^{t} \left[P_t \left(q_t^{BLM} + q_t^{-BLM*}, q_{t-1}^{BLM} + q_{t-1}^{-BLM*} \right) - C_{BLM} \right] q_t^{BLM} \qquad \text{(BLM II–1)}$$

$$\text{s.t.} \quad q_t^{BLM} \leq \eta R_{t-1} + \mu, \qquad \forall t \in \{1,...,T_{BLM}\}, \qquad \text{(BLM II–2)}$$

$$R_t = R_{t-1} - q_t^{BLM}, \qquad \forall t \in \{1,...,T_{BLM}\}, \; R_0 \text{ given}, \qquad \text{(BLM II–3)}$$

$$R_{T_{BLM}} = \underline{R}, \qquad \text{(BLM II–4)}$$

$$q_t^{BLM} \geq 0 \qquad \forall t \in \{1,...,T_{BLM}\}. \qquad \text{(BLM II–5)}$$

where β_{BLM} is the discount factor, q_t^{-BLM*} is used as a short notation for the aggregate quantity of helium supplied by the rivals, C_{BLM} is the unit extraction cost, R_t is the reserve in year t. The objective function (BLM II–1) is the discounted sum of the BLM's annual profits, which are the result of revenues from sales minus production costs. Consistent with the Cournot framework, the aggregate quantity q_t^{-BLM*} is exogenous to the BLM's optimization problem. The geological constraint (BLM II–2) stipulates that, in each year, the quantity extracted cannot be larger than the production ceiling. Equation (BLM II–3) is the reserve accounting identity that keeps track of the BLM reserves. The constraint (BLM II–4) imposes the remaining reserve at the end of the BLM's commercial operations to attain the targeted reserve threshold.

d – The helium separators

We now examine the behavior of the private firms that separate helium from the natural gas extracted at neighboring fields. These market participants are modeled as profit-maximizing agents. In each year t, they do not directly control the flow of the helium-rich gas extracted from the underground reservoirs but they do decide the quantities of helium separated from that flow and sold in the global marketplace.

We successively present the optimization problems for each of the three distinct types of private helium suppliers.

The existing separators with non-increasing future helium-processing capacities

We first consider the subgroup $J_1 \subset J$ that gathers all the helium producers who process helium from neighboring natural gas fields where there will be no further increase in annual production in the future. Accordingly, we let $\overline{H_t^j}$ denote the maximum quantity of helium that can be extracted by producer j in year t. This quantity is determined by two factors: the volume of natural gas supplied to j's separation plant, and the helium concentration in that feed gas. As none of these factors are controlled by j, we assume that the trajectory of $\overline{H_t^j}$ is exogenously determined.[9] We also assume that the installed capacity at each of these helium separation plants is sufficient to process $\overline{H}_t^j$ thereby eliminating the need for further capacity expansion at these plants.

The sizes of the plants in that category are heterogeneous as they include some very big players such as the current world's largest helium production facility (Exxon's LaBarge Shute Creek in Wyoming) and smaller ones (e.g., the helium plants at the Keyes field in Oklahoma and at Odolanów in Poland). While it seems natural to posit that the big players are likely to behave à la Cournot and could conceivably exert market power, that assumption makes little sense for the smaller ones that are more likely to behave as price-taking agents. Hence, there is a producer-specific behavior for each agent in that subgroup. The agents and their individual behaviors will be clarified in the application section.

The producer maximizes profits resulting from selling helium net of the costs. In algebraic terms, the problem is to solve the following optimization program:

$$\underset{q_t^i}{\text{Max}} \quad \Pi_j = \sum_{t \in \mathrm{T}} \beta_j^t \left[\left(1-\delta_j\right) p_t^* + \delta_j P_t \left(q_t^j + q_t^{-j*}, q_{t-1}^j + q_{t-1}^{-j*} \right) - C_j^e \right] q_t^j \qquad (\mathrm{J}_1\text{–}1)$$

$$\text{s.t.} \quad q_t^j \le \overline{H_t^j}, \qquad \forall t \in \mathrm{T}, \qquad (\mathrm{J}_1\text{–}2)$$

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[9] *Hence, we follow Epple and Lave (1980) and assume that helium-specific issues (e.g., prices, supply, demand) play no role in the upstream decisions taken by the natural gas producers who supply the helium separation units.*

$$q_t^j \geq 0, \qquad \forall t \in \mathrm{T}. \qquad (\mathrm{J}_1\text{–}3)$$

where β_j is the players' discount factor,[10] q_t^{-j*} is the aggregate quantity of helium supplied by the rivals, and C_j^e is the unit cost incurred to purchase and refine crude helium from the natural gas producers. The objective function (J$_1$–1) represents the discounted sum of the producer's annual profits which are the revenues from helium sales net of the costs. In that function, the producer-specific binary parameter δ_j indicates whether that agent has a perfect competitive behavior ($\delta_j = 0$) or a Cournot oligopolistic behavior ($\delta_j = 1$). In the former case, the player naïvely considers the price variables p_t^* to be exogenous to his optimization problem whereas in the latter case the player explicitly considers the inverse demand functions $P_t(.)$ in the objective function. The constraints (J$_1$–2) state that helium sales at time t cannot exceed the maximum available quantity $\overline{H_t^j}$ at that date. If the solution of that program is such that, in a given year t, the constraint (J1–2) is not binding, the associated slack $\overline{H_t^j} - q_t^j \geq 0$ can be interpreted as a waste, as that quantity of helium is not separated and will end up being vented in the atmosphere when the fuel gas is burned.

The U.S. separators connected to the BLM infrastructure

The subgroup $J_2 \subset J$ includes the private producers in Kansas, Oklahoma, and Texas that process helium from the natural gas streams extracted from the Reichel, Hugoton, Panoma, and Panhandle fields. Natural gas production at these fields is either plateauing or already steadily declining because of forthcoming geological depletion. Compared to the producers in J_1, the agents in J_2 are physically connected to the federal pipeline infrastructure. They can thus stockpile helium for later sale using the private helium storage service offered at cost by the BLM.[11] The provision of this private storage service will cease once the BLM's commercial operations have been terminated.

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[10] *As the players in our model do not operate in the same region and under the same economic conditions, it makes sense to suppose that they can discount their profits using possibly different rates.*

[11] *Because of the specific structure retained for these storage contracts, the BLM is compelled to use a cost-reflective pricing policy for this service and thus cannot strategically use the provision of that service to maximize its own profits (NRC, 2000).*

Neglecting capacity constraints on the injection and withdrawal operations at the storage site, the behavior of a producer in J_2 can be modeled using the following optimization problem:

$$\underset{q_t^i, h_t^j, i_t^j, w_t^i, v_t^i}{\text{Max}} \quad \Pi_j = \sum_{t \in \mathrm{T}} \beta_j^{\,t} \left[\left[\left(1-\delta_j\right) p_t^* + \delta_j P_t \ \left(q_t^j + q_t^{-j*}, q_{t-1}^j + q_{t-1}^{-j*} \right) \right] q_t^j - C_j^e h_t^j - C_j^i i_t^j - C_j^w w_t^j - S\ v_t^j \right] \quad (\mathrm{J_2}\text{–}1)$$

$$\text{s.t.} \quad h_t^j \le \overline{H_t^j}\,, \qquad \forall t \in \mathrm{T}, \qquad (\mathrm{J_2}\text{–}2)$$

$$q_t^j + i_t^j = h_t^j + w_t^j\,, \qquad \forall t \in \mathrm{T}, \qquad (\mathrm{J_2}\text{–}3)$$

$$v_t^j = v_{t-1}^j + i_t^j - w_t^j\,, \qquad \forall t \in \mathrm{T},\ v_0^j \text{ given}, \qquad (\mathrm{J_2}\text{–}4)$$

$$v_t^j = 0, \qquad \forall t \ge T_{BLM}\,, \qquad (\mathrm{J_2}\text{–}5)$$

$$q_t^j \ge 0,\ \ h_t^j \ge 0,\ \ v_t^j \ge 0,\ \ i_t^j \ge 0,\ \ w_t^j \ge 0, \qquad \forall t \in \mathrm{T}. \qquad (\mathrm{J_2}\text{–}6)$$

where C_j^i, C_j^w and S are the unit cost parameters associated with storage operations and the non-negative decision variables are: q_t^j the annual sales, h_t^j the annual quantity of helium separated from the stream of natural gas, v_t^j the total volume of helium stored at the end of the year (the initial storage v_0^j is given), i_t^j (respectively w_t^j) the annual quantity of helium injected into (respectively withdrawn from) the storage site. The objective function (J$_2$–1) is the discounted sum of the producer's annual profits, which are the result of revenues from sales minus the sum of $C_j^e h_t^j$ the total cost to purchase crude helium from the natural gas producers and refine it, $C_j^i i_t^j$ the total cost of the injection operations conducted at the storage site, $C_j^w w_t^j$ the total cost to extract and purify the helium extracted from the storage site, and $S\ v_t^j$ the storage cost. Again, the binary parameter δ_j indicates whether that producer has a perfect competitive behavior ($\delta_j = 0$) or a Cournot oligopolistic behavior ($\delta_j = 1$). The constraints (J$_2$–2) state that production of helium from natural gas at time t cannot exceed the annual production ceiling $\overline{H_t^j}$. The equation (J$_2$–3) is a balance identity that states that, in each year, the sum of the sales plus the quantity injected into the storage is equal to the sum of the quantity obtained from natural gas separation plus the quantity withdrawn from the storage site. The equation (J$_2$–4) is an accounting identity that keeps track of the storage volume. The constraint (J_2–5) imposes the termination of the storage operations at the end of the BLM's time horizon.

The separators with possibly new helium-processing capacities

The subgroup $J_3 \subset J$ gathers the firms that are capable of investing to further expand their future helium production. The list includes all the existing plants where capacity expansion investments can be considered to increase output beyond current levels (e.g., in Algeria, Qatar) and the greenfield projects aimed at constructing a new helium plant near untapped helium-rich deposits (e.g., in Siberia, Wyoming).

Each producer j in J_3 is modeled as a profit-maximizing agent who has to decide in each year t its annual sales and k_t^j the physical investment (in flow unit) in production capacity. In each year t, its output can neither exceed the total installed capacity K_{t-1}^j at the end of the preceding year nor the maximum available quantity of helium contained in the extracted gas $\overline{H_t^j}$. We also assume: (i) that an investment k_t^j decided in year t becomes productive at the end of that year, and (ii) that the depreciation rate of the total installed capacity is negligible.

Each producer j in J_3 is thus assumed to solve the following optimization program:

$$\underset{q_t^i,k_t^i}{\text{Max}} \quad \Pi_j = \sum_{t\in \mathrm{T}} \beta_j^{\,t} \left[\left[\left(1-\delta_j\right) p_t^* + \delta_j P_t \left(q_t^j + q_t^{-j*}, q_{t-1}^j + q_{t-1}^{-j*}\right) - C_j^e \right] q_t^j - C_j^k k_t^j \right] \qquad (J_3–1)$$

$$\text{s.t.} \quad K_t^j = K_{t-1}^j + k_t^j, \qquad \forall t \in \mathrm{T},\ K_0^j \text{ given}, \qquad (J_3–2)$$

$$q_t^j \le K_{t-1}^j, \qquad \forall t \in \mathrm{T}, \qquad (J_3–3)$$

$$q_t^j \le \overline{H_t^j}, \qquad \forall t \in \mathrm{T}, \qquad (J_3\text{-}4)$$

$$q_t^j \ge 0, \quad k_t^j \ge 0, \qquad \forall t \in \mathrm{T}. \qquad (J_3–5)$$

where C_j^k is the unit cost of a capacity increment. The objective function is the discounted sum of the producer's annual profits.[12] Again, the binary parameter δ_j indicates whether that producer adopts a perfect competitive behavior ($\delta_j = 0$) or a Cournot oligopolistic behavior ($\delta_j = 1$). The constraint (J$_3$–2) is a state equation that describes the evolution of the total installed capacity. In each year t, the annual output is bounded by the capacity constraint (J$_3$–3) and (ii) the exogenous annual production ceiling $\overline{H_t^j}$ (cf., constraint (J$_3$–4)).

3.3 Solution strategy

We consider an open-loop information structure and adopt the Nash equilibrium as the solution concept. In an open-loop equilibria, the players' information sets contain the current calendar date and initial values of the state variables and each player has to choose its control actions as a function of time only (Salant, 1982; Dockner et al., 2000). The underlying problem thus amounts to solving a one-stage game. By definition, the vector $x^\star = \left(x_1^\star, ..., x_j^\star, ..., x_J^\star\right)$ is an open-loop Nash equilibrium of the WHM if no market participant has an incentive to unilaterally deviate from his equilibrium actions, given his opponents' actions, i.e.:

$$\Pi_j\left(x^\star\right) \geq \Pi_j\left(x_1^\star, ..., x_{j-1}^\star, x_j, x_{j+1}^\star, ..., x_J^\star\right), \quad \forall x_j \in \Omega_j,\ \forall j \in J, \tag{3}$$

where x_j denotes the vector of the decision variables of player j specified in his respective optimization problem, and Ω_j represents the set of his feasible actions (i.e., the player's feasible set which is defined by the constraints in his optimization program).

Because of the size of the WHM, the derivation of an analytic solution would be burdensome. Instead, the following numerical procedure can be considered for solving this Nash equilibrium problem. In the WHM, each market participant has to solve a convex mathematical programming problem since each player's objective is to maximize his profit given a set of constraints (such as

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[12] *The planning horizon T_H is chosen to be large enough (i.e., about 40 years) to approximate the infinite-horizon problem. As our analysis concentrates on the first T_{BLM} years (with T_{BLM} in the range 9–25 years), the objective function of this agent does not include a salvage value at the end of the planning horizon.*

production or capacity constraints) and the endogenous actions of the other market participants. For each market participant, the Karush-Kuhn-Tucker (KKT) conditions are necessary and sufficient for an optimal solution of the player's specific maximization problem and thus constitute the player's first-order equilibrium conditions.[13] The essence of the numerical approach is to find an equilibrium that simultaneously satisfies each market participant's KKT conditions for profit-maximization together with the demand equations (1) and the market-clearing conditions (2). As shown in Haurie et al. (2012) and Gabriel et al. (2012a), these conditions together define an instance of a mixed linear complementarity problem,[14] a particular class of mathematical programming problems for which efficient solution algorithms exist. In the application discussed in section 4, the complementarity problem associated with the WHM has been implemented in GAMS and solved with the complementarity solver PATH (Dirkse and Ferris, 1995; Ferris and Munson, 2000) to find Nash equilibria under various assumptions.

4. Application

4.1 Data and counterfactual scenarios

a – Data and empirical specification

The model described above is parameterized to represent the international helium market and be consistent with observed data.

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[13] *For the sake of brevity, the straightforward but tedious derivations of the players' individual KKT conditions are omitted in this manuscript.*

[14] *Technically, a mixed linear complementarity problem is defined by a series of parameters structured into four matrixes (* $M_{11} \in \mathbb{R}^{n\times n}$*,* $M_{22} \in \mathbb{R}^{m\times m}$*,* $M_{12} \in \mathbb{R}^{n\times m}$ *and* $M_{21} \in \mathbb{R}^{m\times n}$ *) and two vectors (* $q_1 \in \mathbb{R}^{n}$ *and* $q_2 \in \mathbb{R}^{m}$ *) and aims at finding two vectors* $z_1 \in \mathbb{R}^{n}$ *and* $z_2 \in \mathbb{R}^{m}$ *such that the following four conditions hold: (i)* $q_1 + M_{11}z_1 + M_{12}z_2 \geq 0$*; (ii)* $q_2 + M_{21}z_1 + M_{22}z_2 = 0$*; (iii)* $z_1 \geq 0$ *and (iv)* $z_1^T\left(q_1 + M_{11}z_1 + M_{12}z_2\right) = 0$ *where* T *is the transpose operator. This class of problem has extensively been studied in the mathematical programming literature and we refer to Cottle et al. (1992) for a comprehensive presentation of this problem, its properties and the specific algorithmic procedures that can solve it.*

We first clarify the planning horizon retained in the analysis. We aim at comparing several solutions: the one obtained when the BLM is compelled to use the rapid depletion trajectory (i.e., the BLM Model I) and the ones whereby that agent is allowed to conduct commercial operations during an extended period of T_{BLM} years. Here, T_{BLM} is in the range 9-25 years and the selection of the date T_{BLM} will be further discussed below. For the moment, we simply note that, because of the presence of an adjustment lag in the helium demand function, this range imposes a planning horizon that at least encompasses the enlarged period of 26 years that follows the implementation of the 2013 Act. In this paper, the model is systematically solved over a longer time horizon. As with all finite time horizon formulations, players in the WHM could avoid investing in incremental production capacity near the end of the modeling time frame because the remaining duration could possibly be too short to recoup that cost. This behavior may lead to the prediction of unacceptably low outputs (and thus high prices) near the end of the planning horizon. To overcome this problem, we solve the model over a 37-year horizon that starts at the end of 2013 (year 0) and ends in 2050 (year T).

Prices and costs are in constant 2014 dollars. To the best of our knowledge, there are no recent econometric studies of the demand for helium that can be tapped for parameter estimates. Thus, we estimated a linear demand equation. This empirical model posits that global helium consumption is explained by the aggregate real GDP in high and upper middle-income economies, the real price of helium, and the lagged consumption. Data sources, assumptions, and estimation results are detailed and commented on in Appendix B. To conduct market simulations, an exogenous future trajectory of that real GDP is needed. In this paper, we assume that the future real income will follow a constant rate of growth path. The posited growth rates are presented hereafter.

On the supply side, Table 1 enumerates, for each type of player discussed in the preceding section, the individual agents considered in the present analysis and clarifies their posited strategic behavior. This list has been derived from the descriptive analyses detailed in IHS (2014) and in a professional journal (Gasworld, 2015, 2016). In this paper, all the players that are capable of producing more than 200 million cubic feet (MMcf) per year are supposed to behave à la Cournot while the others are modeled as price-taking agents.[15] The specific cost and geological parameters used for each player are detailed in Appendix C.

We assume that all the private players located in OECD countries consider a real discount rate of 6 percent and that the rate used by players operating in non-OECD regions is 10 percent.[16] A real discount rate of 3 percent is used for the U.S. BLM.

Table 1. Players

[PLEASE INSERT TABLE 1 HERE]

b – Counterfactual scenarios

We investigate the possible future of the world helium industry through a series of four counterfactual scenarios that are structured along two dimensions. First, we consider two alternative demand trajectories by changing the value of the real income parameters in the demand equation (1). These two cases are chosen to reflect a possible future exogenous increase in demand:

(i) the "base-case" trajectory is aimed at exploring the consequences of an autonomous annual rate of growth of 2.5 percent for the real income trajectory, which is the average rate observed between 1973 and 2013 in these economies.

(ii) the "Slow Growth" trajectory assumes that the total real GDP of the high and upper middle-income economies will grow at an annual rate of 1.5 percent.

A second dimension of the analysis explores the role of future Russian supplies. At present, Russia operates a unique separation unit in Orenburg that has a relatively modest nameplate capacity (230 MMcf per year) but it is likely that Russia could greatly increase its output over the next two decades.

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[15] *Global consumption attained 6,309.3 MMcf in 2013 (source: USGS). The market share of a player endowed with a capacity that does not exceed 200 MMcf per year thus represented at most 3.2% of the world market that year. In the present analysis, we assume that these small players cannot exert market power.*

[16] *For the players located in OECD countries, the discount rate is based on the data assembled by Prof. A. Damodaran on the cost of capital incurred by publicly listed companies (http://www.stern.nyu.edu/~adamodar/). As the firms operating in non-OECD countries are not publicly listed (e.g., Sonatrach, Qatar Petroleum), the posited real discount rate is the one used by Massol and Banal-Estañol (2014) in their analysis of the gas processing projects located in non-OECD countries.*

The country's ambition is to build a large helium plant in Eastern Siberia that could commence operations during the year 2021. If fully developed, the capacity of that project could attain 2,380 MMcf per year, which would make it the world's largest source of helium. Nevertheless, this project will be phased and market analysts believe that it could experience delays because of its remote location (Gasworld, 2015, 2016; Anderson, 2017). The present analysis thus considers two cases that reflect possible alternative trajectories for the country's production ceiling in constraint (J_3–4):

(i) the "Ambitious Russian" (AR) trajectory assumes five successive phases, each providing an incremental processing capacity of 476 MMcf per year. The first phase is scheduled to commence operations in mid-2021 and the four subsequent ones will follow in mid-2025, mid-2029, mid-2033, and mid-2037.

(ii) The "Delayed Russian" (DR) trajectory also considers five phases with capacity increments of the same magnitude but the dates of the last four phases are postponed to mid-2027, mid-2033, mid-2039, and mid-2045 respectively.

For each of these four scenarios, we successively solve the two variants of the oligopolistic equilibrium defined by the two alternative behaviors posited for the U.S. BLM (cf., models I and II in section 3.2).

c – The duration of the less stringent mandate

In Model II, the BLM is allowed to operate during a number of years T_{BLM} chosen in the range 9-25 years. Though we have solved the WHM for each of these possible years, the discussion below concentrates on three noteworthy cases: T_{BLM} = 13, 18 or 23 years. These three cases epitomize the market outcomes obtained with BLM Model II. Indeed, we found that an extended mandate of 13 years maximizes the average net present value of the U.S. BLM's future profits obtained under the four scenarios and could thus represent the best option for a privately-managed BLM. With an extended mandate of 23 years, the average global social welfare obtained under the four scenarios (measured over the first 26 years and discounted using a social real rate of 3 percent) attains its highest value which suggests that the choice T_{BLM} = 23 years could be interpreted as a socially desirable choice. The case T_{BLM} = 18 years is aimed at detailing an intermediate situation between the two polar cases.

4.2 Results and discussion

We shall now compare the solutions for the two possible mandates for the U.S. BLM: either the current one under which the U.S. BLM is imposed to cease its commercial operations as soon as technically possible (i.e., in 2022) or the less stringent one that would allow the U.S. BLM to freely operate as a Cournot player during an extended periods of either 13, 18 or 23 years. Our analysis first focuses on the impacts on the U.S. BLM, then examines the market outcomes, and finally investigates the social consequences.

a – The depletion of the Federal Helium Reserve

To begin with, it is instructive to compare, for each scenario, the BLM's optimal extraction trajectories obtained using each mandate. These paths are shown graphically in Figure 2. Observe that whatever the scenario under scrutiny, the depletion trajectories of the Federal Reserve obtained with the less stringent mandates BLM II are substantially slower than the "as-fast-as-technically-possible" path currently imposed on the U.S. BLM. The remaining reserve at the end of year 2022 is larger than the 3 Bcf threshold and on the order of respectively 5.0–5.6, 6.3–8.7 and 6.6–10.0 Bcf when the BLM is allowed to operate as a profit-maximizing agent during an extended period of respectively 13, 18 and 23 years. This finding confirms that the rapid extraction policy BLM I is not maximizing the total financial return to the U.S. federal budget, thereby generating an opportunity cost. The profits gained by the U.S. BLM under the various scenarios will be further examined in the sequel.

Figure 2. The BLM's remaining reserve at the end of the year (in MMcf)

[PLEASE INSERT FIGURE 2 HERE]

b – The market outcomes

We shall now examine how the adoption of a less stringent mandate modifies the market outcomes and the other players' decisions.

Global helium consumption

Future global consumption trajectories for the four mandates under each of the four scenarios are shown graphically in Figure 3. As can be expected, a less rapid extraction trajectory at the Federal Helium Reserve reduces the total world consumption of helium during the early years and increases it after 2022. Overall, the "as-fast-as-technically-possible" policy (i.e., the one derived from BLM Model I, shown by the dashed lines in blue) artificially stimulates booming consumption figures during the early years followed by a period of relative stagnation after 2022. In contrast, the less stringent mandates based on BLM Model II generate smoothly growing consumption trajectories (particularly if the BLM is allowed to operate during a long period of either 18 or 23 years).

Figure 3. Annual helium consumption (in MMcf)

[PLEASE INSERT FIGURE 3 HERE]

During the years 2014-2022, the cumulated consumption figures are in the range 67.9–68.9 Bcf when the BLM follows the "as-fast-as-technically-possible" extraction path and in the range 65.9–67.0 Bcf when an extended BLM mandate of 13 years is implemented. One can note that the difference between the two models (i.e., 1.9–2.0 Bcf) is smaller than the difference in the BLM's remaining reserves at the end of year 2022. This finding suggests that the adoption of a different mandate for the BLM modifies the supply decisions of the other producers. This issue will be further examined below.

Market price

We now examine the future equilibrium prices in dollar per thousand cubic feet ($/McF). The paths depicted in Figure 4 convey a series of interesting findings. First, as can be expected, the trajectories obtained when the BLM is allowed to operate as a Cournot player (BLM Model II) exhibit higher prices during the initial years and lower ones during the years 2022-2025. During the years 2014-2019, the average market price obtained under the BLM Model II is the range of $153.2 to $180.4 per Mcf which is larger than the $138.6–$145.7 interval obtained when the BLM follows the "as-fast-as-technically-possible" extraction path. During the years 2022-2025, this is the opposite: depending on the scenario, the average equilibrium price is between $231.1 and $298.6 per Mcf under the BLM

Model I and on the order of \$196.5 to \$240.8 per Mcf when that agent behaves à la Cournot. This outcome is consistent with the inter-temporal profit-maximizing behavior of a Cournot player who prefers to reduce its output during the initial years to obtain higher prices.

Second, one can note that, under a less stringent mandate of either 18 years or 23 years, the magnitude of the price shocks that follow the termination of the BLM's commercial operations is attenuated. Lastly, observe that whatever the mandate given to the U.S. BLM, and whatever the scenario under scrutiny, the helium market price which was equal to 200\$/Mcf in 2013 (year 0) declines over the next year and then slowly rises. Unsurprisingly, that decline is more pronounced when the BLM is compelled to adopt the rapid depletion path, but extraction decisions at the BLM only partially explain the observed price decline because it is also observed (though with a lower magnitude) when the BLM behaves à la Cournot and supplies drastically reduced volumes in the early years. In fact, this price pattern is a characteristic result of incorporating an adjustment lag in the helium demand function. Recall that in 2013 there was a global shortage of helium, but there was only a minor impact on consumption figures by the then-prevailing high helium price. Because of the adjustment lag, the 2014 market equilibrium not only reflects the contemporary supply-demand situation but also those of the preceding years. Beyond that technical remark, it is interesting to note that this pattern is also consistent with the current industrial reality: since 2014, market analysts in professional publications have recurrently portrayed an "oversupply" situation and have reported lower helium selling prices than the ones observed before 2014.[17]

Figure 4. Equilibrium prices (in \$/Mcf)

[PLEASE INSERT FIGURE 4 HERE]

<u>Behavior of the other producers</u>

We now examine how the BLM's rapid extraction trajectory (i.e., BLM Model I) is impacting the rivals' decisions. Three interesting series of findings can be derived from the detailed examination of the individual players' supply policies.

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[17] *Cf., the descriptive analyses on the state of the helium market published in Gasworld (2015, 2016).*

First, we examine the supply behavior of the existing private separators in group J_1. Table 2 indicates that for Utah 1 and Wyoming 1 the market equilibrium is such that the constraints (J_1–2) are not binding in the early years. Recall that observing a positive slack $\overline{H_t^j} - q_t^j > 0$ reveals that the player at hand does not capture as much helium as technically possible during that year and thus represents a net waste as the quantities of helium not separated will be vented in the atmosphere when the gas is burned.[18] The figures in Table 2 reveal that, whatever the scenario under scrutiny, the obligation to use a rapid extraction trajectory at the U.S. BLM (i.e., Model I) systematically generates a larger waste of helium compared to the ones obtained under an extended mandate (BLM Model II). Under the BLM Model I, the total waste of helium is between 640.0 and 660.8 MMcf. The adoption of a less stringent mandate of respectively 13, 18 or 23 years lowers that range to 320.0–538.0, 163.4–320.0 or 106.8–320.0 MMcf respectively. Opting for that latter mandate (and preferably with a long duration) is thus preferable to conserve the resource.

Table 2. Annual helium venting by the firms in group J_1 (in MMcf)

[PLEASE INSERT TABLE 2 HERE]

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[18] The rationale for that venting is specific to each of these two players. For Utah 1, the market prices observed in the early years are strictly lower than the player's unit cost (155.0 \$/Mcf) which explains why this price-taking agent finds it rational to cease helium separation on these occasions. For Wyoming 1, prices are always larger than the unit cost (42.8 \$/Mcf) but this player behaves à la Cournot and can thus exert market power. Hence, he considers a marginal revenue function that varies with its own supplies. In year 1, the marginal revenue is the sum of three terms: (i) $P_1\left(q_1^j + q_1^{-j*}, d_0\right)$ *the price of the marginal unit supplied in year 1, (ii)* $q_1^j \frac{\partial P_1}{\partial q_1^j}\left(q_1^j + q_1^{-j*}, d_0\right) = \frac{-1}{\gamma} q_1^j$ *the marginal impact the sale of a marginal unit in year 1 has on the price obtained that year times the total quantity supplied that year, and (iii)* $\beta_j q_2^j \frac{\partial P_2}{\partial q_1^j}\left(q_2^j + q_2^{-j*}, q_1^j + q_1^{-j*}\right) = \beta_j \frac{\lambda}{\gamma} q_2^j$ *the discounted marginal impact the sale of a marginal unit in year 1 will have on the price obtained in year 2 times the total quantity that will be supplied by that player in year 2. Simplifying, the marginal revenue function of that player in year 1 is:* $MR_1^j = \left(\alpha y_1 + \lambda d_0 - 2q_1^j - q_1^{-j*} + \beta_j \lambda q_2^j\right)/\gamma$. *In the slow growth scenarios, the other players' decisions* q_1^{-j*} *are such that there systematically exists a pair of positive supply decision* q_1^j *and* q_2^j *for that player such that the equation* $MR_1^j = 42.8$ *holds with* $q_1^j < \overline{H_1^j}$ *and* $q_2^j = \overline{H_2^j}$.

Second, it is instructive to examine the private storage decisions taken by the U.S. separators connected to the BLM infrastructure (i.e., subgroup J_2). An inspection of Figure 5 shows that there are marked differences in the private inventory levels observed during the initial years, depending on the BLM behavior. Note that, whatever the scenario, there are rapidly declining inventory levels when the BLM behaves à la Cournot. In contrast, the U.S. private inventory levels are increased during the first three years when the BLM implements the rapid extraction trajectory (cf., the dashed lines in blue). At the end of year 2015, that private inventory attains 1.8 Bcf under the base-case scenario and 1.5 Bcf under the "slow growth" demand scenario. The BLM's rapid extraction path (and the depressed prices it generates during the initial years) thus creates profitable storage opportunities for private separators. This pattern is consistent with recent industrial evidence: the private inventory levels reported by the USGS (2015) have slightly increased since the implementation of the 2013 Act. From an aggregate perspective, note that the behavior of the private separators attenuates the price decline caused by the BLM's rapid extraction path during the first five years. Nevertheless, one may question the social efficiency of that policy as the cost of the intertemporal arbitrage operations conducted by private separators is likely to be larger than that of the BLM because of a combination of higher discount rates and higher storage cost (recall that the BLM's injection costs are sunk).

Figure 5. Volume of storage owned by private producers at the end of the year (MMcf)

[PLEASE INSERT FIGURE 5 HERE]

Third, we also inspect the investment decisions taken by the separators in subgroup J_3. Figure 6 (respectively Figure 7) reports the cumulated capacity additions decided in Canada (respectively Qatar) under the various mandates. As a benchmark, these figures also report the cumulated capacity additions that would have been needed to process the exogenously-determined flow of helium $\overline{H_t^j}$ (that curve is labeled production ceiling).[19] We do not report the investment decisions of the other players in J_3 as we found that modifying the BLM's mandate has no impact on their investment decisions.

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[19] *At time* t *, this curve is simply obtained by plotting* $CK_{t+1}^j - K_0^j$ *where* $CK_t^j := \max\left\{\overline{H_t^j}, CK_{t-1}^j\right\}$ *with* $CK_0^j = K_0^j$.

Figure 6. Canada's cumulated investments in new separation equipment (MMcf per year)

[PLEASE INSERT FIGURE 6 HERE]

Figure 7. Qatar's cumulated investments in new separation equipment (MMcf per year)

[PLEASE INSERT FIGURE 7 HERE]

An inspection of these two figures conveys the following observations. From Figure 6, we observe that, under the BLM I mandate, the depressed equilibrium prices observed during the early years generate low marginal gains during these years and make it rational for Canada – a price taking agent – to delay the installation of helium separation capabilities.[20] Qatar's investment behavior is more subtle as it accounts for that agent's ability to exert market power. Under the base-case demand trajectory, Qatar's behavior is similar to that of Canada: during the years 2016-2020, the rapid extraction path used in BLM I results in a slower adoption of helium separation capabilities than the one observed with an extended BLM mandate of either 18 or 23 years. Under the slow-growth demand trajectory, the large volume extracted by the BLM in the years 2013-2018 makes it rational for Qatar to exert market power by: (i) supplying less than its production capacity, and (ii) delaying its investments into new separation capacities. After 2018, the BLM's output becomes small under the rapid path BLM I but not with an extended mandate BLM II which explains why, during the years 2018-2025, Qatar's capacity expansion is more rapid under BLM I than the one observed under BLM II. Altogether, these findings indicate that the BLM's obligation to follow the "as-fast as-technically-possible" trajectory BLM I blurs the investment decisions in Canada and in Qatar during the years 2014-2022.

c – Profits, surpluses, and welfare

The net present values of the social welfare and the surpluses obtained by the market participants over the first 26 years are summarized in Table 3. These values have been obtained using a social real discount rate of 3 percent.

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[20] *The first-order (i.e., the KKT) conditions for optimality of these agents' decision problems indicate that, in each year, if a positive capacity expansion is decided, its level has to be such that the marginal cost of installing that capacity equals the present value of the marginal gains derived from helium processing (i.e., the difference between the marginal revenue and the marginal separation) in all the future years during which the capacity constraint (J_3-3) is binding.*

Table 3. The total discounted surplus obtained by consumers and producers (million $2014)

[PLEASE INSERT TABLE 3 HERE]

It is instructive to examine the net present values of the U.S. BLM's future profits. These figures confirm that the performance of the rapid extraction path currently imposed on the U.S. BLM falls short of "the maximization of the financial return to the U.S. taxpayers," a crucial policy objective yet explicitly stated in the 2013 Act. Under the current policy mandate (BLM I), the net present value of the future U.S. Treasury net revenues attains $835.3 million under the base-case demand trajectory and $780.2 million under the slow demand growth scenario. If the BLM was allowed to behave à la Cournot over a 13-year span (respectively a 23-year span), that net present value would be between +50.2 percent and +61.0 percent larger (respectively between +25.5 percent and +56.4 percent larger).

From a net social welfare perspective, note that under our each of the two base-case demand scenarios, opting for a less stringent mandate (BLM II) systematically augments the global welfare. The total discounted welfare gains are between 836.0 and 1,578.6 million 2014$, corresponding to an 0.59-1.16 percent increase. This is also true, albeit with a lower magnitude, in case of a lower future demand with a delayed deployment in Russia. In that case, the welfare gains are on the order of 72.6-275.7 million 2014$ which represents a modest increase of 0.06-0.22 percent. In the last scenario (i.e., "slow growth – rapid Russia"), the situation is less clear but the magnitude of the welfare changes remains small. So, opting for an extended mandate augments the global welfare in three out of the four scenarios and is nearly welfare neutral in the fourth scenario.

The less stringent mandate Model II systematically yields an augmentation of the total surplus jointly obtained by the BLM and the U.S. producers. It is also important to highlight that, under the base-case demand, the consumer surplus obtained with the BLM Model II is systematically larger than that obtained with the rapid extraction path. The gains in total discounted consumer surplus are between 531.2 and 1,355.5 million 2014$ and represent a 0.47-1.24 percent increase. A similar gain is also observed but with a smaller magnitude under the "slow growth – delayed Russia" scenario when the BLM operates during 18 or 23 years. So, the gain in producers' surplus is not necessarily obtained at the expense of the consumers' surplus. This is a rather counterintuitive result as one might expect that allowing the BLM to behave as a profit-maximizing agent could cause a tradeoff between the consumers' and the producers' surpluses.

It is also instructive to adopt a U.S. perspective when examining the figures presented in Table 3. By definition, only a share of the global consumer surplus accrues to U.S. consumers. If one assumes that the future U.S. share of the world helium consumption remains steady and equal to its 2014 level, i.e., approximately 30 percent (USGS, 2015), and that the willingness-to-pay of U.S. consumers is similar to those of foreign consumers, the following observations naturally emerge. First, with the base-case demand projection, the U.S. consumers are systematically better-off when the BLM operates as a Cournot player and these gains more than outweigh the modest losses of surplus incurred by the U.S. private producers under BLM mandates of either 13 or 18 years. Second, under the slow demand growth scenario, allowing the BLM to operate during an extended mandate always augments the U.S. producers’ surplus but can be detrimental to national consumers (e.g., in the ambitious Russia scenario). That said, it is important to note that, whatever the scenario under scrutiny, the less stringent policy systematically improves the U.S. net social welfare defined as the sums of the surpluses obtained by the domestic consumers, the domestic producers and the U.S. government (through the BLM’s surplus). Overall, these results provide little or no support for the currently implemented policy BLM I as it can hardly represent a rational move for a self-centric government concerned solely with the domestic welfare.

5. Concluding remarks

Between 2010 and 2013, there was anxiety over the adequacy of helium resources for meeting our modern societies’ apparently insatiable appetite for goods and services that can hardly be produced without this substance. At that time, the U.S. Congress passed an Act aimed at organizing the rapid depletion of the Federal Helium Reserve operated by the U.S. BLM. The fundamental public policy issue examined in this paper is, thus, whether that rapid phase out of the Federal Reserve is or is not supported by both the current and future evolution of the world helium market.

To examine it, this paper presents a new partial equilibrium model of the global helium market that captures the essential features of that industry, including: the inertia of global helium consumption, which is impacted by both current and past decisions; the strategic behavior of some of the market participants; the role of both public and private storage inventories; and the endogenous modeling of capacity investments. The model has been calibrated and solved for four different scenarios.

From the insights gained from market simulations, the answer to the public policy question above would appear to be no. Several lines of argument call for a modification of the rapid phase out imposed in the 2013 Act. First, the associated extraction path does not maximize the total financial return to the U.S. federal budget, which contradicts one of the policy objectives stated in the 2013 Act. Our simulation results indicate that the net present value of the future U.S. Treasury net revenues which is between 780.2 and 835.3 million 2014$ under the current policy could rise to 976.7-1,344.8 million 2014$ under a less stringent mandate. Second, from a resource conservation perspective, that policy, and the low prices it generates during the early years, systematically induces a net waste of helium. We estimate that allowing the BLM to operate during an extended period of time would yield a reduction of U.S. helium venting that is on the order of 122.8–533.2 MMcf. Third, from a social perspective, we also found that a higher level of social welfare could be achieved in three out of the four scenarios examined in this paper. Lastly, a noteworthy finding must be highlighted: allowing the BLM to behave as a profit-maximizing agent is not necessarily detrimental for the consumers as the consumer surplus augments in three out of the four scenarios examined in this paper when the BLM is allowed to operate during either 18 or 23 years.

Future possible research directions could include further analysis of the spatial nature of the helium industry. The analysis in this paper is based on a simplified representation of the world helium market that ignores spatial considerations and thus neglects the costly nature of intercontinental helium transportation. The construction of a more detailed and regionally disaggregated model of the world helium market would represent an appealing extension. However, to the best of our knowledge, this objective can hardly be attained at present because of a lack of regionally disaggregated time series on both prices and consumption levels. Should this limitation be slackened in the future, the development of a spatially-extended version of the WHM would usefully inform international helium trade issues.

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Appendix A – Nomenclature

This appendix summarizes the notation used in the paper.

Sets

$t \in \mathrm{T}$	The set of all the time periods $\{1,...,T_H\}$ considered in the WHM.
$j \in J$	The set of all the suppliers.
BLM	The BLM as a supplier ($\{BLM\} \subset J$).
J_1	The subset of all the private suppliers processing helium from gas fields where future production cannot increase ($J_1 \subset J$)
J_2	The subset of all the private U.S. suppliers with plants connected to the BLM's storage system ($J_2 \subset J$).
J_3	The subset of all the private suppliers that can invest to expand their future annual production of helium ($J_3 \subset J$).

Control variables (defined for $t \in \{1,...,T_H\}$)

q_t^j	The quantity of helium supplied by supplier j in period t .
p_t	The price of helium in period t .

h_t^j	The quantity of helium separated in period t by supplier j in J_2.
i_t^j	The quantity of helium injected in period t into the storage by supplier j in J_2.
w_t^j	The quantity of helium withdrawn in period t from the storage site by supplier j in J_2.
k_t^j	The incremental capacity decided in period t by supplier j in J_3.

State variables (defined for $t \in \{0,...,T_H\}$)

d_t	The total quantity of helium demanded in period t. The initial value d_0 is given.
R_t	The BLM's reserve measured at the end of period t. The initial reserve R_0 is given.
v_t^j	The total volume stored by a supplier j in J_2 at the end of period t. The initial volume v_0^j is given.
K_t^j	The total capacity K_t^j available to a supplier j in J_3 at the end of period t. The initial capacity K_0^j is given

Parameters

T_H	The time horizon.
T_{BLM}	The period at the end of which the BLM must cease its commercial operations.
α	The income coefficient in the demand equation.
y_t	The real income in year t.
γ	The slope coefficient in the demand equation.
λ	The lagged coefficient in the demand equation.
$\underline{R}$	The BLM's reserve allocated to non-commercial uses.
$\overline{Q_t^{BLM}}$	The BLM's production ceiling in year t as imposed in Figure 1.
β_j	The discount factor used by agent j.
C_{BLM}	The unit extraction cost incurred by the BLM.
η	The slope coefficient in the geological function describing the BLM's production capacity as a function of the BLM's remaining reserve.
μ	The intercept coefficient in the geological function describing the BLM's production capacity as a function of the BLM's remaining reserve.
δ_j	The binary parameter indicating whether agent j has a perfect competitive behavior ($\delta_j = 0$) or a Cournot oligopolistic behavior ($\delta_j = 1$).

C_j^e	The unit cost incurred by j to purchase and refine crude helium from the natural gas producers.
$\overline{H_t^j}$	The maximum quantity of helium that can be extracted by producer j in year t.
C_j^i	The unit storage cost of injection operations (for agents in the set J_2).
C_j^w	The unit storage cost of withdrawal operations (for agents in the set J_2).
S	The unit cost to hold one unit into the storage (for agents in the set J_2).

Appendix B – Calibration of the demand function

This appendix details the estimation of the empirical demand equation. We first present our approach and the methodology. Then, we clarify the data sources before presenting the estimates.

Methodology

This study assumes that the future levels of world helium consumption are determined using an empirical model that is consistent with observed historical patterns. D*e facto,* this approach solely accounts for already existing commercial uses. One may thus wonder whether the future demand for helium could rise well above the levels predicted by this empirical model if confinement fusion or superconducting transmission became commercially attractive as discussed in Nuttall et al. (2012b). Nevertheless, the demand projections associated with these prospective uses have a speculative nature as little is known about their probabilities of becoming commercial technologies and the associated willingness-to-pay for helium. As our discussion is primarily centered on the next two decades, we believe that this empirical approach is sufficient to generate credible demand projections over that horizon.

We assume that d_t the global helium consumption at year t can be explained using two explanatory variables. First, helium is a normal good. So, we expect to observe a negative relation between helium consumption and its real price p_t . Second, helium consumption is mainly observed in countries that have attained a certain level of technological sophistication and is thus likely to be positively driven by the level of economic development. Hence, we also include y_t , the real GDP (in level), within our specification.

As industrial evidence suggests that a substantial share of helium is used in long-lived equipment (e.g., in medical scanners, in electronic manufacturing), a dynamic specification might be preferable to take into consideration the dependence upon lagged values of the explanatory variables. Assuming a Koyck partial adjustment model, we thus consider the following linear specification:

$$d_t = \phi + \alpha . y_t - \gamma . p_t + \lambda . d_{t-1} + \varepsilon_t \ , \tag{B.1}$$

where ε_t is a random error term. According to this partial adjustment specification, helium consumption levels are explained as functions of the explanatory variables as well as the lagged value of the lagged dependent variable. This latter variable represents the inertia of economic behavior as it allows helium consumption to change gradually over time rather than immediately as each independent variable changes. The following can also be said about the coefficients ϕ, α, γ and λ to be estimated. Normally, we would expect the lagged-adjustment coefficient λ to verify $0 \leq \lambda < 1$. In addition, we would expect that the short-run elasticity of consumption with respect to income is positive (which suggests that the slope coefficient α verifies $\alpha > 0$), and that the short-run elasticity of consumption with respect to price is negative (which imposes that the associated slope coefficient γ verifies $\gamma > 0$).

Data

We use the successive editions of the USGS Minerals Yearbook to assemble annual time series for both helium consumption in million cubic feet (MMcf) and the real helium price (in constant 2014 dollars per thousand cubic feet ($/Mcf) during the period 1995–2014. Regarding the later series, we use the private industry’s price figures for gaseous helium reported in the successive editions of the USGS Minerals Yearbook as these figures are reputed to represent the marginal value of helium in each year. The real GDP (in trillion 2014 dollars) series for the high and upper middle income countries (i.e., those where helium is consumed) have been downloaded from the World Bank database. Table B.1 provides the mean, standard deviation, minimum, and maximum values for all of these variables in levels.

Table B.1. Summary statistics

[PLEASE INSERT TABLE B.1 HERE]

Results

The estimation results are summarized in Table B.2 (Panel 1). The signs and magnitudes of the estimates are consistent with our expectations but the intercept coefficient is clearly not significant. Thus, we follow a general-to-specific procedure whereby the regressors with the lowest absolute t-statistics are successively eliminated and the restricted models are then compared on the basis of the Akaike information criterion to identify the one with the lowest value. That procedure confirms that the intercept coefficient should be eliminated. The estimates obtained with the restricted specification are detailed in Table B.2 (Panel 2). The signs of these estimates are consistent with our expectations and the residuals exhibit no signs of serial correlation. We thus proceed using the restricted model.

Table B.2. Estimation results

[PLEASE INSERT TABLE B.2 HERE]

The coefficient of the lagged demand is positive and statistically significant, which indicates that helium demand slowly adjusts to changes in the explanatory variables. In 2014, helium consumption amounted to 6,561.6 MMcf and the price was \$200 per Mcf which suggests that the short-run and long-run price elasticities were -0.16 and -0.82 respectively. These low values indicate that global helium consumption is little price-sensitive at that price level.

The market simulations presented in this paper are based on an exogenous trajectory for the future real income that is posited to follow a constant rate of growth path. Hence, for each year t in T and each market, the income parameter used in the demand equation (1) is given by $y_t = Y_{2014} \cdot (1+g)^{t-1}$, where Y_{2014} is the GDP at year 2014 (i.e., 71.809 trillion dollars), and g is the posited autonomous rate of growth. To initialize the demand trajectory, we also need the global consumption observed in year 0, i.e., d_0 = 6,309.3 MMcf (source: USGS).

Appendix C – Cost and geological parameters

This appendix details the cost and geological parameters used in the market simulations for each market participant.

a – The U.S. BLM

The BLM's initial helium reserve R_0 at the end of year 0 is 10,840.9 MMcf (source: U.S. BLM). The unit extraction cost C_{BLM} is equal to \$33.7 per Mcf. The BLM's geological parameters η and μ that jointly determine the production ceiling function at the Cliffside reservoir (cf., equations BLM II – 2 and BLM III – 2) have been estimated using the production and reserve series (in MMcf) publicly announced by the US BLM (cf., Figure 1). The ordinary least squares estimates are presented in Table C.1 (Panel 1). These estimates are statistically significant and this simple linear model provides an excellent fit. We thus proceed using this empirical model.

Table C.1. Estimation results

[PLEASE INSERT TABLE C.1 HERE]

b – The existing helium separators

Three types of parameters are required to simulate the behavior of the already existing helium separators (i.e., the firms in groups J_1 and J_2). First, the unit cost data C_j^e used in our simulations are presented in Table C.2. By convention, these values include all the costs incurred to purchase crude helium from the natural gas producers and refine it to obtain commercial-grade helium. These unit cost figures have been derived from cost engineering studies that consider a variety of factors including helium concentration in the source gas, the plant's separation technology, its date of construction, and its location.

Table C.2. Cost data for the firms in groups J_1 and J_2 (in \$/Mcf)

[PLEASE INSERT TABLE C.2 HERE]

Second, exogenous production trajectories $\overline{H_t^j}$ are needed for each of these players. These trajectories are detailed in Table C.3.

Table C.3. Extraction trajectories $\overline{H_t^j}$ for the firms in groups J_1 and J_2 (in MMcf)

[PLEASE INSERT TABLE C.3 HERE]

Lastly, we have to consider the storage-related parameters needed for the firms in group J_2 that can store helium. Recall that the unit cost C_j^e = \$60.4 per Mcf detailed in Table C.2 assumes that the crude helium is refined to obtain commercial-grade helium. As the concentration of the helium stored in the underground reservoir is lower than that commercial specification, injecting commercial-grade helium in the storage site would generate a waste. Therefore, the producers in group J_2 typically inject half-refined helium (i.e., helium that is enriched to attain the specification needed for storage activities but not the commercial grade) in the storage site. Therefore, consistent with the convention used in this paper, the unit injection cost C_j^i considered here is the sum of two components: a negative one which gives the cost savings generated by less stringent refining needs, and a positive one which is directly related to the injection operations. As the magnitude of the former component is larger than that of the latter, the resulting unit cost C_j^i is negative and equal to -\$9.54 per Mcf. We assume that C_j^w the unit cost to extract and purify the helium withdrawn from the storage site is \$13.7 per Mcf and that S the unit storage cost is \$5.91 per Mcf. At the end of 2013, the helium volume collectively stored by the private firms at the Hugoton-Panhandle complex amounted to 1,440.0 MMcf (source: USGS). Because of a lack of publicly available information on the amount individually stored by each firm, an assumption is needed to apportion that total volume. Here, we posit that each player j in J_2 is endowed with an initial volume v_0^j reflecting the size of its processing plants that is 537.4 MMcf (respectively 64.7, 449.4, and 388.5 MMcf) for the player Hugoton-Panhandle 1 (respectively Hugoton-Panhandle 2, 3, 4).

d – The new players

The cost data for the players in group J_3 are detailed in Table C.4.

Table C.4. Cost data for the firms in group J_3 (in \$/Mcf)

[PLEASE INSERT TABLE C.4 HERE]

Table C.5. details the time path of the exogenous production trajectories $\overline{H_t^j}$ posited for each player in J_3.

Table C.5. Extraction trajectories $\overline{H_t^j}$ for the firms in group J_3 (in MMcf)

[PLEASE INSERT TABLE C.5 HERE]

These trajectories are based on the following assumptions. For Canada, Wyoming 2, South Africa and Utah 2, the trajectories are derived from IHS (2014) and Gasworld (2015, 2016). The extraction path for Colorado 2 is the one detailed in Brock (2014). In Algeria, Iran and Qatar, the helium concentration in the crude natural gas is low and the future availability of helium-rich gas is directly connected to the future development of a Liquefied Natural Gas (LNG) industry in these countries (Reinoehl, 2012; IHS, 2014; Anderson, 2017).[21] So, for Algeria, we assume that the country's unique expansion possibility is in the equipment of the LNG train in Skikda. Consistent with the projections presented in EIA (2016) and Cedigaz (2016), we assume that there will be no future expansion of the country's LNG processing capacity. For Qatar, we assume that the capacity additions that can be decided during the first decade are bounded by the availability of helium-rich tail gases emanating from existing LNG train (IHS, 2014). Beyond that horizon, the posited trajectory accounts for the country's ambition to expand by 30 percent its LNG processing capabilities in the mid-2020s (Rogers, 2017). Regarding Iran, we follow Cedigaz (2016) and the discussion in IHS (2014) and assume that the commencement of helium separation activities will not occur before the end of the 2020s.

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[21] *The LNG manufacturing process involves a number of gas purification stages. In the tail gases emanating from these operations, the helium concentration is: (i) greater than that originally found in the LNG plant's natural gas feedstock, and (ii) large enough to support helium separation. Hence, the future availability of crude helium in these countries directly mirrors the future deployment of LNG processing capabilities.*

Table 1. Players

Type of player	Player	Posited Strategic Behavior
BLM	U.S. BLM	See Section 3.2
J_1	Australia	Cournot
	China	Price-taking
	Poland	Price-taking
	Colorado 1	Price-taking
	Kansas	Price-taking
	New Mexico	Price-taking
	Wyoming 1	Cournot
	Utah 1	Price-taking
J_2	Hugoton-Panhandle 1	Cournot
	Hugoton-Panhandle 2	Price-taking
	Hugoton-Panhandle 3	Cournot
	Hugoton-Panhandle 4	Cournot
J_3	Algeria	Cournot
	Canada	Price-taking
	Iran	Cournot
	Qatar	Cournot
	Russia	Cournot
	South Africa	Price-taking
	Colorado 2	Cournot
	Wyoming 2	Cournot
	Utah 2	Price-taking

Table 2. Annual helium venting by the firms in group J_1 (in MMcf)

	Base-case demand		Slow growth scenario	
	Ambitious Russian	Delayed Russian	Ambitious Russian	Delayed Russian
Imposed trajectory (BLM Model I)				
Utah 1				
Year 1	160.0	160.0	160.0	160.0
Year 2	160.0	160.0	160.0	160.0
Year 3	160.0	160.0	160.0	160.0
Year 4	160.0	160.0	160.0	160.0
Wyoming 1				
Year 1	0.0	0.0	20.8	20.8
Total helium wasted	*640.0*	*640.0*	*660.8*	*660.8*
Cournot player (BLM Model II – 13 years)				
Utah 1				
Year 1	160.0	160.0	160.0	160.0
Year 2	160.0	160.0	160.0	160.0
Year 3	0.0	0.0	146.7	95.8
Year 4	0.0	0.0	71.3	37.5
Total helium wasted	*320.0*	*320.0*	*538.0*	*453.3*
Cournot player (BLM Model II – 18 years)				
Utah 1				
Year 1	160.0	160.0	160.0	160.0
Year 2	43.3	3.4	160.0	160.0
Total helium wasted	*203.3*	*163.4*	*320.0*	*320.0*
Cournot player (BLM Model II – 23 years)				
Utah 1				
Year 1	160.0	106.8	160.0	160.0
Year 2	0.0	0.0	160.0	160.0
Total helium wasted	*160.0*	*106.8*	*320.0*	*320.0*

Note: A zero slack is observed in the other years and/or the other agents and has not been reported for the sake of brevity.

Table 3. The total discounted surplus obtained by consumers and producers (million $2014)

			Imposed trajectory (BLM I)	BLM II 13 years		BLM II 18 years		BLM II 23 years	
				Value	*Difference with BLM I*	Value	*Difference with BLM I*	Value	*Difference with BLM I*
Basecase demand	Ambitious Russian	Consumer Surplus	112,403.4	**112,934.7**	*531.2*	**113,530.2**	*1,126.8*	**113,758.9**	*1,355.5*
		BLM's Surplus	835.3	**1,317.7**	*482.4*	**1,184.9**	*349.6*	**1,236.9**	*401.6*
		US Producers' Surplus	9,250.8	9,223.2	*-27.6*	9,230.4	*-20.4*	**9,284.2**	*33.4*
		Foreign Producers' Surplus	18,577.5	18,427.4	*-150.0*	18,378.3	*-199.1*	18,315.4	*-262.0*
		Social Welfare	141,067.0	**141,903.0**	*836.0*	**142,323.9**	*1,256.9*	**142,595.4**	*1,528.5*
	Delayed Russian	Consumer Surplus	106,161.6	**106,739.0**	*577.3*	**107,385.3**	*1,223.7*	**107,479.1**	*1,317.5*
		BLM's Surplus	835.3	**1,344.8**	*509.5*	**1,239.0**	*403.7*	**1,306.7**	*471.4*
		US Producers' Surplus	9,738.8	9,712.5	*-26.3*	9,716.2	*-22.5*	**9,777.3**	*38.5*
		Foreign Producers' Surplus	18,935.0	18,778.5	*-156.4*	18,726.3	*-208.6*	18,686.1	*-248.8*
		Social Welfare	135,670.7	**136,574.8**	*904.1*	**137,066.8**	*1,396.2*	**137,249.2**	*1,578.6*
Slow demand growth	Ambitious Russian	Consumer Surplus	106,766.7	106,245.4	*-521.3*	106,660.7	-106.0	106,528.9	*-237.8*
		BLM's Surplus	780.2	**1,171.5**	*391.3*	**976.7**	196.4	**979.2**	*199.0*
		US Producers' Surplus	6,796.2	**6,866.5**	*70.3*	**6,860.3**	64.1	**6,877.9**	*81.7*
		Foreign Producers' Surplus	11,596.8	11,506.7	*-90.0*	11,447.1	-149.6	11,447.1	*-149.7*
		Social Welfare	125,939.9	125,790.1	*-149.8*	**125,944.9**	4.9	125,833.1	*-106.8*
	Delayed Russian	Consumer Surplus	102,990.0	102,712.7	*-277.3*	**103,161.7**	*171.7*	**103,020.3**	*30.3*
		BLM's Surplus	780.2	**1,191.9**	*411.6*	**997.7**	*217.4*	**1,001.2**	*221.0*
		US Producers' Surplus	7,121.6	**7,174.4**	*52.8*	**7,166.0**	*44.5*	**7,186.2**	*64.7*
		Foreign Producers' Surplus	12,146.7	12,032.2	*-114.5*	11,988.7	*-157.9*	11,984.8	*-161.9*
		Social Welfare	123,038.4	**123,111.1**	*72.6*	**123,314.1**	*275.7*	**123,192.5**	*154.1*

Note: These figures are the net present values measured over the first 26 years using a social discount rate of 3 percent. The figures in bold in the columns BLM Model II indicate a value higher than the one obtained with the BLM Model I.

Table B.1. Summary statistics

	d_t *[MMcf]*	GDP_t *[10^{12} 2014 USD]*	p_t *[2014 USD/Mcf]*
Mean	5,512.31	55.11	109.33
Median	5,627.86	53.18	82.63
Maximum	6,561.63	71.81	203.22
Minimum	3,753.11	42.35	59.68
Standard deviation	800.34	11.31	49.79
Skewness	-0.859	0.299	0.699
Kurtosis	2.953	1.474	1.966

Table B.2. Estimation results

	Constant ϕ	GDP_t α	p_t γ	d_{t-1} λ	$\overline{R}^2$	*S.E.*	*LM(2)*
Panel 1: d_t	176.322 (596.589)	29.044 (21.067)	4.537 (4.212)	0.787* (0.116)	0.903	249.526	2.631
Panel 2: d_t	–	33.435* (14.531)	5.514* (2.536)	0.795* (0.110)	0.908	242.736	2.152

Note: OLS estimates. The variables are in levels and not in logarithms. Standard errors of coefficient estimates are shown in parentheses. Asterisks indicate significance at the 0.05 level. $\overline{R}^2$ is the adjusted R-squared, S.E. is the standard error of regression and LM(2) is the Breusch-Godfrey LM-test for 2nd order autocorrelation.

Table C.1. Estimation results

	R_{t-1} η	Constant μ	$\overline{R}^2$	*S.E.*	*LM(2)*
q_t^{BLM}	0.1385* (0.0011)	22.634* (6.025)	0.999	13.576	4.208

Note: OLS estimates. Standard errors of coefficient estimates are shown in parentheses. Asterisks indicate significance at the 0.05 level. $\overline{R}^2$ is the adjusted R-squared, S.E. is the standard error of regression and LM(2) is the Breusch-Godfrey LM-test for 2nd order autocorrelation.

Table C.2. Cost data for the firms in groups J_1 and J_2 (in \$/Mcf)

	Players in group J_1								Players in group J_2			
	AU	CN	PL	CO-1	KS	NM	WY-1	UT1 (a)	HP-1	HP-2	HP-3	HP-4
Unit costs C_j^e	90.0	80.3	79.0	87.0	67.9	100.4	42.8	155.0	60.4	60.4	60.4	60.4

Note: AU: Australia; CN: China; PL: Poland; CO-1: Colorado 1; KS: Kansas; NM: New Mexico; WY-1: Wyoming 1; UT-1: Utah 1; HP-1 to HP-4: Hugoton-Panhandle 1 to 4. These cost data are based on detailed cost-engineering studies available at IFP Energies Nouvelles—a French public R&D center focused on geoscience and chemical engineering—and have been double-checked by industry contacts. These values reflect a variety of factors including helium concentration in the source gas, the chemical composition of the feed gas, the separation technology, the plant's design, and its location. (a) The large cost of that plant is explained by the costly nature of the feed gas used for that plant because it has to be transported to the plant via tube trailers.

Table C.3. Extraction trajectories $\overline{H_t^j}$ for the firms in groups J_1 and J_2 (in MMcf)

	Players in group J_1								Players in group J_2			
	AU (a)	CN (b)	PL (c)	CO-1 (c)	KS (d)	NM (c)	WY-1 (d)	UT1 (d)	HP-1 (c)	HP-2 (c)	HP-3 (c)	HP-4 (c)
Year 1	150.0	10.6	137.0	55.2	36.5	1.3	1,450.0	160.0	469.5	56.6	392.7	339.8
Year 2	150.0	10.6	137.0	43.5	36.5	1.0	1,450.0	160.0	445.7	53.8	372.8	322.7
Year 3	150.0	10.6	137.0	34.3	36.5	0.8	1,450.0	160.0	404.5	48.8	338.3	292.8
Year 4	150.0	10.6	137.0	27.1	36.5	0.6	1,450.0	160.0	357.1	43.1	298.7	258.5
Year 5	150.0	10.6	137.0	21.3	36.5	0.5	1,450.0	160.0	323.4	39	270.5	234.1
Year 6	150.0	10.6	123.3	16.5	36.5	0.4	1,450.0	160.0	287.8	34.7	240.7	208.3
Year 7	150.0	10.6	111.0	10.8	36.5	0.3	1,450.0	160.0	256	30.9	214.2	185.3
Year 8	150.0	10.6	99.9	8.4	36.5	0.2	1,450.0	160.0	226.2	27.3	189.2	163.7
Year 9	150.0	10.6	89.9	6.0	36.5	0.2	1,450.0	160.0	194.9	23.5	163	141
Year 10	120.0	10.6	80.9	4.8	36.5	0.1	1,450.0	160.0	174	21	145.5	125.9
Year 11	96.0	10.6	72.8	3.7	36.5	0.1	1,450.0	160.0	157.3	19	131.6	113.9
Year 12	76.8	10.6	65.5	2.5	36.5	0.0	1,450.0	160.0	137.6	16.6	115.1	99.6
Year 13	61.4	10.6	59.0	2.0	36.5	0.0	1,450.0	160.0	120.6	14.5	100.9	87.3
Year 14	49.2	10.6	53.1	1.5	36.5	0.0	1,450.0	160.0	110.4	13.3	92.4	79.9
Year 15	39.3	10.6	47.8	0.8	36.5	0.0	1,450.0	160.0	94.5	11.4	79.1	68.4
Year 16	31.5	10.6	43.0	0.7	36.5	0.0	1,450.0	160.0	85.8	10.3	71.7	62.1
Year 17	25.2	10.6	38.7	0.5	36.5	0.0	1,450.0	160.0	72.3	8.7	60.5	52.4
Year 18	20.1	10.6	34.8	0.4	36.5	0.0	1,450.0	160.0	63.4	7.7	53	45.9
Year 19	16.1	10.6	31.3	0.0	36.5	0.0	1,450.0	160.0	51.9	6.3	43.4	37.6
Year 20	12.9	10.6	28.2	0.0	36.5	0.0	1,450.0	160.0	46.4	5.6	38.8	33.6
Year 21	10.3	10.6	25.4	0.0	36.5	0.0	1,450.0	160.0	38.5	4.6	32.2	27.9
Year 22	8.2	10.6	22.8	0.0	36.5	0.0	1,450.0	160.0	31.3	3.8	26.2	22.7
Year 23	6.6	10.6	20.6	0.0	36.5	0.0	1,450.0	160.0	24.2	2.9	20.2	17.5
Year 24	5.3	10.6	18.5	0.0	36.5	0.0	1,450.0	160.0	18.8	2.3	15.8	13.6
Year 25	0.0	10.6	16.7	0.0	36.5	0.0	1,450.0	160.0	14.2	1.7	11.9	10.3
Year 26	0.0	10.6	15.0	0.0	36.5	0.0	1,450.0	160.0	10.9	1.3	9.1	7.9
Year 27	0.0	10.6	13.5	0.0	36.5	0.0	1,450.0	160.0	8.4	1	7.1	6.1
Year 28	0.0	10.6	12.1	0.0	36.5	0.0	1,450.0	160.0	6.5	0.8	5.4	4.7
Year 29	0.0	10.6	10.9	0.0	36.5	0.0	1,450.0	160.0	5	0.6	4.1	3.6
Year 30	0.0	10.6	9.8	0.0	36.5	0.0	1,450.0	160.0	3.8	0.5	3.2	2.7
Year 31	0.0	10.6	8.9	0.0	36.5	0.0	1,450.0	160.0	2.8	0.3	2.3	2
Year 32	0.0	10.6	8.0	0.0	36.5	0.0	1,450.0	160.0	2.1	0.3	1.8	1.5
Year 33	0.0	10.6	7.2	0.0	36.5	0.0	1,450.0	160.0	1.6	0.2	1.3	1.1
Year 34	0.0	10.6	6.5	0.0	36.5	0.0	1,450.0	160.0	1.1	0.1	0.9	0.8
Year 35	0.0	10.6	5.8	0.0	36.5	0.0	1,450.0	160.0	0.8	0.1	0.7	0.6
Year 36	0.0	10.6	5.2	0.0	36.5	0.0	1,450.0	160.0	0.6	0.1	0.5	0.5
Year 37	0.0	10.6	0.0	0.0	36.5	0.0	1,450.0	160.0	0.4	0	0.3	0.3

Notes: AU: Australia; CN: China; PL: Poland; CO-1: Colorado 1; KS: Kansas; NM: New Mexico; WY-1: Wyoming 1; UT-1: Utah 1; HP-1 to HP-4: Hugoton-Panhandle 1 to 4. (a) As the feed gas for the Australian plant comes from an LNG plant, this extraction path has been obtained from commercial information related to the scheduled sales of LNG at that plant. (b) This trajectory has been derived from IHS (2014). (c) These trajectories are derived from Mohr and Ward (2014, high growth scenario). (d) This extraction path has been derived from the analyses published in Gasworld, a professional journal.

Table C.4. Cost data for the firms in group J_3 (in \$/Mcf)

	Algeria	Canada	Iran	Qatar	Russia	South Africa	Colorado 2	Wyoming 2	Utah 2
Unit operation cost C_j^e	55.0	157.9	72.0	72.0	69.0	40.0	77.0	42.8	75.0
Unit investment cost C_j^k	107.3	218.9	270.7	274.7	383.3	230.0	240.2	220.2	250.5

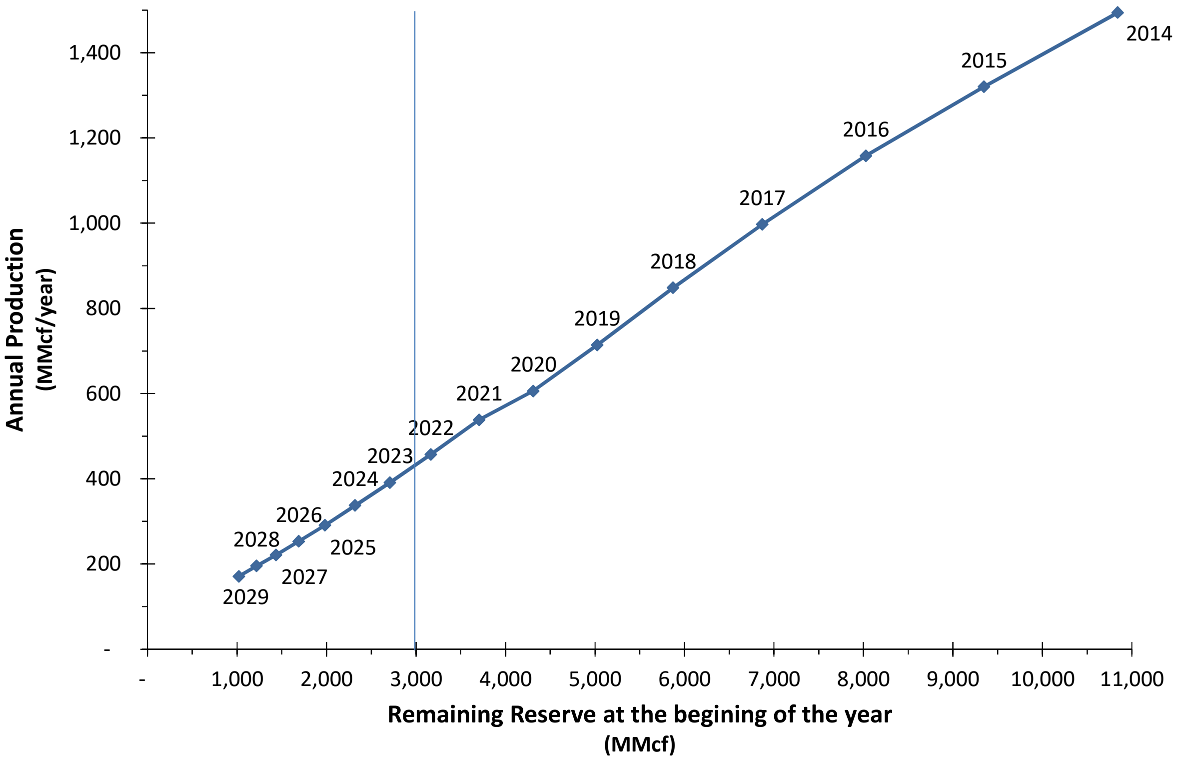
Notes: These data are based on detailed cost-engineering studies available at IFP Energies Nouvelles—a French public R&D center focused on geoscience and chemical engineering—and have been double-checked by industry contacts. These unit cost data reflect a variety of factors including helium concentration in the source gas, the chemical composition of the feed gas, the plant's possible design, and its location.

Table C.5. Extraction trajectories $\overline{H_t^j}$ for the firms in group J_3 (in MMcf)

	Algeria	Canada	Iran	Qatar	Russia (a)		South Africa	Colorado 2	Wyoming 2	Utah 2
					AR Path	DR Path				
Initial capacity K_0^j	870.0	0.0	0.0	1990.0	230.0	230.0	0.0	0.0	0.0	0.0
Year 1	870.0	0.0	0.0	1,990.0	230.0	230.0	0.0	0.0	0.0	0.0
Year 2	870.0	0.0	0.0	1,990.0	230.0	230.0	0.0	230.0	100.0	36.5
Year 3	870.0	0.0	0.0	1,990.0	230.0	230.0	0.0	230.0	200.0	36.5
Year 4	1,200.0	40.0	0.0	1,990.0	230.0	230.0	0.0	230.0	200.0	36.5
Year 5	1,200.0	40.0	0.0	2,203.0	230.0	230.0	50.0	230.0	200.0	36.5
Year 6	1,200.0	40.0	0.0	2,415.0	230.0	230.0	100.0	230.0	200.0	36.5
Year 7	1,200.0	40.0	0.0	2,415.0	230.0	230.0	100.0	230.0	200.0	36.5
Year 8	1,200.0	40.0	0.0	2,415.0	468.0	468.0	100.0	230.0	200.0	36.5
Year 9	1,200.0	40.0	0.0	2,415.0	706.0	706.0	100.0	230.0	400.0	36.5
Year 10	1,200.0	40.0	0.0	2,415.0	706.0	706.0	100.0	230.0	400.0	36.5
Year 11	1,200.0	40.0	0.0	2,415.0	706.0	706.0	82.0	230.0	400.0	36.5
Year 12	1,200.0	40.0	0.0	2,415.0	944.0	706.0	69.0	201.0	400.0	36.5
Year 13	1,200.0	40.0	0.0	2,415.0	1,182.0	706.0	58.0	175.0	400.0	36.5
Year 14	1,200.0	40.0	0.0	2,564.0	1,182.0	944.0	49.0	153.0	400.0	36.5
Year 15	1,200.0	40.0	0.0	2,834.0	1,182.0	1,182.0	41.0	133.0	400.0	36.5
Year 16	1,200.0	40.0	0.0	3,103.0	1,420.0	1,182.0	34.0	116.0	400.0	36.5
Year 17	1,200.0	40.0	250.0	3,103.0	1,658.0	1,182.0	28.0	101.0	400.0	36.5
Year 18	1,200.0	40.0	500.0	3,103.0	1,658.0	1,182.0	23.0	88.0	400.0	36.5
Year 19	1,200.0	40.0	500.0	3,103.0	1,658.0	1,182.0	19.0	77.0	400.0	36.5
Year 20	1,200.0	40.0	500.0	3,103.0	1,896.0	1,420.0	16.0	67.0	400.0	36.5
Year 21	1,200.0	40.0	500.0	3,103.0	2,134.0	1,658.0	13.0	58.0	400.0	36.5
Year 22	1,200.0	40.0	750.0	3,103.0	2,134.0	1,658.0	11.0	50.0	400.0	36.5
Year 23	1,200.0	40.0	1,000.0	3,103.0	2,134.0	1,658.0	0.0	43.0	400.0	36.5
Year 24	1,200.0	40.0	1,000.0	3,103.0	2,372.0	1,658.0	0.0	0.0	400.0	36.5
Year 25	1,200.0	40.0	1,000.0	3,103.0	2,610.0	1,658.0	0.0	0.0	400.0	36.5
Year 26	1,200.0	40.0	1,000.0	3,103.0	2,610.0	1,896.0	0.0	0.0	400.0	36.5
Year 27	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,134.0	0.0	0.0	400.0	36.5
Year 28	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,134.0	0.0	0.0	400.0	36.5
Year 29	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,134.0	0.0	0.0	400.0	36.5
Year 30	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,134.0	0.0	0.0	400.0	36.5
Year 31	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,134.0	0.0	0.0	400.0	36.5
Year 32	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,372.0	0.0	0.0	400.0	36.5
Year 33	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,610.0	0.0	0.0	400.0	36.5
Year 34	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,610.0	0.0	0.0	400.0	36.5
Year 35	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,610.0	0.0	0.0	400.0	36.5
Year 36	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,610.0	0.0	0.0	400.0	36.5
Year 37	1,200.0	40.0	1,000.0	3,103.0	2,610.0	2,610.0	0.0	0.0	400.0	36.5

Note: The initial capacities are based on IHS (2014). (a) This table details two trajectories for the future Russian deployment: either the rapid one assumed in the “Ambitious Russian” path or the slower one (i.e., the “Delayed Russian” case).

Figure 1. The time-path of the FHR's planned production trajectory



Source: www.blm.gov/style/medialib/blm/nm/programs/0/helium_docs.Par.6729.File.dat/Helium%20Delivery%20Model.pdf

Figure 2. The BLM's remaining reserve at the end of the year (in MMcf)

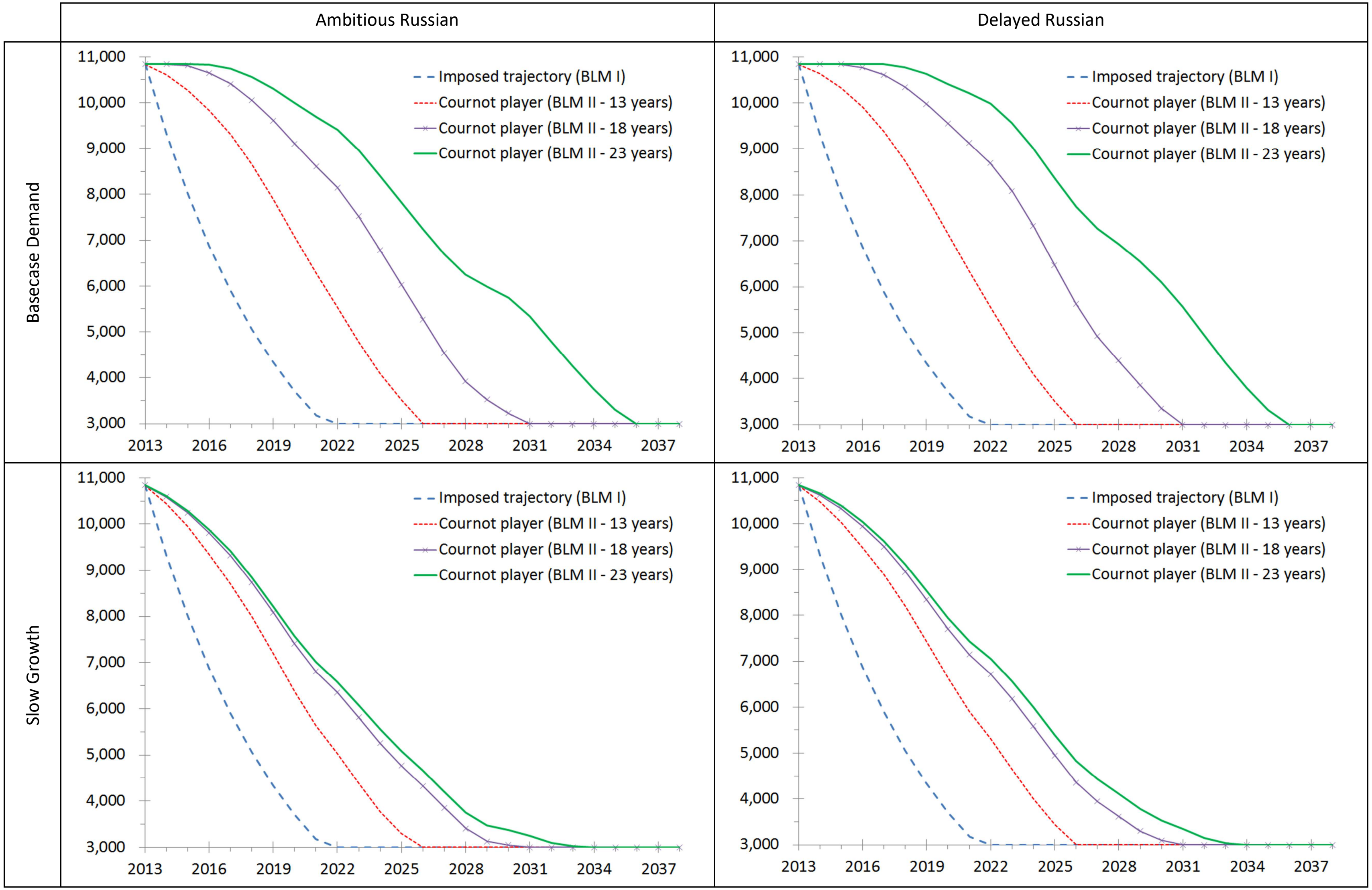


Figure 3. Annual helium consumption (in MMcf)

Figure 4. Equilibrium prices (in $/Mcf)

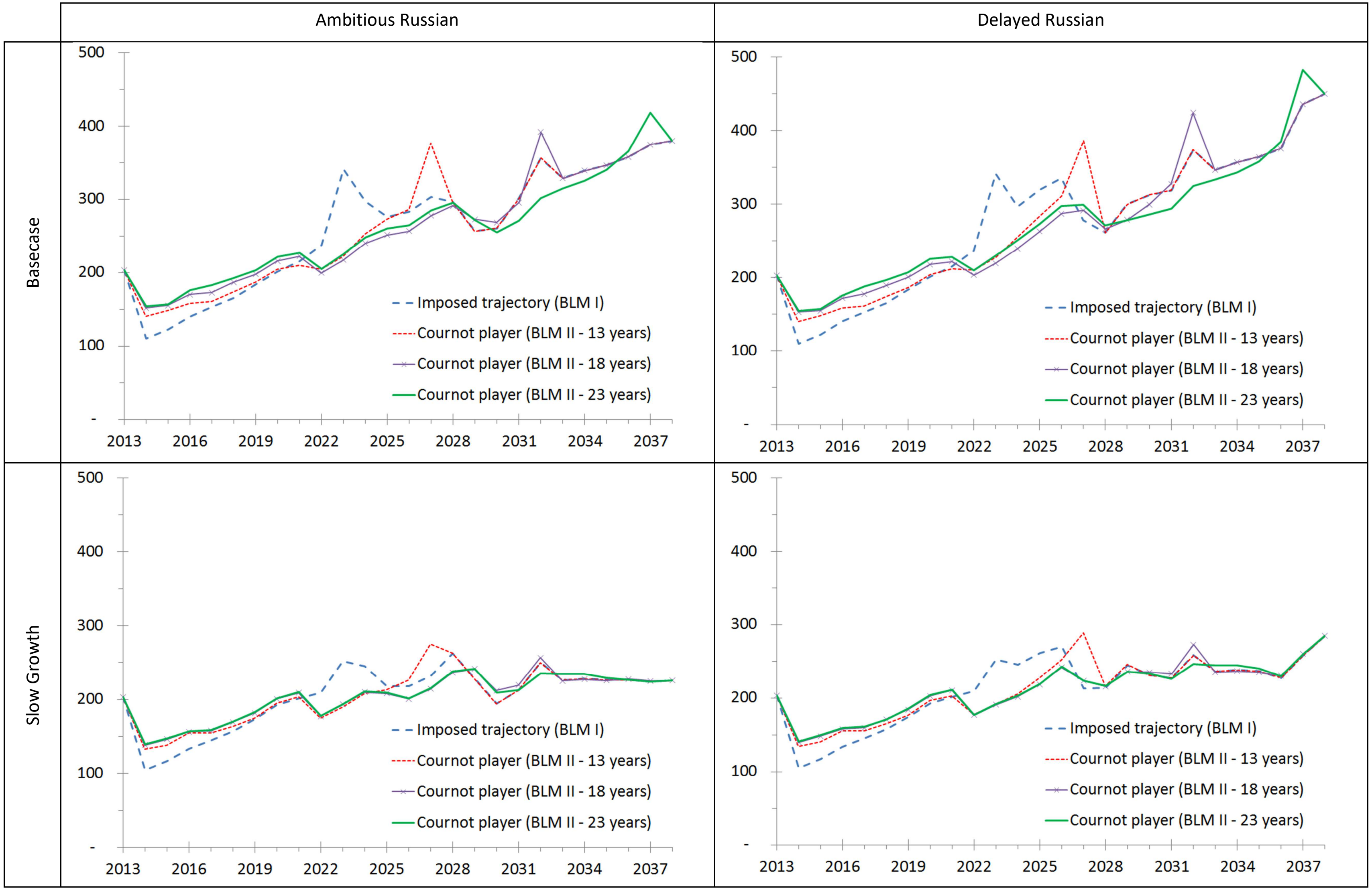


Figure 5. Volume of storage owned by private producers at the end of the year (MMcf)

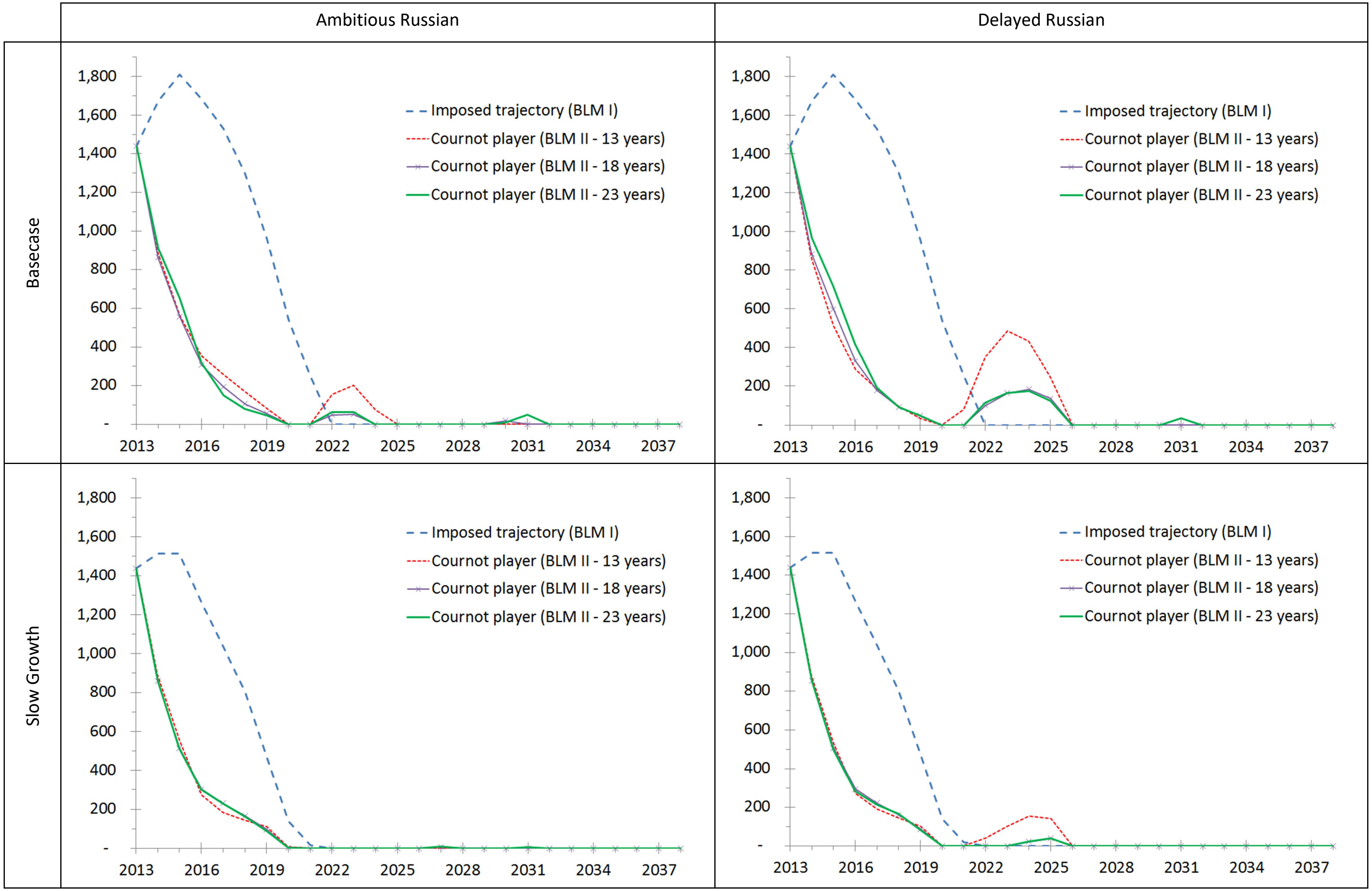


Figure 6. Canada’s cumulated investments in new separation equipment (MMcf per year)

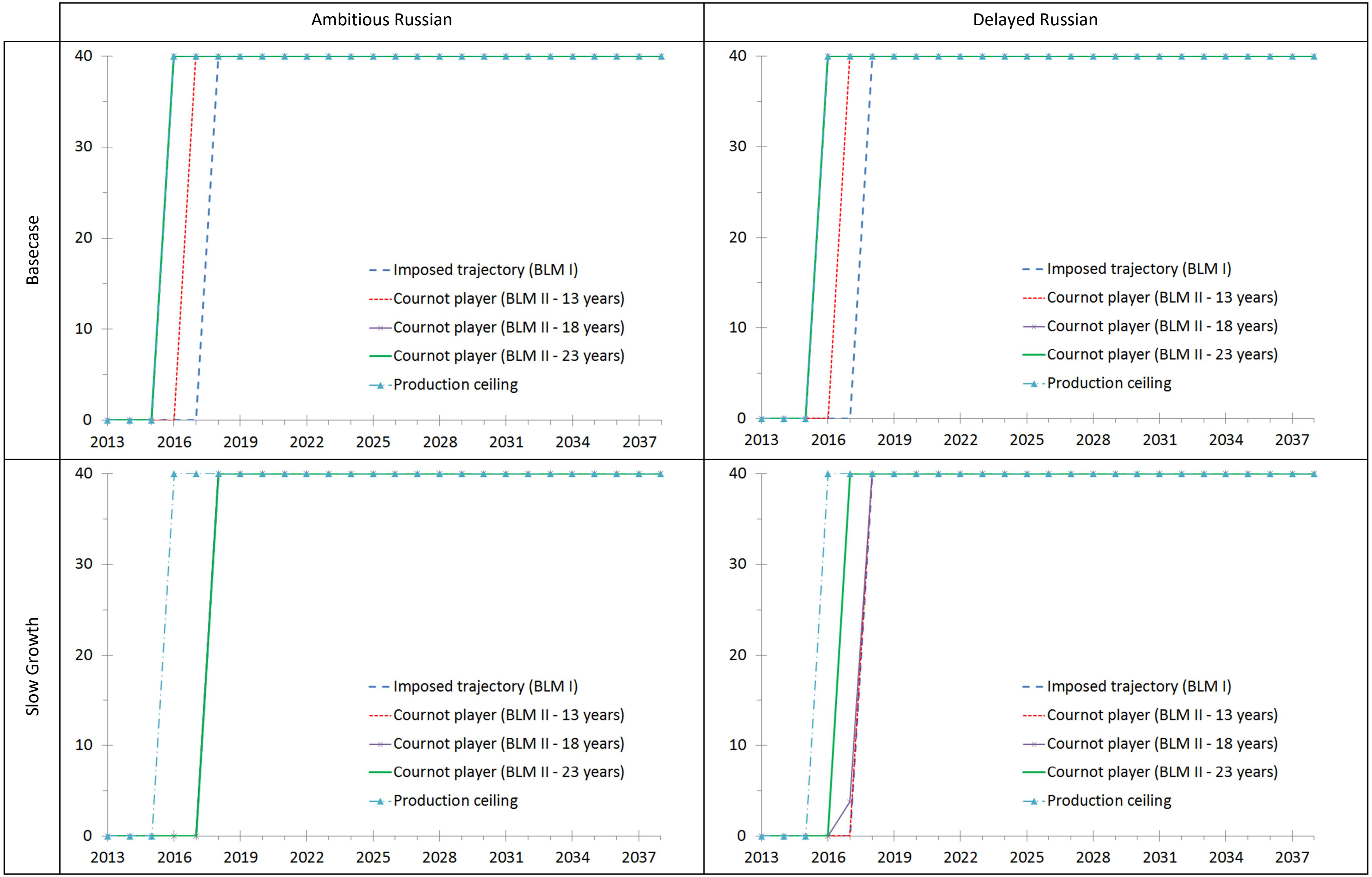


Figure 7. Qatar's cumulated investments in new separation equipment (MMcf per year)