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Department of Economics

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

Olivier Massol[1]
IFP Énergies Nouvelles, Rueil-Malmaison, France
IFP School, Rueil-Malmaison, France
City University London, UK

Omer Rifaat
IFP School, Rueil-Malmaison, France

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[1] Corresponding author: Olivier Massol, Department of Economics, City University London, Northampton Square, London EC1V 0HB, UK. Email: olivier.massol.1@city.ac.uk; olivier.massol@ifpen.fr

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

Olivier MASSOL [a,b,c] *

Omer RIFAAT [b]

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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 a 20-year extended period. Evidences gained from a series of market simulations indicate that, compared to the current policy, the 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.

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a IFP Énergies Nouvelles, 1-4 av. de Bois Préau, F-92852 Rueil-Malmaison, France.

b Center for Economics and Management, IFP School, 228-232 av. Napoléon Bonaparte, F-92852 Rueil-Malmaison, France.

c Department of Economics, City University of London, Northampton Square, London EC1V 0HB, UK.

* Corresponding author. Tel.: +33 1 47 52 68 26; fax: +33 1 47 52 70 66. E-mail address: olivier.massol@ifpen.fr

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, breathing mixtures for deep-sea diving) 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) and the future availability of helium resources subsequently became the topic of a burgeoning literature authored by science and technology experts (Cai et al., 2010; Glowacki et al., 2013; Mohr and Ward, 2014).[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.

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

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[1] Helium is a highly permeable gas, has also 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] These studies typically examine the future availability of helium supplies. 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 is based on a sophisticated model that has its methodological roots in the predominantly geoscience-based literature aimed at predicting *Hubbert's* peak oil.

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' investment 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. A sensitivity analysis aimed at assessing the impact of some of the model's key parameters on the results is also conducted. 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.

From a methodological perspective, the rich applied 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 the MCP 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

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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).

effects of 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). This paper represents the very first application of the MCP approach 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, details on the calibration of the demand function are presented in Appendix A.

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 the fact 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 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

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

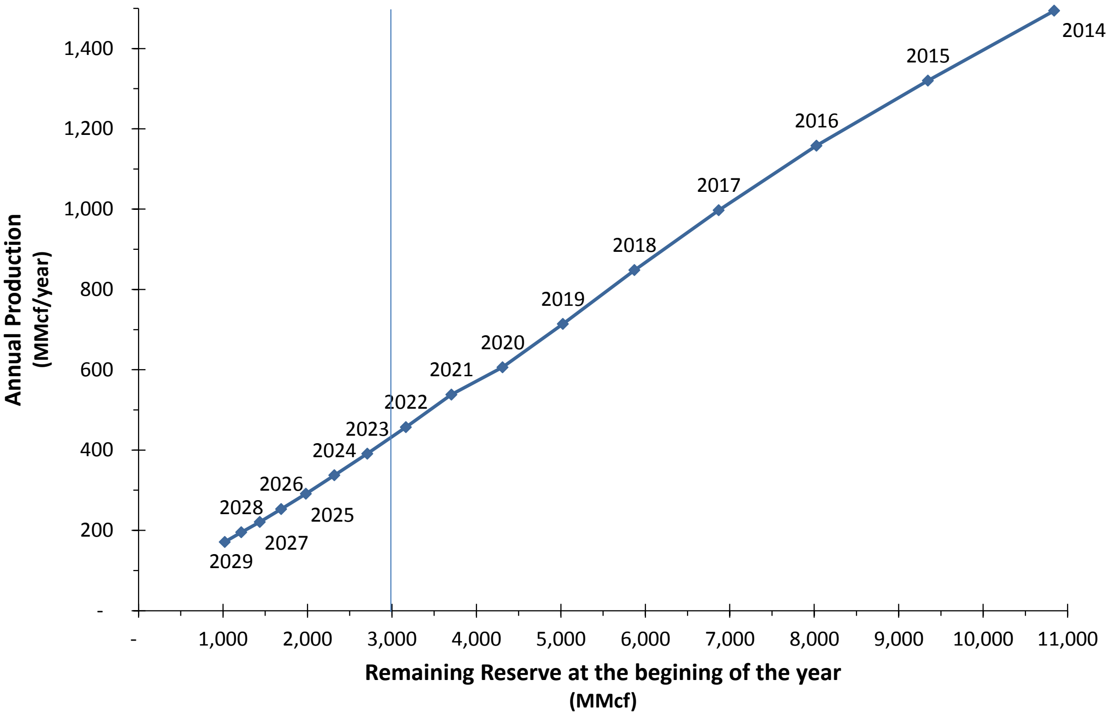
[6] One of the unintended consequences of the 1996 Act was that the BLM's posted price gradually became a market benchmark for the global price of helium in the contracts signed by private industrial gas companies. During 2007–2013, there was a global shortage of helium but the posted price of federal 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.

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.

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 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 20 years.

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

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.[7] 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.

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[7] "*Helium*: a market update" Gasworld, January 2016.

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 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 private suppliers located in resource-rich regions that are capable of expanding their future annual production of helium.

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

We consider a discrete time model with periods $t \in \{0,1,...,T\}$ that have a standard duration of one year and aim at modeling the decisions to be taken in years $t \in \mathrm{T} := \{1,...,T\}$. We let: $\mathrm{T}_{BLM} := \{1,...,T_{BLM}\} \subset \mathrm{T}$ denote the first periods during which the BLM is allowed to conduct commercial operations. Hereafter, we assume that the time horizon T is large.[8]

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[8] In the present paper, we assume that this large time horizon is not sufficient for the world helium consumption to cease being entirely supplied by underground helium sources. Hence, we follow Cai et al., (2010) and Mohr and Ward (2014) and assume that helium extraction from the atmosphere plays zero role in the analysis. In the 1970s (e.g.: Epple and Lave, 1980), this extremely costly technology was occasionally presented as a potential backstop source (i.e., a source that once in use in a distant future would be capable of producing enough helium in each year to serve the annual world consumption for an indefinite future time).

We let $J := \{1,...,J\}$ 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 located in resource-rich regions 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.

In the remainder of this subsection, we explicitly write out the market-clearing conditions and the optimization problem for each individual market participant (i.e., the consumers, the U.S. BLM, and the private helium suppliers), 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 which is determined empirically.[9] Hence, 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 and an increasing function of the lagged consumption:

$$d_t = \alpha_t - \gamma \, p_t + \lambda \, d_{t-1}, \qquad \forall t \in T, \ d_0 \text{ given.} \qquad (1)$$

where the intercept α_t, the slope γ and the lagged coefficient λ are empirically-determined parameters (with $\alpha_t > 0$, $\gamma > 0$ 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:

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

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[9] The linear demand specification is frequently retained in numerical resource economics models (e.g., Pindyck, 1978).

c – The BLM

This agent controls the extraction operations conducted at the FHR and is endowed with the reserve R_0 at the end of 2013. According to the policy objectives mentioned in the 2013 Act, the BLM's sales must be conducted so as to "maximize the total financial return to the taxpayer" (Helium Stewardship Act, 2013). We thus model the BLM as a profit-maximizing agent that is allowed to conduct commercial operations during the time horizon T_{BLM}. In each year t, the BLM can decide the non-negative quantity q_t^{BLM} that will be extracted and sold to commercial users. After the cessation of its commercial operations, the BLM's reserve level has to be equal to $\underline{R}$ (i.e., the 3 Bcf allocated to non-commercial uses).

We now clarify the behavior of this agent and how the extraction trajectory is determined. In this paper, we first define a generic model used to mimic the rapid extraction behavior stipulated in the 2013 Act before presenting a variation of that generic model.

The rapid extraction trajectory in the 2013 Act

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. We let $\overline{Q_t^{BLM}}$ denote that imposed production trajectory in year t. From the data in Figure 1, we let the time horizon be $T_{BLM} = 9$ years and the imposed trajectory be defined as follows: (i) from 2014 (year 1) to 2021 (year 8), $\overline{Q_t^{BLM}}$ is equal to the annual production ceiling in Figure 1; (ii) in year 2022 (year 9), this quantity is equal to 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 production at the maximum extraction rate during 2014 to 2021); and (iii) from 2023 on, the quantity $\overline{Q_t^{BLM}}$ is equal to zero. Therefore, the behavior of the BLM can be modeled using the following optimization problem:

BLM – Model I ($T_{BLM} = 9$)

$$\underset{q_t^{BLM}}{\text{Max}} \quad \Pi_{BLM} = \sum_{t \in T_{BLM}} \beta_{BLM}{}^{t} \left[p_t^* - C_{BLM} \right] q_t^{BLM} \qquad \text{(BLM I – 1)}$$

$$\text{s.t.} \quad q_t^{BLM} \le \overline{Q_t^{BLM}}, \qquad \forall t \in T_{BLM}, \qquad \text{(BLM I – 2)}$$

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

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

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

where β_{BLM} is the discount factor, C_{BLM} is the unit extraction cost, R_t is the reserve in year t and the initial reserve R_0 is given. The price in year t is p_t^* where the asterisk indicates that this price variable is exogenous to the BLM's optimization problem but endogenous to the market model as a whole.

Hence, the BLM naïvely views this variable as fixed even though the full market model equilibrates price to equate supply with demand. The BLM is thus assumed to behave as a price-taking agent that ignores the impact of its sales on the wholesale price.

The objective function (BLM I – 1) is the discounted sum of the BLM's annual profits, which are the result of revenues from sales minus production costs. The constraint (BLM I – 2) stipulates that, in each year, the quantity extracted cannot be larger than the predefined extraction trajectory. Equation (BLM I – 3) is the reserve accounting identity that keeps track of the BLM reserves. In this identity, we use the convention that the remaining reserves R_t is measured at the end of year t (i.e., once the quantity q_t^{BLM} has been extracted and sold). The constraint (BLM I – 4) imposes the remaining reserve at the end of the BLM's commercial operations to be equal to the desired reserve threshold.

By construction, the unique solution to that problem is the rapid extraction trajectory such that the extraction ceiling constraint (BLM I – 2) is binding. From this base-case model, one may question the rationality of that imposed "as-fast-as-technically-possible" extraction trajectory and explore the economics of an alternative policy prescription that would allow the BLM to operate over a possibly longer time horizon $T_{BLM} > 9$ years. For example, the application discussed in section 4 considers an enlarged time horizon of 20 years.

The case of a possibly slower extraction trajectory with Cournot behavior

Compared with the previous model, we now consider a longer time horizon $T_{BLM} > 9$ years. Because of this enlarged time horizon, the BLM is no longer compelled to adopt the "as-fast-as-technically-possible" 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.[10] We thus proceed, assuming that in each year t the quantity extracted by the BLM cannot exceed the value determined by that linear function, and modify the left-hand side of (BLM I – 2) accordingly.

Regarding the latter, one should note that, 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 early years of the planning horizon. Therefore, we assume that this agent is able to behave à la Cournot and assess how extraction decisions are modifying equilibrium prices.

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[10] 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 made in models of the oil industry (e.g., Griffin and Teece, 1982).

We thus consider the following alternative model where the preimposed extraction trajectory is replaced by the geological restrictions discussed above and the inverse demand function is explicitly considered in the revenue component of the BLM's objective function.

BLM – Model II ($T_{BLM} > 9$)

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

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

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

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

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

where q_t^{-BLM*} is used as a short notation for the aggregate quantity of helium supplied by the rivals. Consistent with the Cournot framework, this aggregate quantity q_t^{-BLM*} is exogenous to the BLM's optimization problem. In the objective function (BLM II – 1), the initial consumption at time 0 is given and is equal to d_0.

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.[11] We also assume that

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[11] Hence, we 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. This assumption is also adopted in Epple and Lave (1980).

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:

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

$$\underset{q_t^i}{\mathrm{Max}} \quad \Pi_j = \sum_{t \in T} \beta_j^t \left[\left(1-\delta_j\right) p_t^* + \delta_j P_t \left(q_t^j + q_t^{-j*}, q_{t-1}^j + q_{t-1}^{-j*}\right) - C_j^e \right] q_t^j \qquad \text{(J1–1)}$$

$$\text{s.t.} \quad q_t^j \le \overline{H_t^j}, \qquad \forall t \in T, \qquad \text{(J1–2)}$$

$$q_t^j \ge 0, \qquad \forall t \in T. \qquad \text{(J1–3)}$$

where β_j is the players' discount factor,[12] 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 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 (J1–2) 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 $\overline{H_t^j} - q_t^j \ge 0$ 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

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[12] 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 possibly using different interest factors.

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. The provision of this private storage service will cease once the BLM's commercial operations have been terminated.

In this paper, we assume that these agents behave as price-takers. 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:

The U.S. producers connected to the BLM infrastructure

$$\underset{q_t^i, h_t^j, i_t^j, w_t^i, v_t^i}{\text{Max}} \quad \Pi_j = \sum_{t \in T} \beta_j^{\,t} \left[p_t^* q_t^j - C_j^e h_t^j - C_j^i i_t^j - C_j^w w_t^j - S\, v_t^j \right] \qquad \text{(J2–1)}$$

$$\text{s.t.} \quad h_t^j \le \overline{H_t^j}, \qquad \forall t \in T, \qquad \text{(J2–2)}$$

$$q_t^j + i_t^j = h_t^j + w_t^j, \qquad \forall t \in T, \qquad \text{(J2–3)}$$

$$v_t^j = v_{t-1}^j + i_t^j - w_t^j, \qquad \forall t \in T,\ v_0^j \text{ given}, \qquad \text{(J2–4)}$$

$$v_t^j = 0, \qquad \forall t \ge T_{BLM}, \qquad \text{(J2–5)}$$

$$q_t^j \ge 0,\ h_t^j \ge 0,\ v_t^j \ge 0,\ i_t^j \ge 0,\ w_t^j \ge 0, \qquad \forall t \in T. \qquad \text{(J2–6)}$$

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 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. The constraints (J2–2) state that production of helium from natural gas at time t cannot exceed the annual production ceiling $\overline{H_t^j}$. The equation (J2–3) 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 (J2–4) is an accounting identity that keeps track of the storage volume. The constraint (J2–5) imposes the termination of the storage operations at the end of the BLM's time horizon.

The new players

The subgroup $J_3 \subset J$ gathers the firms that are capable of investing to further expand their future helium production. The list includes 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). Though helium is an exhaustible resource, we assume that these players are located in resource-rich regions where geological depletion will not be a concern during the planning horizon T.

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, sales cannot exceed the total installed capacity K_{t-1}^j at the end of the preceding year. 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. We also assume that, in each year t, the total capacity K_t^j that can be available at the end of the year is bounded by an exogenously-determined ceiling $\overline{K_t^j}$.

Regarding the competitive behavior in the helium market, these agents are modeled as Cournot players except in Canada, South Africa and Utah where the sizes of the helium-processing plants will remain modest relative to the world helium consumption. These three small players are thus modeled as price-taking agents.

Overall, a producer j in J_3 is assumed to solve the following optimization program:

The new players

$$\operatorname*{Max}_{q_t^i,k_t^i} \quad \Pi_j = \sum_{t \in T} \beta_j^{\,t} \left[\left[\left(1-\delta_j\right) p_t^* + \delta_j P_t \left(q_t^j + q_t^{-j*}, q_{t-1}^j + q_{t-1}^{-j*}\right) - C_j^e \right] q_t^j - C_j^k k_t^j \right] \qquad \text{(J3–1)}$$

$$\text{s.t.} \quad K_t^j = K_{t-1}^j + k_t^j, \qquad \forall t \in T,\ K_0^j \text{ given}, \qquad \text{(J3–2)}$$

$$q_t^j \le K_{t-1}^j, \qquad \forall t \in T, \qquad \text{(J3–3)}$$

$$K_t^j \le \overline{K_t^j}, \qquad \forall t \in T, \qquad \text{(J3-4)}$$

$$q_t^j \ge 0, \quad k_t^j \ge 0, \qquad \forall t \in T. \qquad \text{(J3–5)}$$

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.[13] As in (J1–1), 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 constraint (J3–2) is a state equation that describes the evolution of the total installed capacity. The constraint (J3–3) imposes that, in each year t, the annual sales cannot exceed the total capacity K_{t-1}^j installed at the end of the preceding year. From the constraints (J3–4), the total installed capacity in each year cannot exceed the exogenous capacity ceiling determined for that year.

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[13] The entire planning horizon T is chosen to be large enough (40–50 years) to approximate the infinite-horizon problem. As our analysis concentrates on the first T_{BLM} year (where T_{BLM} is in the 9–25 year range), the objective function of this agent does not include a salvage value at the end of the planning horizon T.

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.:

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

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 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.[14] 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). This collection of conditions can be expressed as a mixed complementarity problem[15] 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 (Ferris and Munson, 2000) to find Nash equilibria under various assumptions.

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

[15] We refer to Cottle et al. (1992) and Gabriel et al. (2012a) for comprehensive presentations of the MCP framework and applications in energy economics and simply note here that a complementarity problem is a problem of the following general form: Find vector X such that $X \geq 0$, $F\left(X\right) \leq 0$ and $X^T F\left(X\right) = 0$, where $F\left(.\right)$ is a vector-valued function of the same dimension as X and ^{T} i*s the transpose operator. The term “complementarity” applies because either* x_i or $f_i\left(X\right)$ can be positive, but not both, where x_i is the i^{th} element of X and $f_i\left(X\right)$ is the i^{th} element of $F\left(X\right)$. A mixed complementarity problem is more general: find vectors X and Y, such that $X \geq 0$, $F\left(X,Y\right) \leq 0$, $X^T F\left(X,Y\right) = 0$, and $G\left(X,Y\right) = 0$, where $G\left(.\right)$ is a vector-valued function of the same length as Y.

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.

We first have to clarify the planning horizon retained in the analysis. We aim at comparing two solutions: the one obtained when the BLM is compelled to use the rapid depletion trajectory (i.e., the BLM Model I) and the one whereby that agent is allowed to conduct commercial operations during an extended time horizon T_{BLM} of 20 years. To account for the presence of an adjustment lag in the helium demand function, our discussion of the market outcomes will be centered on the enlarged period of 22 years that follows the implementation of the 2013 Act. Yet, 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 A. 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[16] and clarifies their posited strategic behavior. In this paper, all the players that are capable of producing more than 200 MMcf per year are supposed to behave à la Cournot while the others are modeled as price-taking agents.[17] The specific cost and geological parameters used for each player are detailed in Appendix B.

We assume that all the private players located in OECD countries consider a real discount rate of 7 percent and that the rate used by players operating in non-OECD regions is 10 percent. A real discount rate of 3 percent is used for the U.S. BLM.

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[16] This list has been derived from the descriptive analyses detailed in IHS (2014) and in Gasworld, a professional journal.

[17] 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.

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 complex (a)	Price-taking
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

Note: (a) Because of the lack of individual data on storage inventories, we had to consider an aggregate player gathering all the private plants connected to the BLM helium pipeline.

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 intercept coefficients A_{mt} in 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 1995 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. 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. The present analysis thus considers two cases that reflect possible alternative trajectories for the country's capacity ceiling $\overline{K}_t^j$ in equation (J3–4):

(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).

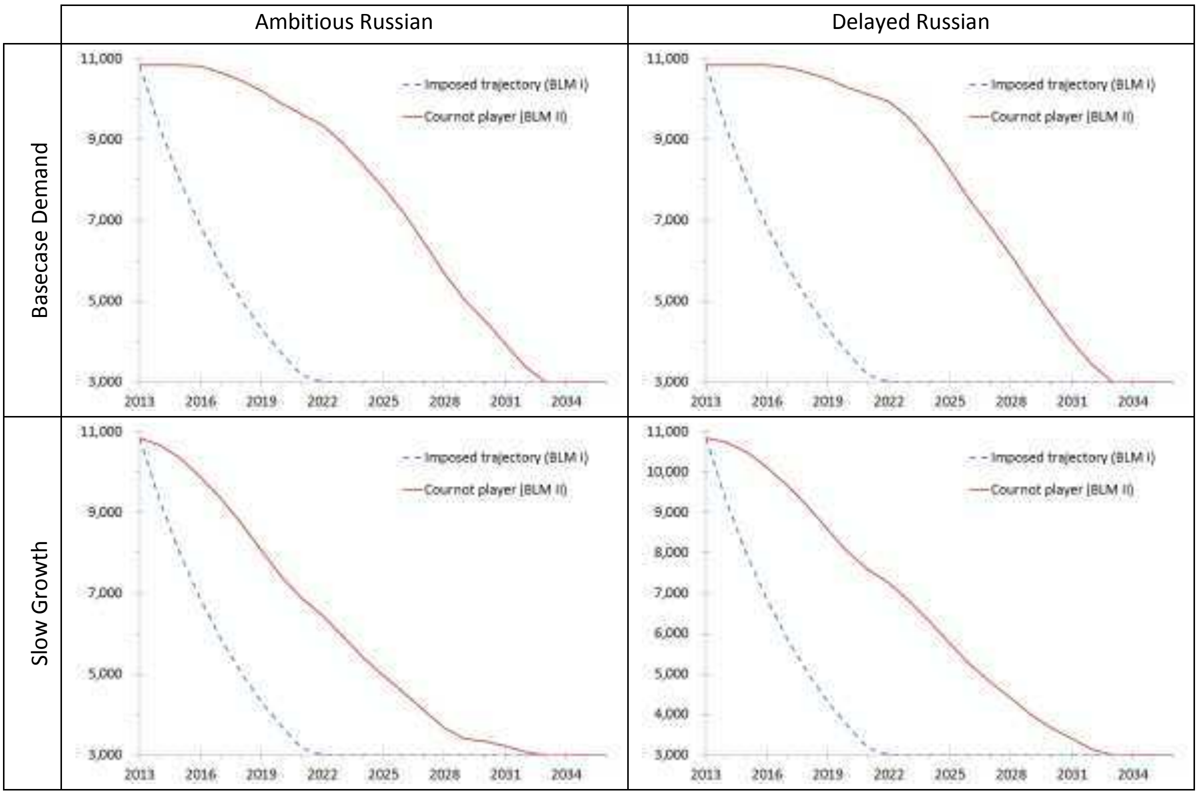
4.2 Results and discussion

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 period of 20 years. Our discussion 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 trajectory of the Federal Reserve obtained with the less stringent mandate is substantially slower than the "as-fast-as-technically-possible" path currently imposed on the U.S. BLM. This finding suggests 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)



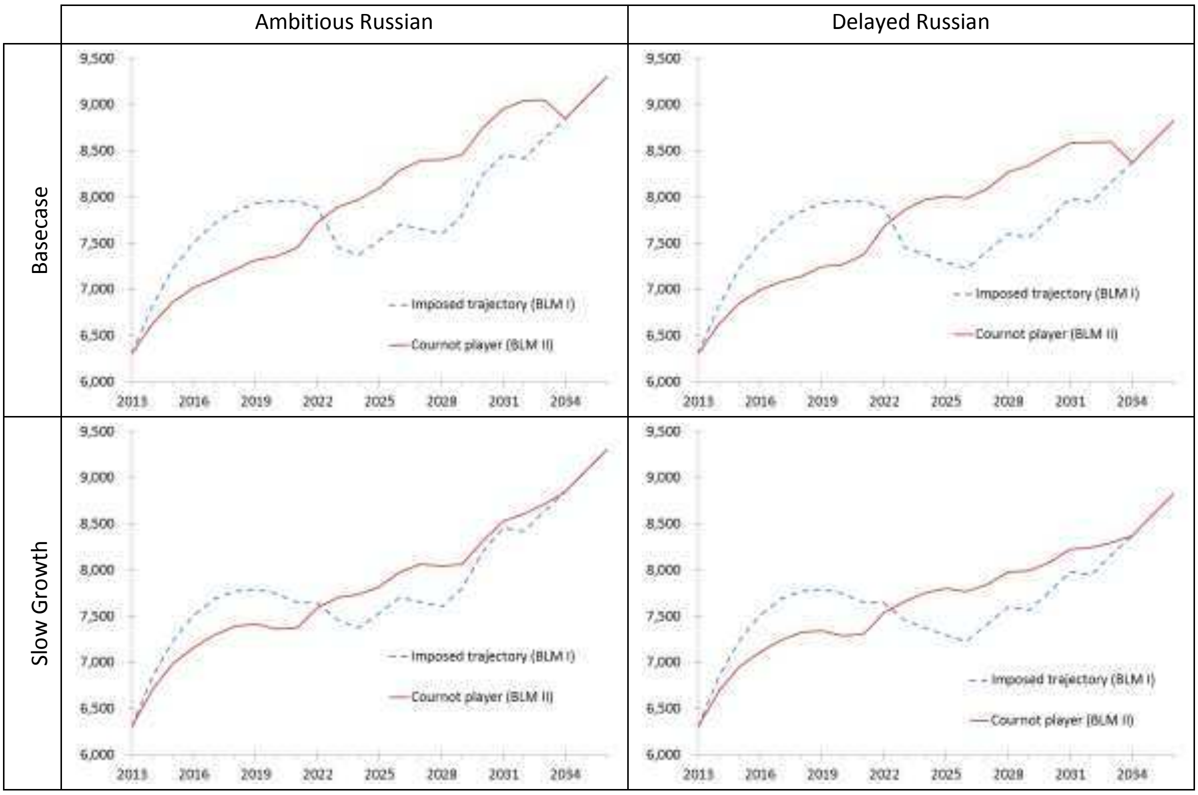
b – The market outcomes

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 both mandates under each of the four scenarios are shown graphically for the first 20 years 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) artificially stimulates booming consumption figures during the early years followed by a period of relative stagnation after 2022. In contrast, the less stringent mandate generates smoothly growing consumption trajectories.

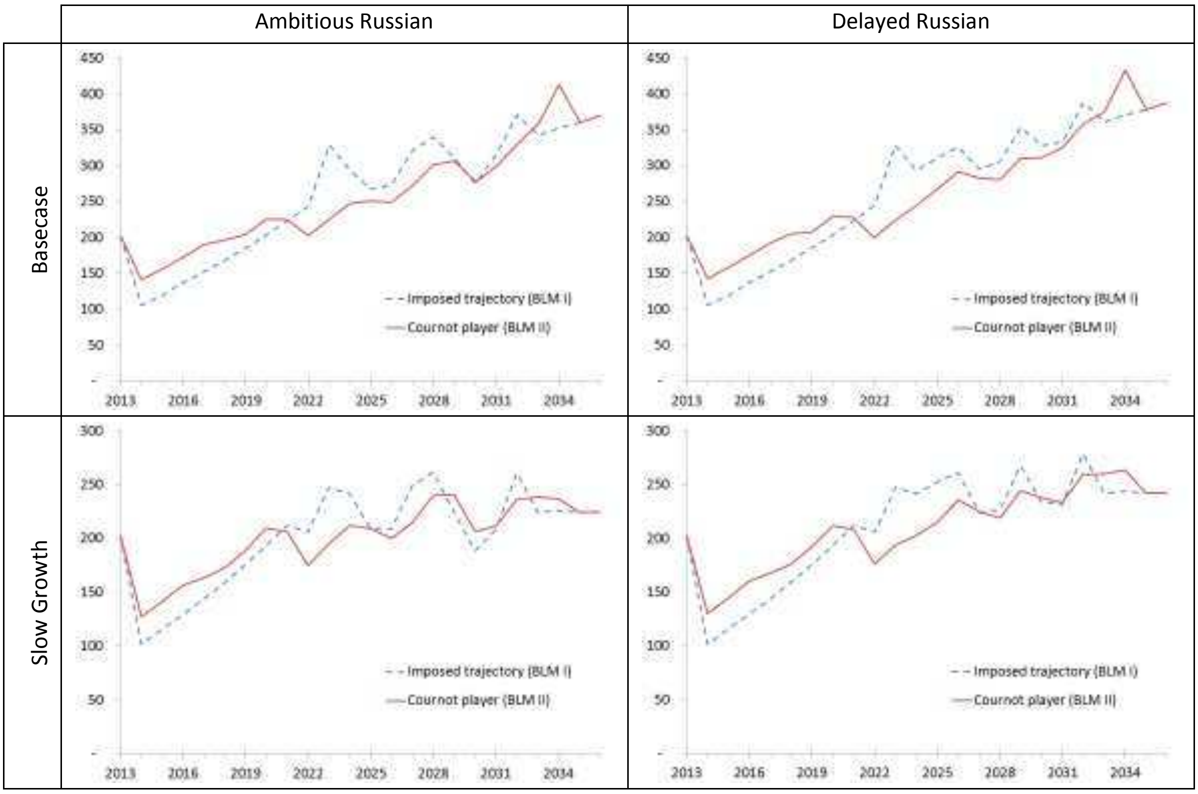
Figure 3. Annual helium consumption (in MMcf)



Market price

Regarding future equilibrium prices, 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 behave à la Cournot (i.e., BLM Model II) exhibit higher prices during the initial years and lower ones after 2022. 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 this less stringent mandate also smoothens the price shocks related to the commencement of Eastern Siberian operations after 2021. 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 adopts 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.[18]

Figure 4. Equilibrium prices (in $/Mcf)



Behavior of the other producers

We now examine how the BLM’s rapid extraction trajectory is impacting the rivals’ decisions. Two interesting series of findings can be derived from the detailed examination of the individual players’ supply policies.

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 (J1–2) 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.[19] The figures in Table 2 reveal that, whatever the scenario under scrutiny, the obligation to use

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[18] Cf., the descriptive analyses on the state of the helium market regularly published in Gasworld, a professional journal.

[19] 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)

a rapid extraction trajectory at the U.S. BLM (i.e., Model I) systematically generates a larger waste of helium compared to the Cournot mandate (BLM Model II). Opting for that latter mandate is thus preferable to conserve the resource.

Table 2. Annual helium venting (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	48.7	24.1	48.7	48.7
Total helium wasted	*688.7*	*664.1*	*688.7*	*688.7*
Cournot player (BLM Model II)				
Utah 1				
Year 1	160.0	160.0	160.0	160.0
Year 2	0.0	0.0	160.0	160.0
Year 3	0.0	0.0	0.0	0.0
Year 4	0.0	0.0	0.0	0.0
Wyoming 1				
Year 1	0.0	0.0	0.0	0.0
Total helium wasted	*160.0*	*160.0*	*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.

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 the amount of private inventory levels becomes insignificant after 2022. Neither the speed of future Russian deployments nor the rate of demand growth exerts any sort of influence on this pattern. That said, 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 behave à la Cournot (cf., the solid lines). In contrast, the U.S. private inventory levels are either maintained or even increased during the first three years when the BLM implements the rapid extraction trajectory (cf., the dashed lines). This 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 three years. Nevertheless, one may question the social efficiency of that policy as the cost of the intertemporal arbitrage operations

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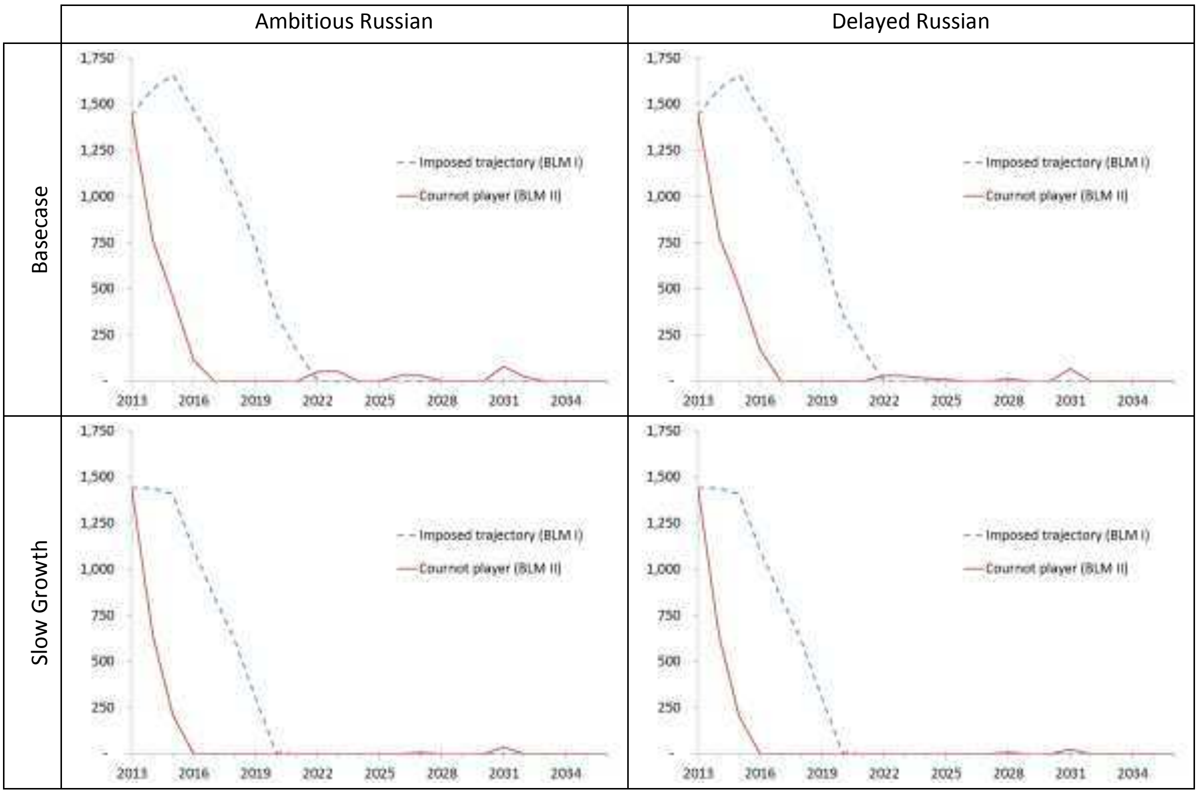
$\beta_j q_2^j \frac{\partial P_2}{\partial q_1^j}\left(q_2^j + q_2^{-j*}, q_1^j + q_1^{-j*}\right) = \beta_j \frac{\lambda}{\gamma} q_2^j$ the discounted marginal impact the sale of a marginal unit in year 1 will have on the price obtained in year 2 times the total quantity that will be supplied by that player in year 2. Simplifying, the marginal revenue function of that player in year 1 is: $MR_1^j = \left(A_1 + \lambda d_0 - 2q_1^j - 1q_1^{-j*} + \beta_j \lambda q_2^j\right)/\gamma$. In each of the scenarios under *scrutiny, 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 $q_2^j = \overline{H_2^j}$.

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)



c – Profits, surpluses, and welfare

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

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. Depending on the scenario under scrutiny, the net present value of the future U.S. Treasury net revenues is between +30.7 percent and +60.8 percent larger when the BLM is allowed to behave à la Cournot over a 20-year span.

From a social welfare perspective, note that under our base-case demand scenario, the global welfare is larger when the less stringent mandate (BLM II) is adopted. In case of lower future demand, the social welfare-maximizing policy varies depending on the deployment scheme that will be adopted in Russia but, in each of these two scenarios, the magnitudes of the social welfares obtained with the two policies are close.

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

				Imposed trajectory (BLM I)	Cournot Player (BLM II)
Scenarios	Basecase demand	Ambitious Russian	Consumer Surplus	91,425.3	**92,759.0**
			BLM's Surplus	831.4	**1,263.7**
			US Producers' Surplus	8,290.0	**8,290.7**
			Foreign Producers' Surplus	13,853.2	**13,613.0**
			Social Welfare	*114,399.9*	***115,926.3***
		Delayed Russian	Consumer Surplus	87,796.7	**88,968.1**
			BLM's Surplus	831.4	**1,337.1**
			US Producers' Surplus	8,641.7	**8,653.1**
			Foreign Producers' Surplus	**14,074.1**	13,851.5
			Social Welfare	*111,343.9*	***112,809.8***
	Slow demand growth	Ambitious Russian	Consumer Surplus	**90,284.6**	89,815.0
			BLM's Surplus	776.9	**986.7**
			US Producers' Surplus	6,134.8	**6,229.3**
			Foreign Producers' Surplus	**9,280.4**	9,137.4
			Social Welfare	***106,476.6***	*106,168.5*
		Delayed Russian	Consumer Surplus	**86,691.6**	86,639.6
			BLM's Surplus	776.9	**1,015.5**
			US Producers' Surplus	6,483.9	**6,556.0**
			Foreign Producers' Surplus	**9,743.9**	9,575.7
			Social Welfare	*103,696.4*	***103,786.8***

Note: For the sake of readability, the maximum values attained under each scenario are in bold.

From a U.S. perspective, domestic public policy debates frequently emphasize issues such as the preservation of the consumers' and/or the U.S. producers' interests. Here again, a comparison of the outcomes obtained with the base-case demand projection indubitably recommends the use of the less stringent mandate in these two scenarios. With the two scenarios involving lower future demand levels, there seems to be some debate: the consumer surplus is maximized with the rapid extraction path whereas the producer surpluses for both the BLM and the U.S. producers are larger when the BLM behaves à la Cournot. Yet, if one considers the sum of these three surpluses as a decision criteria, the less stringent mandate should be selected in the "slow demand – delayed Russian" as the surplus gains by U.S. suppliers and the BLM more than outweigh the surplus lost by global consumers. Lastly, in the "slow demand – ambitious Russian" scenario, the sum of these three surpluses is maximized when the rapid path BLM I is implemented but one could conceivably argue that only a share of that global consumer surplus would accrue 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 less stringent mandate would again be a rational move for a self-centric government concerned solely with U.S. 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. At least three 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. 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. 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.

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. Another line of future research could also consider the role of uncertainty in future demand growth rates.

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Appendix A – 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. De 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.[20] 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.

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[20] We refer to Nuttall et al. (2012b) for comprehensive discussions about these potential uses of helium.

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:[21]

$$\mathrm{d_t} = \phi + \varphi.\mathrm{y_t} - \gamma.\mathrm{p_t} + \lambda.\mathrm{d_{t-1}} + \varepsilon_\mathrm{t} \,, \tag{A.1}$$

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, φ, γ and λ to be estimated. Normally, we would expect the lagged-adjustment coefficient λ to verify $0 \le \lambda < 1$. In addition, we would expect that the short-run elasticity of consumption with respect to income is positive (which suggests that the slope coefficient φ verifies $\varphi > 0$), 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 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 A.1 provides the mean, standard deviation, minimum, and maximum values for all of these variables in levels.

Table A.1. Summary statistics

	$\mathrm{d_t}$ *[MMcf]*	$\mathrm{GDP_t}$ *[10^{12} 2014 USD]*	$\mathrm{p_t}$ *[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

Results

The estimation results are summarized in Table A.2 (Panel 1). The signs and magnitudes of the estimates are consistent with our expectations but the intercept coefficient is clearly not significant.

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[21] The assumption of a linear specification for the demand function is usual in the natural resource economics literature (e.g., Pindyck, 1978).

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 A.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 A.2. Estimation results

	Constant ϕ	GDP_t φ	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.

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 intercept coefficient α_t in the demand equation (1) is given by $\varphi.y_{2014}.(1+g)^{t-1}$, where φ is the empirically-determined coefficient, 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 B – 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 B.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 B.1. Estimation results

	R_{t-1} η	Constant μ	$\bar{R}^2$	*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. $\bar{R}^2$ 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.

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 B.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 scale of the plant, the plant's separation technology, its date of construction, and its location. We can note that there are substantial variations between the plants.

Table B.2. Cost data (in \$/Mcf)

	Players in group J_1								J_2
	Australia	China	Poland	Colorado 1	Kansas	New Mexico	Wyoming 1	Utah 1 (a)	Hugoton-Panhandle complex
Unit costs C_j^e	90.0	80.3	79.0	87.0	67.9	100.4	42.8	155.0	60.4

Note: 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.

Second, exogenous production trajectories $\overline{H_t^j}$ are needed for each of these players. These trajectories are detailed in Table B.3. 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 B.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 v_0^j stored by the private firms at the Hugoton-Panhandle complex amounted to 1,440.0 MMcf (source: USGS).

Table B.3. Extraction trajectories $\overline{H_t^j}$ (in MMcf)

	Players in group J_1								J_2
	Australia [(a)]	China [(b)]	Poland [(c)]	Colorado 1 [(c)]	Kansas [(d)]	New Mexico [(c)]	Wyoming 1 [(d)]	Utah 1 [(d)]	Hugoton-Panhandle complex [(c)]
Year 1	150.0	10.6	137.0	55.2	36.5	1.3	1450.0	160.0	1258.6
Year 2	150.0	10.6	137.0	43.5	36.5	1.0	1450.0	160.0	1195.0
Year 3	150.0	10.6	137.0	34.3	36.5	0.8	1450.0	160.0	1084.4
Year 4	150.0	10.6	137.0	27.1	36.5	0.6	1450.0	160.0	957.3
Year 5	150.0	10.6	137.0	21.3	36.5	0.5	1450.0	160.0	866.9
Year 6	150.0	10.6	123.3	16.5	36.5	0.4	1450.0	160.0	771.6
Year 7	150.0	10.6	111.0	10.8	36.5	0.3	1450.0	160.0	686.4
Year 8	150.0	10.6	99.9	8.4	36.5	0.2	1450.0	160.0	606.4
Year 9	150.0	10.6	89.9	6.0	36.5	0.2	1450.0	160.0	522.4
Year 10	120.0	10.6	80.9	4.8	36.5	0.1	1450.0	160.0	466.4
Year 11	96.0	10.6	72.8	3.7	36.5	0.1	1450.0	160.0	421.8
Year 12	76.8	10.6	65.5	2.5	36.5	0.0	1450.0	160.0	369.0
Year 13	61.4	10.6	59.0	2.0	36.5	0.0	1450.0	160.0	323.3
Year 14	49.2	10.6	53.1	1.5	36.5	0.0	1450.0	160.0	296.1
Year 15	39.3	10.6	47.8	0.8	36.5	0.0	1450.0	160.0	253.4
Year 16	31.5	10.6	43.0	0.7	36.5	0.0	1450.0	160.0	229.9
Year 17	25.2	10.6	38.7	0.5	36.5	0.0	1450.0	160.0	193.9
Year 18	20.1	10.6	34.8	0.4	36.5	0.0	1450.0	160.0	170.0
Year 19	16.1	10.6	31.3	0.0	36.5	0.0	1450.0	160.0	139.1
Year 20	12.9	10.6	28.2	0.0	36.5	0.0	1450.0	160.0	124.3
Year 21	10.3	10.6	25.4	0.0	36.5	0.0	1450.0	160.0	103.2
Year 22	8.2	10.6	22.8	0.0	36.5	0.0	1450.0	160.0	83.9
Year 23	6.6	10.6	20.6	0.0	36.5	0.0	1450.0	160.0	64.9
Year 24	5.3	10.6	18.5	0.0	36.5	0.0	1450.0	160.0	50.5
Year 25	0.0	10.6	16.7	0.0	36.5	0.0	1450.0	160.0	38.2
Year 26	0.0	10.6	15.0	0.0	36.5	0.0	1450.0	160.0	29.3
Year 27	0.0	10.6	13.5	0.0	36.5	0.0	1450.0	160.0	22.6
Year 28	0.0	10.6	12.1	0.0	36.5	0.0	1450.0	160.0	17.4
Year 29	0.0	10.6	10.9	0.0	36.5	0.0	1450.0	160.0	13.3
Year 30	0.0	10.6	9.8	0.0	36.5	0.0	1450.0	160.0	10.1
Year 31	0.0	10.6	8.9	0.0	36.5	0.0	1450.0	160.0	7.5
Year 32	0.0	10.6	8.0	0.0	36.5	0.0	1450.0	160.0	5.7
Year 33	0.0	10.6	7.2	0.0	36.5	0.0	1450.0	160.0	4.2
Year 34	0.0	10.6	6.5	0.0	36.5	0.0	1450.0	160.0	2.9
Year 35	0.0	10.6	5.8	0.0	36.5	0.0	1450.0	160.0	2.1
Year 36	0.0	10.6	5.2	0.0	36.5	0.0	1450.0	160.0	1.7
Year 37	0.0	10.6	0.0	0.0	36.5	0.0	1450.0	160.0	1.0

Notes: (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) That trajectory is the one detailed in Mohr and Ward (2014, high growth scenario). (d) This extraction path has been derived from the analyses published in Gasworld, a professional journal.

c – The new players

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

Table B.4. Cost data (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 B.5. details the time path of the maximum capacity deployment posited for each player in J_3.

Table B.5. Allowed capacity deployment $\overline{K_t^j}$ (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	1990.0	230.0	230.0	0.0	0.0	0.0	36.5
Year 2	870.0	0.0	0.0	1990.0	230.0	230.0	0.0	230.0	100.0	36.5
Year 3	870.0	40.0	0.0	1990.0	230.0	230.0	0.0	230.0	200.0	36.5
Year 4	1200.0	40.0	0.0	1990.0	230.0	230.0	0.0	230.0	200.0	36.5
Year 5	1200.0	40.0	0.0	2202.5	230.0	230.0	50.0	230.0	200.0	36.5
Year 6	1200.0	40.0	0.0	2415.0	230.0	230.0	100.0	230.0	200.0	36.5
Year 7	1200.0	40.0	0.0	2415.0	230.0	230.0	100.0	230.0	200.0	36.5
Year 8	1200.0	40.0	0.0	2415.0	468.0	468.0	100.0	230.0	200.0	36.5
Year 9	1200.0	40.0	0.0	2415.0	706.0	706.0	100.0	230.0	400.0	36.5
Year 10	1200.0	40.0	0.0	2415.0	706.0	706.0	100.0	230.0	400.0	36.5
Year 11	1200.0	40.0	0.0	2415.0	706.0	706.0	100.0	230.0	400.0	36.5
Year 12	1200.0	40.0	0.0	2415.0	944.0	706.0	100.0	230.0	400.0	36.5
Year 13	1200.0	40.0	0.0	2415.0	1182.0	706.0	100.0	230.0	400.0	36.5
Year 14	1200.0	40.0	0.0	2415.0	1182.0	944.0	100.0	230.0	400.0	36.5
Year 15	1200.0	40.0	0.0	2415.0	1182.0	1182.0	100.0	230.0	400.0	36.5
Year 16	1200.0	40.0	0.0	2415.0	1420.0	1182.0	100.0	230.0	400.0	36.5
Year 17	1200.0	40.0	250.0	2415.0	1658.0	1182.0	100.0	230.0	400.0	36.5
Year 18	1200.0	40.0	500.0	2415.0	1658.0	1182.0	100.0	230.0	400.0	36.5
Year 19	1200.0	40.0	500.0	2415.0	1658.0	1182.0	100.0	230.0	400.0	36.5
Year 20	1200.0	40.0	500.0	2415.0	1896.0	1420.0	100.0	230.0	400.0	36.5
Year 21	1200.0	40.0	500.0	2415.0	2134.0	1658.0	100.0	230.0	400.0	36.5
Year 22	1200.0	40.0	750.0	2415.0	2134.0	1658.0	100.0	230.0	400.0	36.5
Year 23	1200.0	40.0	1000.0	2415.0	2134.0	1658.0	100.0	230.0	400.0	36.5
Year 24	1200.0	40.0	1000.0	2415.0	2372.0	1658.0	100.0	230.0	400.0	36.5
Year 25	1200.0	40.0	1000.0	2415.0	2610.0	1658.0	100.0	230.0	400.0	36.5
Year 26	1200.0	40.0	1000.0	2415.0	2610.0	1896.0	100.0	230.0	400.0	36.5
Year 27	1200.0	40.0	1000.0	2415.0	2610.0	2134.0	100.0	230.0	400.0	36.5
Year 28	1200.0	40.0	1000.0	2415.0	2610.0	2134.0	100.0	230.0	400.0	36.5
Year 29	1200.0	40.0	1000.0	2415.0	2610.0	2134.0	100.0	230.0	400.0	36.5
Year 30	1200.0	40.0	1000.0	2415.0	2610.0	2134.0	100.0	230.0	400.0	36.5
Year 31	1200.0	40.0	1000.0	2415.0	2610.0	2134.0	100.0	230.0	400.0	36.5
Year 32	1200.0	40.0	1000.0	2415.0	2610.0	2372.0	100.0	230.0	400.0	36.5
Year 33	1200.0	40.0	1000.0	2415.0	2610.0	2610.0	100.0	230.0	400.0	36.5
Year 34	1200.0	40.0	1000.0	2415.0	2610.0	2610.0	100.0	230.0	400.0	36.5
Year 35	1200.0	40.0	1000.0	2415.0	2610.0	2610.0	100.0	230.0	400.0	36.5
Year 36	1200.0	40.0	1000.0	2415.0	2610.0	2610.0	100.0	230.0	400.0	36.5
Year 37	1200.0	40.0	1000.0	2415.0	2610.0	2610.0	100.0	230.0	400.0	36.5

Note: The initial capacities are based on IHS (2014). The deployment paths are consistent with IHS (2014) and the analyses published in Gasworld, a professional journal. (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).