Assessing the Past and Future Sustainability of Global Helium Resources, Extraction, Supply and Use, Using the Integrated Assessment Model WORLD7

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Abstract
The sustainability of the helium production, supply and use was assessed using the WORLD7 integrated model. The use of helium is at present concluded to be unsustainable with respect to long-term supply security, because of lack of significant recycling. There is no risk for significant helium scarcity in the short term (before 2030), but in the long term, the scarcity risk is unavoidable under business as usual. The helium supply runs into limitations by 2090, under business as usual and supply declines after that. The study shows that the present helium recycling rate is far too low, causing helium to be squandered in one-way use and that is driving helium prices up. A scenario analysis with the WORLD7 model suggests that a sustained program for helium recycling and demand management, combined with political efforts to ban unnecessary use, will be able to significantly improve the long-term helium supply situation. The outputs show that such efforts may be sufficient for avoiding any scarcity under the demand assumptions taken.

Keywords Helium · System dynamics · Modelling · Global modelling · WORLD7 · Resources

Introduction
Helium is a non-renewable resource of great importance to science and modern medicine and advanced physics research. It is essential for achieving the extremely cold temperatures required by many current and emerging technologies as well as for advanced scientific research (APS 1995) (see Table 1 for a list of main uses). The demand for helium has been steadily increasing, and likely that will continue. The biggest consumer of helium is NASA, followed by the USA Department of Defense, which uses a significant quantity to cool liquid hydrogen and oxygen for rocket fuel (Scholes 2012). Helium is made on earth via nuclear decay of uranium, and recovered from mines. It boils at just 4 K, and during normal lab operations much inevitably evaporates. Once it is released into the atmosphere, it becomes uneconomical to recapture it, and since it is so light, atmospheric helium will eventually escape earth altogether. Continuing on the current path (business as usual, BAU), a shortage of helium is therefore bound to happen in the near future, the big question is when will we run into hard scarcity and what can we do to manage the situation?

Currently humanity is squandering this strategically important resource and nearly no significant recycling occurs (Bardi 2013; R. Heinberg 2001; R. Heinberg 2011; Sverdrup and Ragnarsdottir 2014). Medical uses, most importantly MRI imaging, used 30–35% of the helium supply in 2018, entertainment use (party balloons) uses 15%, other scientific use takes about 17%, welding uses 9%, engineering use takes 6%, leak detection uses 5%, and other unspecified uses take about 14% (Anderson 2017; Boreham et al. 2018; Mohr and Ward 2014). Of these, the medical use and the scientific use are of high importance for modern health care and the advancement of science. Therefore, during shortages, science is far down the delivery list, because bigger customers get priority (Vishik 2016). And without

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helium, scientists can be forced to reschedule or abandon experiments, and to place costly and complicated equipment in shutdown (Nature 2017).

The annual production in 2018 is about 36,000 ton per year. The size of the United States of America National Reserve was at the maximum before the great sell-off, about 1,000,000,000 m³ or 170,000 ton of helium, comparable to 5 years of global production. Helium that is lost to the atmosphere, is slowly diffused into space and, in the real long term, is lost forever into space. It is produced in the underground from radioactive decay at a very low rate, about 5,000 ton per year (Kelly and Matos 2011). It accumulates in the same locations as natural gas. Helium is found as a trace gas in natural gas wells. A few wells have elevated concentrations of helium (Tongish 1980; Zartmann et al. 1961). The first such wells were discovered in the United States in the 1920s (Mohr and Ward 2014). For a long time, the United States was the only significant producer of helium in the world. The United States has been a dominant supplier because they found their helium resources early, mapped them well and developed the production industry first. There is probably not more helium in North America than other places with natural gas, the point is that the United States focused on it early. Lately, more helium has been found in natural gas fields (Algeria, Qatar, Tanzania, Australia, Russia). The United States, Algeria and Qatar remain as the only significant suppliers to the present. By 2022, Gazprom will be a significant producer, planning to supply the Russian and Chinese markets from the eastern Siberian natural gas fields (Gazprom 2019). Possibly, as more attention is given to the subject, more helium resources will be discovered and extracted. Much helium available in natural gas is not extracted at present but dispersed as the natural gas is burned or used otherwise (Fig. 1).

It is noted that there was no real trade market price for helium available until 1996 (Anderson 2017). The price was set by a governmental board, later by a small cartel of companies in the United States, and this was a command-and-control type of structure. Newspapers reported in 2019 about the third helium shortage, where supply fell short of demand, and deliveries could not be made to important

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Table 1 Overview of the main uses of helium and the available recycling situation for helium. The actual recycling is quite low. Numbers are %

| Use             | Market share | Recycling possible? | Recycling | System recycling effect |
|-----------------|--------------|---------------------|-----------|------------------------|
| Medical use     | 30           | Yes                 | 10        | 3                      |
| Scientific use  | 17           | Yes                 | 0         | 0                      |
| Balloons        | 17           | No                  | 0         | 0                      |
| Leak detection  | 5            | No                  | 0         | 0                      |
| Welding         | 9            | No                  | 0         | 0                      |
| Engineering     | 6            | Partially           | 10        | 0.6                    |
| Subsea          | 3            | No                  | 0         | 0                      |
| Other uses      | 13           | No                  | 0         | 0                      |

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Fig. 1 Helium production as recorded by USGS (2018, compiled by Mohr and Ward (2014) and integrated in the WORLD7 model. The diagrams show how dominating the United States was for the global helium production and supply from 1950 to 2005

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1 kg = 213 cf or 5.91 m³
purposes (Condez 2016; Kornbluth 2015). Thus, the helium price is difficult to model as it is a mixture of a command-and-control type of price setting and a smaller partial private helium market. Before 2005, the helium market was mostly a controlled market, with the United States government setting the price.

One challenge with helium is that it is very difficult and expensive to store, a property that is shares with hydrogen. It is a very small molecule and will tend to leak out through usual gas seals from conventional containers.

The helium content in the atmosphere is 5 ppm, neon is 18.2 ppm, argon is 1.3 ppm, krypton 1 ppm and xenon 20 ppm by weight. These are long-term stable, steady-state concentrations (Anderson 2017). Neon, argon, krypton and xenon are all extracted from the air, and since the concentration is very low, neon, krypton and xenon are very expensive. Argon is a by-product of air liquefaction, it is produced in industrial amounts, but it is still costly. There is no real physical shortage of argon, neon, krypton and xenon, despite the relatively high cost of production. The largest reserve of helium is in the air, but the cost of taking it from air is very high. Helium from natural gas is a finite resource, and its availability is quite low (Nuttall 2012a, b, c). One of the problems is that recycling is not widely practised, and that the end disposal of helium is to vent it to the atmosphere and lose it (Table 1). From the atmosphere, helium will leak into space, being irreversibly lost from the planet. The leakage rate to space is about 5,000 ton of helium per year. Mining helium from air is seen as far too expensive to ever become a significant source.

Recycling and Recovering

Even though recycling or recovering helium seems like a straightforward solution to the shortage situation, it does come with obstacles needed to be overcome. The biggest one being the cost, as the recycling technology does not come cheaply, in fact quite the opposite (Nature 2017). The good news is that the technology exists and in fact while it certainly is costly in the short run, recovery and recycling systems should eventually save enough money to provide future savings (National Research Council 2010). In order to prevent liquid helium from evaporating into thin air, and capture this vented gas, up to 95% of it can be stored and used after being reliquefied (Nature 2017).

Recycling sources of helium are often associated with waste and leakages gas from applications such as pressure tank testing (Clarke et al. 2013).

These sources generally consist of a mixture of air and helium, with a much higher helium concentration than found in natural gas. The helium concentrations in these applications are often diluted with air due to direct exposure to the environment, but it can be up to 99%. Nevertheless, the quantity of gas to be treated is generally very small and present only in niche industries. For example, helium leakage from modern MRIs is low and, hence, in many of these industries the focus is on reducing helium wastage (Scholes and Ghosh 2017).

In the USA, helium is rarely recycled, somewhat more recycling is practised in Europe (Glowacki et al. 2013; Mohr and Ward 2014; Scurlock and Francis 2012). Most of the balloon use is for entertainment purposes. The overall recycling degree of helium is insignificant. Even so the American Physical Society urges that measures be adopted that will both conserve and enhance the nation’s helium reserves and states that failure to do so would not only be wasteful, but would be economically and technologically shortsighted (APS 1995).

Early Modelling

Anderson (2017) makes a good review of earlier modelling effort. His conclusion is that there are several attempts, which are all early attempts and only partially sufficient. Cai et al. (2010) tried to develop a system dynamics model for the helium market. Their integrated model included production, investment, the market, demand, and the authors tried to account for many factors that could be important to the development of helium markets, such as the effects of changes in the production of natural gas, the development of helium-intensive technologies, and the rates of helium being vented during natural gas processing and combustion on the rate of depletion of helium resources. Their assessment suggested that helium production could accommodate increasing consumption until about 2030, and a decline after 2060, depending on the amount of venting, finally running out by 2100.

Mohr and Ward (2014) used mass flow analysis to estimate future production of helium, suggesting a decline in the United States production after 2080–2100 and on the global level during the same time. These are simplified dynamic models that roll mass balances foreword. Cai et al. (2007) developed a simple dynamic model for helium supply. These models do not contain any market mechanisms, and thus have some limitations.

Massol and Rifaat (2016) attempted to model the effect of the phasing out of the United States strategic helium reserve on the helium supply, using a mixture of an agent-based model and a general equilibrium model for the market. The assumptions behind general equilibrium economic models have limited representation of the reality. To cite Anderson (2017) in his final assessment, “In general, existing models of helium either do not account for an oligopoly controlling supply, or they do not evaluate potential helium extraction.
and storage programs based on an intertemporal maximization of the value of the resource. Such models could be of very limited use to decision makers. This review found only one working paper with a helium market model that has incorporated both of these vital considerations”.

Objectives and Scope of the Study

From the introduction it was stated that if continuing on the current path (business as usual, BAU), a shortage of helium would be bound to happen in the near future. The goal of this paper is to predict when that will happen, when we will run into hard scarcity and to analyse what can be done to manage the situation. Therefore, the objective of this study contains two main parts:

1) To analyse the market dynamics and make predictions for the helium price, extraction, production, supply and recycling based on business as usual.
2) To investigate the likelihood of a potential scarcity (under different helium demand and recycling scenarios), and to assess the long-term sustainability of the helium supply.

Methods, Theory and Definitions

Basic Methodology

The methodology used is based on systems analysis as the standard tool for conceptualization, as the preparation for building a simulation System Dynamics model. The main standard methods of systems analysis and system dynamics modelling are used (Meadows et al. 1972, 2005; Roberts et al. 1982; Senge 1990; Haraldsson and Sverdrup 2005; Sverdrup et al. 2018a). The system is analysed with stock-and-flow charts combined with causal loop diagrams. The entering of the code follows from the causal loop diagrams and flow charts developed in the conceptualization stage. The mass balance expressed differential equations resulting from the flow charts and the causal loop diagrams will be numerically solved using the STELLA® modelling environment (Sterman 2000; Senge 1990; Senge et al. 2008; Haraldsson and Sverdrup 2005). Scenario runs were used to explore the impact of different policy measures to improve long-term sustainability and sensitivity analysis was used to look at the output range based on different initial value stocks for parameters with the most uncertainty.

The modelling process is an iterative process and the model is constantly being re-evaluated and new adjustments made (see Fig. 2). The validation process is mostly based on comparison between observed data (OD) and simulation outputs from the business as usual case (BAU). When the fit between BAU and OD is good, the model structure is assumed to represent the underlying system well enough to make predictions. Until the fit is good, adjustments are made to the conceptual structure that leads to adjustments in the simulation model. When the quality of the simulation model is good enough, the scenario analysis is performed leading to solutions for the real system.

Fig. 2 Learning loop, methodology process

Defining Scarcity

In order to define scarcity, the time perspective needs to be defined. For this study, short term implies one to two human generations, thus 30–50 years forward. Long term is three times the longest delay in the system and more. Thus, long term reflects looking 150 to 500 years into the future (Sverdrup and Ragnarsdottir 2014). Earlier, resource scarcity has been evaluated from burn-off times (the extractable reserves divided by the present extraction, or alternatively ultimately recoverable reserves divided by present extraction. Another approach has been bulk supply rate versus time graphs (ton per year plotted versus time). These are crude assessment tools, and they will only give qualitative evaluations at best. The outputs span times from now and several decades or centuries into the future, where both demand and population can be expected to change. In this study, the following definitions are used to assess scarcity:

- Soft scarcity is when demand is reduced because of a high price.
- Hard scarcity is when the price modified demand cannot be satisfied, and there is a shortfall in supply.
Soft scarcity frequently occurs for many commodities, and soft scarcity is well handled by society without major disruptions. For example, what we have experienced with cobalt, i.e. after the price spike around 1980, use of substitutes increased and the demand reduced also on platinum (Sverdrup and Ragnarsdottir 2016) and rhenium (Sverdrup et al. 2018b). Further commodities that have experienced physical scarcity during short intervals are substances like antibiotics, vaccines or rare blood types. For metals and materials, the major effect of soft scarcity is less demand from increased prices. The precious metals gold, silver, platinum, palladium, rhodium, iridium, ruthenium or rhenium are all examples of metals that are in soft scarcity as the normal state of affairs (Sverdrup and Ragnarsdottir 2014, 2016, 2017). Hard scarcity is not as well handled (Kennedy 1987; Greer 2008; Heinberg 2011) nor by society (Zhang et al. 2007) and normally leads to disruptions. Hard economic scarcity is when the commodity is available, but the business or citizen lacks the disposable income to purchase any significant amount. The United States had a strategic reserve of helium since 1950s, but that was sold off from 1996 as a privatization policy, but a helium stewardship was reinstated in 2013 (McGuire 2013; Nutall et al. 2012a, b; National Research Council 2000). The resource estimates presented in this study are based on estimates assembled by Mohr and Ward (2014) and additional information from the US Geological Survey Mineral Commodities Survey programme (USGS 2018).

For assessment of soft and hard physical scarcity in the WORLD7 model, the following two metrics are investigated to evaluate if there is a scarcity or not (Sverdrup 2019). These are as follows:

1. Actual helium supply per person per year (kg per person$^{-1}$ year$^{-1}$)
2. Actual helium stocks-in-use per person (kg per person$^{-1}$).

These variables are bolded and made bigger in Fig. 4. Supply per person per year is serving maintenance of stocks-in-use and the surplus over the maintenance will determine how much is left for growth or if a material contraction will occur. Stocks-in-use are a measure of the present utility of the resource. A decrease in stocks-in-use, which is not paralleled by a substitute that increases, will be an indicator of reduced service provision. The scarcities discussed are on an average global level. The model is global, and thus does not differentiate between countries or population groups. To address that will require a discussion of the systemic aspects of poverty and fundamental wealth distribution mechanisms of society. Strategic scarcity is a result of making evaluations for longer periods of time. Typically, the demand and supply are integrated over a longer period of years before decisions are made.

Another important metric is when the supply falls below the price feedback modified demand. Then supply falls short of demand and a physical shortage appears. This has already occurred during short periods during 2019. The natural production of helium is about 5,000 ton per year. Any use larger than that plus what can be recycled is strictly speaking not sustainable. The true sustainable use of helium is here defined as shown in Eq. (1):

\[
\text{Sustainable use rate} = \frac{\text{Extraction yield} \times \text{Production rate by radioactivity}}{(1 - \text{Recycling rate})},
\]

We can address what the real sustainable use of helium would be using Eq. (1). The extraction yield for helium is estimated to be less than 50%, possibly as low as 30%. The recycling rate is at present about 3.6%. If we fill in the above mentioned values in Eq. (1), i.e. extraction yield = 30%, recycling rate = 3.6 and production rate = 5,000 ton per year, we get that the present sustainable use rate is about 1556 ton of Helium per year. Increasing the extraction yield to 40% and the recycling rate to 40% would increase the sustainable helium use to 3,333 ton of helium per year. At 60% recycling and extraction yield of 60%, it would be 10,000 ton helium per year. This can be compared to the supply in 2020 which was about 45,000 ton/year. Thus, the supply is in 41,666 ton overshoot with respect to the long-term sustainable use rate.

### The WORLD7 Model

The WORLD7 model is an integrated assessment model for the global level. It links the biophysical world and the social world, and from them it generates the global economy, population size and GDP. That is, those variables are generated internally in the WORLD7 model (Sverdrup and Koca 2017, 2018).

The dynamic properties are based on causal link relationship between variables and feedback between all modules. It includes change in supply, change in demand, change in price, change in production rates, change in population, change in recycling, change in use efficiency, and all are linked. The population size is used together with GDP for generating demand (Sverdrup and Olafsdottir 2019). An overview of the WORLD7 and its submodules is shown in Fig. 3. It is noted that only operational modules are presented, and more modules are currently being developed and are partially ready. Every red line represents one or more feedback connections between the modules.

The WORLD7 model is based on the WORLD6 model (Sverdrup and Koca 2017); the main difference lies in added
number of submodels in the WORLD7 model including transforming sectorial-based structure into modules in the STELLA software. The WORLD7 model is process-oriented, and the values have mostly been set based on observations. Supply is composed of both primary production, secondary extraction as a by-product of the production of other metals and recycling of used material. Based on mass balance, Eq. (2) is generated:

\[
\text{Helium production + recycling} = \text{change in total stock + recycling + losses Helium production} + \text{recycling} = \text{change in total stock + recycling + losses.}
\]

The “change in total stock” is change in the total helium stock that is divided up into four differential mass balance equations in the model, i.e. for medical, science, engineering and market stock. This equation is therefore a generic one and explains the mass balance in the model though the representation is a bit more complex given the number of different stocks in the model. Note carefully that recycling appears on both sides, increasing the flux inside the system, while keeping net supply low. It can mathematically be cancelled out of the equation. It expands the total flux going through the system, without demanding new primary material to be added. Thus, if 50% of the waste stream is recycled, then the internal flux is increased by 50% or kept the same with 50% less supply. If the resource is scarce that would be a significant improvement.

The helium submodule is shown in Fig. 4. It is noted that the US reserve is modelled as a special stock variable as it is a specific helium reserve that is not connected to the natural gas. Natural gas extraction runs in parallel. In the model, helium is extracted in a number of natural gas fields. Only a fraction of the natural gas is subject of helium extraction. This has been added to the paper.

**Parameterization**

To the largest degree, all constants and settings have been based on observed system parameters, in order to eliminate the need for calibration. The “data” are divided on harvest into several different categories: (1) system boundary and initial conditions, (2) system structures, (3) system parameters settings and (4) system states. Of these, categories 1–3 are used to parameterize the model before the simulations start. The state data (4) are not used for model initialization or for calibrating the WORLD7 model (Hirschnitz-Garbers et al. 2015, 2017, 2018, Koca et al. 2017, Lorenz et al. 2017, Sverdrup and Koca 2017, 2018, Sverdrup and Olafsdottir 2019), but saved and used for evaluation of model performance. Some of the data used for the parameter setting for the helium submodule are presented in Tables 1 and 3.
Table 1 shows an overview of the main uses of helium at present (2018) and the available recycling situation for helium. The main medical use is for magnetic resonance imaging (MRI) coolant. This use has brought great medical progress and is a prioritized use. It can safely be assumed to increase in the future, probably faster than present economic growth rates. The actual helium recycling is quite low at present, and the potential for recycling is substantial.

Fig. 4 The helium submodule inside WORLD7 in the STELLA software. This is inside the little frame called “helium” in Fig. 3.
Demand

In the WORLD7 model, demand is assumed to be depending on a need per capita and the population size. With increasing price, the demand will be reduced as the price reaches high levels. It is assumed that use of helium for balloon makes up 17–20% of the consumption (not scientific balloons, but party balloons). Use of helium for welding may also use other gases and is assumed to decrease with increasing price. The medical use is important and therefore it will likely tolerate a high price better than other uses. Figure 5 shows the scaling of demand over time used in the model. The use of helium per person has increased strongly after 1990. The peak during 1960 to 1980 represents the build-up of the United States Strategic Reserve. The demand scaling is very central to the simulations. This scaling is a per person use of helium in society and is multiplied with the global population and a constant to get the total demand.

Based on the law of normal market behaviour, the production will increase with price, as it gets more profitable. It is assumed to increase only up to the potential level, where it cannot increase more. The potential level corresponds to when all helium in the available feed-stream is extracted. Only some natural gas producers do extract helium, depending on whether their natural gas has interesting contents of helium or not. Especially when liquid natural gas (LNG) is made, will there be an opportunity for extraction of helium. The opportunity comes to fruition only if the producer has invested in the necessary infrastructure. If not, the helium will be lost.

Figure 6 shows the feedback curves used in the sub-model for production and demand. Some uses are price sensitive like leak detection, welding, party balloons and some engineering uses. Other uses like scientific research and medical use are rather price insensitive. When there has been no profit from helium production for a year, the production is turned off in the simulation. This mechanism is only turned on after 1996. Before 1996, the US Government would sell helium at politically motivated pre-set prices, being insensitive to profits or deficits in the big picture.

The demand scaling is very important for the simulations and if the issue of scarcity will disappear or not. The authors assume it is unlikely that the demand will go substantially down in the future. It is quite possible that it will increase, perhaps very substantially. This additional assessment work will not be reported here. Table 2 presents some policy options in regard to demand.

Resources

Helium resources have been estimated to be more than 15 million ton of helium, which is significantly more than earlier anticipated, but perhaps as much as 20 million ton. If fossil fuels were to be phased out 2025–2050, a resource estimate of 8–10 million ton would be more appropriate.
Table 3 shows an overview of the available helium resources (extracted, known and hidden, i.e. estimated to exist but not yet found) in 2018 in million ton of helium. The data were based on the estimates by the United States Geological Survey but adapted and update by data extracted from the read literature (Mohr and Ward 2014). Mohr and Ward (2014) concluded that the ultimately recoverable resources were 9.5 million ton of helium in 2013. Since then, more helium has been found. New finds have been reported from Tanzania and Russia, and the detected resources may be expected to increase (Condez 2016). The find in East Africa may be very large, and the reports vary from 0.450 to 2 million ton (Sample 2016; Gazprom 2019; Condez 2016). How much of that which is extractable remains unknown so far, but it is likely to produce from 2012 to 2022. Likely there will be more helium resources found as time passes. South Africa expects to become a medium-size helium exporter (Arnoldi 2019).

A recent article by Boreham et al. (2018) works through Australian natural gas wells, and in particular those where LNG production is planned. The initial assessment states that the deposits hold as much as 10 million ton of helium. The helium concentrations down to 0.015% will be interesting. Most of the deposits above have concentrations in the range 0.21% to 0.012%. Interesting are three deposits with 4.35 billion cubic feet at 0.13% and 16 billion cubic feet at 0.21% and 1.46 billion cubic feet at 0.05%. With a cut-off at 0.03%, this yields an extractable base of 0.105 million ton. Note that there are no helium resources reported for South America, nor the major gas producers in the Middle East like Iraq, Iran or Saudi-Arabia, except for Qatar.

An alternative method for estimating the total amount helium available would be to look at the total resources of natural gas. These have been mapped by several over the years, and compiled, evaluated and summarized by Campbell (2009). The important cut-offs for helium contents are 0.8% in the best helium-containing natural gas fields, assuming that 0.3% in the fields considered interesting, and 0.08% as the global average (Zartmann et al. 1961). The stock of natural gas is estimated as conventional high grade; 180 billion ton oil equivalents, conventional low grade; 100 billion ton oil equivalents, near offshore; 80 billion ton oil equivalents, deep sea; 50 billion ton oil equivalents, shale gas; 110 billion ton oil equivalents (Campbell 2009). According to this assessment, it is estimated that oil equivalent of high-grade natural gas is about 270 billion ton, 180 billion ton oil equivalents in the middle quality grade deposits and 60 billion ton oil equivalents in the low, a total of 510 billion

Table 2 Policy options, reducing demand

| Use          | Market share (%) | Potential for change in demand | System effect (%) |
|--------------|------------------|--------------------------------|------------------|
| Medical use  | 30               | No                             | 0                |
| Scientific use | 17              | No                             | 0                |
| Balloons     | 17               | − 99%                          | − 17             |
| Leak detection | 5               | − 60%                          | − 3              |
| Welding      | 9                | − 60%                          | − 6              |
| Engineering  | 6                | − 30%                          | − 2              |
| Subsea       | 3                | No                             | 0                |
| Other uses   | 13               | No                             | 0                |
| Sum          |                  |                                | − 28             |

Overview of the main options for substitution and limiting unnecessary dissipative use of helium. The system demand may probably be reduced by 25–30%. These demand reductions were partly included the second sensitivity run, i.e. from the Ban run.

Table 3 Overview of the available helium resources in 2018 in million ton of helium, working through on a country-by-country basis

| Country       | Million ton per year | Extracted to now | Known reserves | Hidden resources | URR    |
|---------------|----------------------|------------------|----------------|-----------------|--------|
| United States | 0.750                | 0.660            | 3.491          | 4.901           |        |
| Qatar         | 0.023                | 0.288            | 1.710          | 2.021           |        |
| Algeria       | 0.050                | 0.305            | 1.388          | 1.743           |        |
| Russia        | 0.100                | 0.450            | 1.151          | 1.701           |        |
| Tanzania      | –                    | 0.471            | 1.000          | 1.471           |        |
| South Africa  | 0.004                | 0.046            | 1.054          | 1.100           |        |
| Canada        | 0.001                | 0.030            | 0.339          | 0.370           |        |
| Australia     | 0.003                | 0.100            | 0.117          | 0.217           |        |
| China         | 0.004                | 0.017            | 0.186          | 0.207           |        |
| Poland        | 0.010                | 0.005            | 0.005          | 0.025           |        |
| Others        | 0.001                | 0.005            | 0.050          | 0.050           |        |
| Yet undiscovered | –                  | –                | 2.000          | 2.000           |        |
| Sum           | 0.905                | 2.279            | 12.325         | 15.765          |        |

The data were extracted from the literature (Mohr and Ward 2014; USGS 2018; Sample 2016; Condez 2016; Boreham et al. 2018) by the authors.
ton oil equivalents of gas. Using the average content of 0.8% given by Zartmann et al. (1961) gives about 36.7 million ton helium. Assuming half the natural gas to be available would give 18.5 million ton. The conclusion is that the ultimately recoverable resources (URR) of helium are in the order of 37–40 million ton.

The market value of 1 ton of liquid natural gas is currently about 700–1000$ that corresponds to an oil price of 60–90$ per barrel. A helium content of 0.8% in the liquid natural gas represents a value of 120$ per ton LNG, 0.3% helium content is 45$ per ton LNG, whereas 0.08% is 12$ per ton LNG. As a side product made at marginal cost, 45$ per ton natural gas produced is a profit. But if helium is made to carry its own production cost, with natural gas being waste and not giving any income, then the helium price would have to be 5 to 10 times higher than at present (that would imply a price of 50,000 to 150,000$ per ton of helium). At present, cooling and liquefying natural gas to extract helium does not really pay off below the content of 0.3%. In this study, it is assumed that the extractability for helium is about 30% and the accessibility in terms of the gas being extracted at all, and that what is extracted is about 30%, a total of about 9–10%. To extract helium, a requirement is that all the gas is high pressurized and cooled. This occurs when liquid natural gas (LNG) is produced, but not else. Thus, the low percentages given above. All-in-all, it is likely that the total resource is more than 10 million ton but less than 30 million ton.

Results

Business-As-Usual Simulations

The “business-as-usual” runs presented in this chapter are based on the assumption that there is free use at will of helium, no enhancement of recycling, use of helium for party balloons and no active management of demand. The results of the business-as-usual run have been shown in a number of diagrams shown in Figs. 6, 7 and 8. Figure 7a shows a prediction to 2230 for the demand, demand after price feedback, supply, production and recycling based on BAU compared to data from 1990 to 2015 and also with simulated future scenario based on BAU to 2250. Diagrams below show the simulation of the price, on the left side from 1930 to 2250 and on top from the right side from 1930 to 2015, bottom to the right from 1990 to 2015 with observed data. The dotted lines on the diagrams on the right side are the observed production. Figure 7b shows the same variables from 1930 to 2015 compared to production data that can be seen to fit well to the simulation outputs.
the simulated price as compared to the data recorded by the USGS (2018) from 1990 to 2015. The dotted line is the observed production describing the reality in the past. The model reproduces the observed production and supply fairly well. The ups and downs of the price show an unbalanced market, with poor corrective feedback mechanisms before 2005. It is emphasized that the officially recorded price was not always the final price being actually paid. Before 1996, there was no free market for helium, and the price was set with a state control mechanism. The misfit of what would have been the market price (solid line) and the politically set price shows how command-and-control markets normally do not do a good job.

Figure 8a shows the costs, income and profits in the helium sector. Figure 8b shows the flow of helium to different sectors. Note that reserve sales are just a part of all United States sales.

Fig. 8  a the costs, income and profits in the helium sector. b The helium flow to different sectors. Note that reserve sales are just a part of all United States sales.

Fig. 9  a The diagram shows the stock in use and supply per person per year under business as usual. b The cumulative amount as compared to the available data

Fig. 9  a The diagram shows the stock in use and supply per person per year under business as usual. b The cumulative amount as compared to the available data
Scenario Analysis

Scales of Improvement: Recycling, Recovering and Restrictions on Use

Recycling rates can be considerably increased when based on implementing strong governmental policies (see Table 4 for policy options). With increased focus on the “circular economy”, it may be expected that a greater policy focus on this matter will be in place in the future. Figures 9, 10, 11 and 12 show some of the policy options involved in reducing the helium demand and the prioritization of uses for helium, and possible effects of improving recycling. The system demand may be reduced by 25–30%. Reducing system demand with 28% would make 9,800 ton of helium per year available for other

Table 4  Policy options, increasing recycling

| Use             | Priority | Substitutes available? | \( R \) now (%) | System effect % | Possible \( R \) (%) | System effect possible (%) | Target policy value |
|-----------------|----------|------------------------|-----------------|-----------------|-----------------------|------------------------|---------------------|
| Medical use     | Very high| No                     | 10              | 3               | 80                    | 24                     | \( R = 65\% \)       |
| Scientific use  | Very high| Some                   | 0               | 0               | 80                    | 14                     | \( R = 65\% \)       |
| Balloons        | Low      | Hydrogen               | 0               | 0               | 0                     | 0                     | Prohibit             |
| Leak detection  | Modest   | Yes                    | 0               | 0               | 0                     | 0                     | Limit use            |
| Welding         | Modest   | Argon, \( N_2 \)       | 0               | 0               | 0                     | 0                     | Limit use            |
| Engineering     | Modest   | Some                   | 10              | 0.6             | 30                    | 2                      | \( R = 30\% \)       |
| Subsea air      | High     | None                   | 0               | 0               | 0                     | 0                     | No action            |
| Other uses      | Modest   | Yes                    | 0               | 0               | 30                    | 4                      | Conserve             |
| Sums            |          |                        | 3.6             |                 |                       | 42                    |                     |

Overview of the main uses of helium and the prioritization of uses for helium, and possible effects of improving recycling

\( R \) recycling

Fig. 10  Scenario 1. Helium resources and price, showing “BAU” (business as usual) and “Ban” run when party balloons have been banned
banning useless helium consumption for uses like party balloons from 2025 (Ban). Recycling is stepped up in 6 steps from no effort (BAU) to 6 times the present (RFx6) from the year 2020. BAU = 8% total recycling and RFx2 = 17%, RFx3 = 25%, RFx4 = 33%, RFx5 = 40%, RFx6 = 50% total recycling

 prioritized uses and increasing recycling to 42% would make an extra 14,700 ton of helium per year available in the system. A deposit on helium may be introduced, helping to increase recycling. Recycling may also be made mandatory by regulation. Regulation may also be used for banning useless helium consumption for uses like party balloons. Additional improvement option is to build a strategic global reserve. The United States had such a National strategic reserve and is the only one that still has the industrial facilities to do so in place. Such a reserve can help alleviate scarcity for strategically important sectors.
a strategic reserve demands long-term political thinking and many politicians lack such a capability.

Exploring the Future Through Simulation Outputs Based on Different Policies

The WORLD7 model can be used to test policies and look at simulation outputs based on policy changes. The following sensitivity runs on the WORLD7 model were made to explore the possible future scenarios based on different policy options. The demand was kept the same during these runs.

1. Scenario 1: Business as usual (BAU) and ban party balloons to reduce demand from 2025 (Ban), assuming that the available resource is 15.5 million ton. Figure 10 shows both BAU run and Ban run.

2. Scenario 2: A complex sensitivity run, based on 12 runs that are named under each figure. “Ban” stands for a ban that is placed on party balloons from 2025 (Ban). It is assumed that the use of helium for balloon makes up 17–20% of the consumption (not scientific balloons, but party balloons). Recycling is stepped up in 6 steps from no effort (BAU) to 6 times the present (RFx6) from the year 2020. BAU = 8% total recycling and RFx2 = 17%, RFx3 = 25%, RFx4 = 33%, RFx5 = 40%, RFx6 = 50% total recycling (Fig. 11).

Figure 10 (scenario 1) shows that the supply is lower and with less scarcity when the party balloon policy is in place (Ban) and recycling also increases with the Ban policy. This alone will reduce demand by 28%. Total use is less as a result, and the scarcity occurs later and is less severe. The price also takes a more moderate approach.

Changing the recycling rate changes the supply to the market significantly. Figure 11 shows the output from the second scenario used, involving all possible runs based on different recycling step ups (up to 6 times the present) and banning the use of helium in balloons from 2025. The scenario is based on the most realistic resource estimate of roughly 15 million ton of helium. For no scarcity to occur, total recycling must reach a level of close to 50%. This corresponds to medical and scientific uses reaching at least 60% recycling, and that engineering use reaching 30% recycling. Figure 12a shows 50% total recycling and there it is still visible that the supply goes a little bit below the demand shortly before 2230. Another option would be to have total recycling at 25% combined with the ban of helium balloons, see Fig. 13a. Under those conditions, the helium system will be sustainable until after 2230 based on the simulation outputs. Figure 12b shows the BAU case with 8% recycling and in that case the supply line goes below the demand line in 2120. From Fig. 13b, it can be seen that by only including the Ban policy on top of the BAU case the split between supply and demand gets much less severe and it starts later, around 2180.

Discussion

Uncertainties are Substantial

The conclusions are made from the simulation outputs based on the runs from the WORLD7 model and they involve uncertainties and assumptions. The uncertainties are large in many of the input data and assumptions with significant uncertainty must be made in order to make an assessment. This affects the conclusions, which must be treated with caution. It can be concluded that there is substantial risk for scarcity and that the supply situation is probably unsustainable, but this cannot be proven with any certainty. The assessment presented is systemic, which means it is a best estimate according to the available information, which is better than making none or applying belief.
The simulation outputs are sensitive to changes in demand. This shows up in the helium price which is unstable in the model before 1990, Fig. 7c. The demand before 1960 is not very well documented, and much based on guesswork from very little information. The undocumented nature of the interference with the helium market by the United States government and military made the modelling of price dynamics and the private and public production quite difficult. The market was a mixture of partial "command and control" with little or no real feedbacks, with a helium side stream going to a "free dynamic" commodity market with price feedback dynamics (See Sverdrup and Olafsdottir 2019 for explanations of how different market types function). The basic run is based on the assumption that a functioning free helium market exists, but the difficulty of making more exact price predictions may suggest that this may not be correct. The fit is not perfect, but running the model on the observed values for the key parameters yields a reasonable fit with the data. The demand and supply number are also somewhat obscure because of governmental and military interference.

Based on the estimates from this research, helium resources are estimated to be more than 15 million ton of helium, 15.5 million ton in the BAU run, which is significantly more than earlier anticipated (Table 1). The range is from 10 million ton of helium (Mohr and Ward 2014) to not more than 20 million ton of helium, all depending on how much is considered to be in natural gas and how much of that can actually be extracted. The estimation of URR is very uncertain, and it is impossible to make an estimate without making many assumptions. The resources are potentially large enough to prevent scarcity if managed carefully, but not under business-as-usual management. If a global policy to phase out fossil fuels between 2025 and 2050 occurs, then a helium resource size of 8–10 million ton is the most realistic. Figure 14 shows scenario analysis based on different sizes of initial available helium resource (in 1930). The graphs present 5 runs, the BAU run that equals 15 million ton of available helium resource in 1930, then 40, 20, 10 and 5 million ton of available helium resource in 1930.

Further Work

An unforeseen threat to the helium supply would be a turn away from all fossil fuels by 2050, a global variant of the German policy called "Energiewende" (Hirschnitz-Garbers et al. 2017). Helium production is totally dependent on...
natural gas production and a stop in the natural gas production could result in a stop in the helium production. If a global "Energiewende" were to take place in 2025 and be completed, the available helium resource would be a maximum 8–10 million ton, unless people are willing to pay a much higher price for helium. The price for extracting helium from natural gas for its own sake, pumping the natural gas back into the ground, would be in the range of 30,000 to 50,000$ per ton of helium. The price for extraction helium from air might be in the range from 210,000$ per ton to 1,900,000$ per ton (Anderson 2017), with an average at 340,000$ per ton (Epple and Lave 1980). This is perhaps acceptable for important medical use and prioritized scientific use, but not much for other uses. To further investigate, this would imply to set up the WORLD7 helium model with a sharp increase in production cost from 2040 and onwards. Under a Global "Energiewende" scenario, the natural gas would be separated off and pumped back into an empty underground reservoir.

Conclusions

The conclusion from the study is that helium is a limited resource and that present use is not long term sustainable and will lead to physical scarcity after 2120 (see Fig. 7a). The use of helium is at present concluded to be unsustainable with respect to long-term supply security. The results indicate that the present helium recycling rate is significantly too low, causing helium to be squandered in one-way use. The wasteful use is driving helium prices up. Most helium used is vented to the atmosphere after use, and irreversibly lost. The market supply runs into supply limitations by 2090 under business as usual, and the simulations suggest that the supply declines rapidly after that.

Part of the helium use is wasteful and useless. For outdoor use, helium can be substituted with hydrogen for most applications. If helium recycling from serious use is improved to 50% (see Fig. 12a), or total recycling goes to 25% combined with the ban of helium party balloons (see Fig. 13a), the helium system can be sustainable until after 2230 based on the simulation outputs.

A sensitivity analysis with the WORLD7 model suggests that a sustained program for helium recycling and conservation, combined with political efforts to ban wasteful use, will be able to significantly improve the long-term helium supply situation. The authors suggest the following policy measures that should be global: (1) ban the use of helium in party balloons from 2025 and (2) increase recycling with a target of 50% recycling as fraction of supply. By doing this, the price is likely to stabilize, and the scarcity could be eliminated to beyond 2250. The recycling might be incentivized with a deposit system where the deposit goes to the helium recycler.

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Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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