IRANIAN ECONOMIC REVIEW
Print ISSN: 1026-6542
Online ISSN: 2588-6096
https://ier.ut.ac.ir/
University of Tehran

Common Pool Problem: South Pars-North Dome Gas Field

Jalal Dehnavi[a,*], **Yuri Yegorov**[b]

a. Department of Economics, Faculty of Social Science and Economics, Alzahra University, Tehran, Iran.

b. Department of Industry, Energy and Environment, Faculty of Business, Economics and Statistics, University of Vienna, Vienna, Austria.

* Corresponding Author, E-mail: j.dehnavi@alzahra.ac.ir

Article Info

Article Type: Research Article

Article History:
Received: 23 June 2021
Received in revised form: 18 August 2021
Accepted: 05 September 2021
Published online: 01 July 2023

Keywords:
Common Pool Problem,
Games,
Optimal Extraction Dynamics,
South Pars - North Dome Gas Field.

JEL Classification:
C7, Q32.

ABSTRACT

The aim of this paper is to investigate possible problems of efficiency arising from the joint exploitation of the common gas pool (South Pars - North Dome, the largest natural gas reservoir in the world) by Iran and Qatar. The problem is related to the difference between private incentives and common goals. In the case of non-renewable resources, a Pareto-optimal joint extraction path could exist, but it is unlikely to occur in reality. We studied the difference in incentives for an optimal exploitation path for Iran and Qatar and found that their joint behavior was likely suboptimal from the perspective of the optimal dynamics of gas resource exploitation. In part, this is related to the difference in wealth, and in part to the sanctions against Iran, which have so far not allowed Iran to participate freely in the world market. Considering that the cost of future gas extraction in Russia's northern fields is likely to increase, a delay in the optimal presence of Iranian gas on the world market may lead to a suboptimal sequence of exploitation of various gas fields, which would mean both problems for the profitability of investments in Russia and higher world prices for natural gas in the future.

Cite this article: Dehnavi, J., & Yegorov, Y. (2023). Common Pool Problem: South Pars-North Dome Gas Field. *Iranian Economic Review, 27*(2), 619-654. DOI: https://doi.org/10.22059/ier.2021.83919

Publisher: University of Tehran Press.
DOI: https://doi.org/10.22059/ier.2021.83919

1. Introduction

The future supply of natural gas depends heavily on the behavior of the two major holders of natural gas reserves, Iran and Qatar. The aim of this paper is to analyze the problems in the joint exploitation of the largest global reserve of conventional gas. Iran and Qatar jointly own the world's largest natural gas reserve, South Pars - North Dome.[1] It is located under the waters of Persian Gulf, and the maritime border between Iran and Qatar divides the reserves, so Iran holds about 1/3 of it, while Qatar holds -2/3. While for Qatar it is the main gas reserve, containing almost all the gas they have, for Iran it is about 30% of the gas reserves.

Oil and gas laws in the United States are governed by the principle of non-liability known as the "rule of capture" (Schitka, 2014). This rule is applied as an unwritten contract by countries that own common oil and gas fields, and has an important feature: it allows landowners or countries to extract oil from a common field (a common pool) without liability, regardless of whether or not the oil extracted was originally under private land. For many years, scholars have criticized the rule of capture on the grounds that extracting fossil fuels from a common pool can impose revenue externalities on other players (firms).

The extraction of exhaustible resources (such as fossil fuels) from communally owned deposits can impose externalities on actors (firms). As a result, production is often inefficient, both from the perspective of society as a whole and from the perspective of other firms in the industry. Ostrom (2002) argues that non-renewable resources, such as oil and gas, can be depleted by competition between producers. Due to the uncoordinated race, the amount of the resource (the recovery rate) that can be extracted decreases, while the cost of extraction increases significantly.

1. South Pars is the name of northern part, which is located in the Iranian waters and North Dome is the name of southern part, which is located in Qatar's waters.

2. Physical Interaction

However, the reality of economic interaction between Iran and Qatar is much more complex, and this complexity is related to physics. Both oil and gas fields have vertical pressure profiles[1]. In the early stages of development, it allows the free flow of hydrocarbons, but later external pressure must be applied to get them out of the ground. Since reservoirs have a certain porosity, the initial disturbance of the field by the construction of the well and further extraction changes the overall pressure pattern. This disturbance decreases with distance. If two wells are constructed in the same field at a sufficient distance, the interaction between them is negligible. However, if they are built a short distance apart, the pressure migrates. Then depletion of one well will lead to partial depletion of the neighboring wells. Similarly, pumping substances into one well not only increases its pressure, but to some extent also increases the pressure in the neighboring wells.

If we have one owner of the hydrocarbon reservoir, there could be an optimal density of wells to maximize the discounted profit stream, and the pressure shift does not matter for the total cost and benefit of the owner. However, with multiple owners, the interaction between wells due to pressure migration is of great importance. Typically, we have two stages of extraction: the first stage with free flow (when drilling cost is the main cost) and the second stage with depleted field (when pressure generation is the main cost). It is clear that the negative externality due to over-exploitation of the field by excessive drilling plays an important role: this is the common-pool problem considered above. However, a positive externality caused by pressure migration can cause the possibility of free riding (if your competitor generates pressure, some of it will reach your neighboring well). We will consider a simple model with this case of two externalities in Section 6.

1. See, for example, http://petrowiki.org/Reservoir_pressure_data_interpretation

Since gas can migrate, asymmetric exploitation by one part leads to future resource depletion by its neighbor as well. It is difficult to monitor this gas migration and thus account for the remaining resources of both parts. This gives both sides an incentive to exploit the reservoir symmetrically. However, the preferences for the dynamics of gas exploitation may be different for both sides, leading to the emergence of a non-cooperative game.[1]

Extraction by one actor affects the volume and cost of production for other players (firms). The outcome of competitive extraction of gas is clear. Each side follows the optimal number of wells they will drill (given its own optimal production path) to maximize its private profits, but ignores the costs and externalities imposed on other producers. Such asymmetric extraction increases overall costs by reducing the amount of recoverable and associated gas over the life cycle of that field. The subsurface pressures that push the gas to the surface become lower and less gas can be produced. It becomes necessary to increase the decreasing pressure within the field by pumping and injecting other propellants.

The asymmetric (higher) production of one player (who makes a rational decision but ignores the externality) causes a migration of gas from the other part of the reservoir to the emptied part, reducing the gas supply (and future extraction) of the neighbor.[2] Since all players (agents) recognize these conditions, they have an incentive to drill competitively and empty the reservoir.[3] In this short-term, non-cooperative constellation, each side maximizes its profit but not the economic value of the entire reservoir (long-term and cooperative strategy). This competition leads to a phenomenon known in the

1. http://pseez.ir/home-en.html
2. As a country drills additional wells, gas immigrate more rapidly into the low-pressure zone, raising the firm's share of field output. Increase in the rate of production, however, reduces ultimate gas recovery.
3. As firms compete for migratory oil and gas, they dissipate reservoir rents then with excessive capital, too rapid production, and lost total recovery (Libecap and Smith, 1999).

literature as the "*tragedy of the commons*." It demonstrates an important insight from economics: individually rational behavior with respect to extraction from a common reservoir can lead to a suboptimal outcome (Gordon, 1954). However, since the degree of cooperation (competition) and negative (positive) externalities varies in different common pools, this phenomenon is called "tragedy" according to Hardin (1968), "drama" according to Ostrom (2002), and "comedy" according to Rose (1986).

The innovative approach of this paper is taking into account both physical possibility of natural gas to migrate and difference of incentives for exploitation of common field into a formal game theoretical model, which is analyzed using realistic assumptions.

Section 2 is a literature review on the common pool issue. Section 3 examines the status of gas extraction for Qatar and Iran. This paper addresses the question of optimal exploitation of the joint gas field, taking into account both physical property of gas (possibility to migrate) and economic incentives of both exploiters – Iran and Qatar. Given economic conditions, the optimal policies of exploitation differs for Qatar (section 4) and Iran (section 5). Section 6 models interaction between Qatar and Iran as a game. It includes several specifications. Section 7 addresses cooperative approach for efficient joint exploitation. Section 8 forecasts future demand for gas and analyses the roles of Qatar and Iran in this market. Section 9 concludes and states policy implications.

3. The Literature Review on Common Pool Problem

There is an enormous literature on the tragedy of the commons, starting with Hardin's (1968) seminal article entitled "The Tragedy of the Commons", followed by Weaver (1986), Libecap (1998), Ostrom (1994), Ostrom et al. (2002), and several other works (Gari et al., 2017; Lalehzari and Kerachian, 2020; Djiguemde, 2020; Anderson et al., 2021). The common pool problem occurs when more than one firm extracts from a common reservoir. In our case of natural gas, the underlying resources are connected through interconnected pressure gradients and recourse migration (Libecap and Smith, 1999). Competition for extraction from common reservoirs introduces externalities and reduces efficiency.

To avoid such a problem (competition for gas extraction), the incentives for cooperation must be linked to a common incentive to maximize the total economic value of the field. However, the problem posed here arises from heterogeneous interests. Numerous empirical studies suggest that it may be possible to ensure collective action if players can enforce conservational institutions (Libecap, 1990; Grainger and Costello, 2016).

Some scholars argue that high-level public goods can be provided if players can monitor other players' decisions and punish antisocial players (see Bochet et al., 2003; Sefton et al., 2000; Baerlein et al., 2015). In contrast to them, Ostrom (1998) emphasizes self-governance of common pool resources as a solution. She claims that the actual governance of common pools is more complex than just the dynamics of economic exploitation. This occurs because legal issues and monitoring must also be considered. Libecap and Wiggins (1984) propose three contractual solutions to the common pool problem, namely: a- lease condition, b- use of production under a single firm, and c- division of field production among firms.

In energy markets, the problem of competitive extraction was recognized when oil was first discovered in the United States in 1859. However, the nature and magnitude of externalities were not fully understood, and no measures were provided to coordinate strategies and constrain firms. By the early twentieth century, the economic value of oil became high enough to raise concerns about losses (Libecap, 2007; Esmaeili and Shayanrad, 2015).

Most of the studies were related to oil extraction, but they can also be applied to the case of natural gas. When an excessive number of wells are drilled (more than geologic conditions require or price and interest rate projections justify), capital costs are driven up and rents evaporate. Building surface storage facilities where the oil can be held safely from being drained by other companies is also expensive. Rapid extraction also raises production costs by releasing subsurface pressure prematurely, forcing the early use of pumps and injection wells. Overall recovery decreases as pressure is released because the oil becomes trapped in the surrounding formations, which can only be recovered at very high extraction costs. Finally, rents disappear when production patterns deviate from those that would maximize the value of production over time (Squillace, 2015).

When non-cooperative users profit from free riding on the resources of others, the "tragedy of the commons" is inevitable (Lai et al., 2003; Smyčka and Herben, 2017). In order to avoid this problem, there should be incentives for cooperation. The gains from an agreement can be enormous, both by saving capital costs and by increasing total production; these gains can be a factor of 2 to 5 compared to unregulated production. In addition, more gas is left for future generations (savings effect; sustainable development).

Costs include both the direct costs of additional production and the increased costs of infra-frontier production (Liebecap, 2007; Gross and De Dreu, 2019). However, there is another problem that arises in the cooperative game. There is no guarantee that each player (as rational agents) will always behave in a way that maximizes the value of equity, because partners may have conflicting interests. In the case under study, the main challenge is the lack of institutions for property rights between Iran and Qatar. According to Schlager and Ostrom (1992), "are best seen as sets of rules that define access, use, exclusion, management, monitoring, sanctioning, and arbitration behavior of users with respect to specific resources". Moreover, regulation, monitoring and obligation are really a big problem in this case. Establishing a rationing system for gas production and export that is approved by both sides and enforceable is not feasible. At the same time, rationing production and export (excess capacity) is not economical for either country (especially Qatar). Since monitoring is impossible (or too costly), rational players prefer to play their non-cooperative strategy and behave as free riders. Given the rationality of the players, the tragedy of the commons is therefore inevitable.

Another issue is the technological means available to exploit the common pool. The rapid emergence of new technologies and access to new markets will affect the incentives of actors in terms of the dynamics of exploitation (Oates, 1999; Azhar, 1993; Almeida and Filgueiras, 2020; Ridley and Bull, 2021), and this is the case of our study. As we expect the lifting of Iranian sanctions, this country will soon have access to new markets and technologies. This will also change its preferences regarding the dynamics of exploitation of the common pool.

3.1 The Role of Iran and Qatar in Natural Gas Market Today

It is important to find out whether the current gas production of Iran and Qatar is consistent with their natural gas stocks. Table 1 provides a summary for Iran and Qatar in terms of their role (shares) in the natural gas market. According to this table, these two countries held about 31% of the world's gas reserves at the end of 2013, which is quite a significant share.

Table 1. Iran and Qatar shares in natural gas market

Country	Reserves (trln.cm)	Production (Bcm)	Consumption (Bcm)	Reserves Share (%)	Production share (%)	Consumption share (%)	R/P* (years)
Iran	33.8	166.6	162.2	18.2	4.9	4.8	213
Qatar	24.7	158.5	25.9	13.3	4.8	0.8	216

Source: BP statistical review of world energy, 2020.
Note: * Reserve to production ratio.

According to this table, Iran's gas production is slightly higher than Qatar's, which is in line with their gas reserves. However, Iran has a large domestic gas market and therefore cannot export as much gas as Qatar. We can suppose that one of the most important reasons for the excessive gas consumption in Iran's domestic market is the relatively low domestic gas price. For example, in the first half of 2011, gas prices in Iran were only $0.11 (per one cubic meter) for domestic customers and $0.06 for industrial customers (www.nigc.ir).[1] These prices are significantly lower than gas prices in the EU and cause excessive consumption.

For both countries, the ratio of reserves to production[2] is more than 200 years. As shown in Table 2, Iran's share of world LNG exports is zero, all of its gas exports are via pipelines, and it accounts for only 1.3% of world gas trade via pipelines.[3] On the other hand, Qatar's share in global LNG exports is high (32.5%), and its share in pipeline exports is modest (2.6%). Therefore, Iran does not play an important role in global gas exports today, while Qatar does.

Table 2. Iran and Qatar role in world Gas trade (BCM)

Country	Exp (pipe)	Exp (LNG)	Imp (Pipe)	Total Export	Exp–Imp	Share of world pipe export (%)	Share of world LNG export (%)
Iran	9.4	----	5	8.42	4.4	1.3	0
Qatar	19.9	105.6	----	94.9	125.5	2.6	32.5

Source: BP statistical review of world energy, 2020

As we can see from Figure 1, Qatar increased its production sharply between 2000 and 2012, but then entered a plateau.

1. At the same time, the retail gas price for household customers in Australia, Belgium and Germany were approximately 0.6 Euro per one cubic meter (http://www.energy.eu/).
2. Reserve-production ratio is based on the current production level. It can change over time due to both depletion, growth of output, and new discoveries.
3. Besides, Iranian next export is close to zero. Iran does not export considerably due to high domestic consumption. Up to 2009, Iran's gas trade balance had been negative (BP, Statistical Review, 2010; 2011).

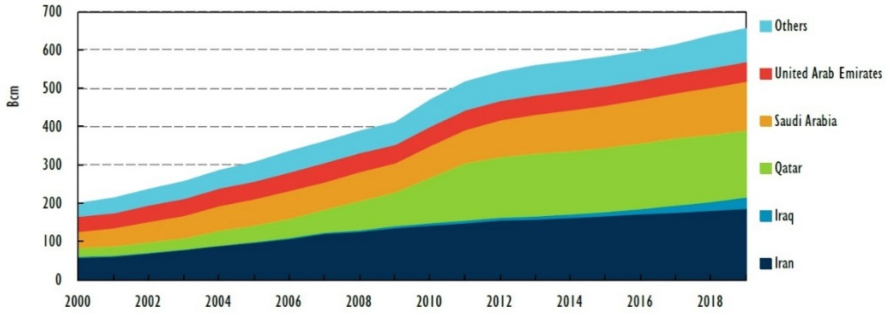

Figure 1. Dynamics of Gas Production in the Middle East
Source: IEA, Gas medium term market report, 2020.

Iran has a steady growth of gas production between 2000 and 2014, but the growth rate was not as high as Qatar. Iran has accelerated the development of gas fields and gas export projects to benefit from its shared gas field (see Table 3).[1] Many projects are marked 2020+, which implies a high degree of uncertainty regarding the speed of future development. In view of the fierce competition between the two countries for the exploitation and extracting of gas from this common field, it seems unlikely that the two countries will commit to production delineations based on the information presented in Table 3.

Table 3. Production and Capacity Addition during 2000-2020+ by Iran

	Production (bcm)	**Start**
In operation		
Phase 1	10.2	2004
Phases 2, 3	20.4	2002
Phases 4-6	20.4	2004
Phases 7, 8	38.0	2008-9
Phases 9, 10	18.2	2012
Planned/ under development		
Phase 11	20.4	2020+
Phase 12	31.0	2014-15
Phase13	19.8	2020+
Phase 14	19.8	2020+
Phases 15, 16	18.2	2016+
Phases 17, 18	18.2	2018+
Phase 19	19.8	2020+

1. In 2010, natural gas liquefaction in Qatar witnessed an almost 56% growth, reaching 77 million tons per year (Kanai, 2011).

	Production (bcm)	Start
Phases 20, 21	18.2	2020+
Phases 22-24	18.2	2020+

Source: IEA, Gas medium term market report, 2019.

3.2 Natural Gas Spot Prices and Opportunity for Cooperation

In recent years, a number of changes, including the development of LNG trade, deregulation and liberalization policies in the gas market, the expansion of the exploitation of unconventional gas reserves, and the economic downturn have led to a supply surplus in the market and a significant decline in gas spot market prices. In the long-run, the decline in gas prices will certainly lead to a response from the major gas producers - they will curtail production in order to raise prices. In fact, the decline in gas prices spurs member countries to develop cooperation (Kanai, 2011). Accordingly, the continued decline in gas price may catalyze the process of consensus building between Iran and Qatar, the second and third largest gas reserve holders, respectively.

As mentioned in Table 2, Qatar is the largest LNG exporter and its share in total LNG export in the world is about 32%. Thus, Qatar has a significant impact on LNG price in spot markets. On the other hand, gas prices have a major impact on the Qatari economy. In recent decades, Qatar has developed many projects to extract more and more gas, and this is one of the important reasons that lead to a gradual decline in gas prices in the spot market[1]. Relatively low gas spot prices in 2010–2012 provided an incentive for cooperation between Qatar and Iran to control the speed of gas extraction development. Indeed, we see in Figure 2 that in 2009–2012, the EU contract gas price was higher than the NBP spot price. This puts a lot of pressure on the reshaping of contract prices. Finally, it leads to the use of a formula that is not only linked to the average oil price but also includes a term for the gas spot price (which differs from region to region). However, there have been big changes in the last 3 years.

1. Another reason is a drop of US demand for LNG imports after successful development of their shale gas.

First, the Asian market became more attractive for LNG. Secondly, Qatar restricted the development of LNG itself and it became scarcer. From the Iranian side, sanctions have prevented sufficient investment in South Pars projects, which Iran uses even less compared to Qatar. According to Iranian reports (25 January 2015),[1] gas production from the South Pars gas field has increased by 105 mcm/d (38 bcm/year) in the last 19 months. There is a good chance for a change if sanctions are lifted in 2015 following the recent negotiations between the US and Iran.

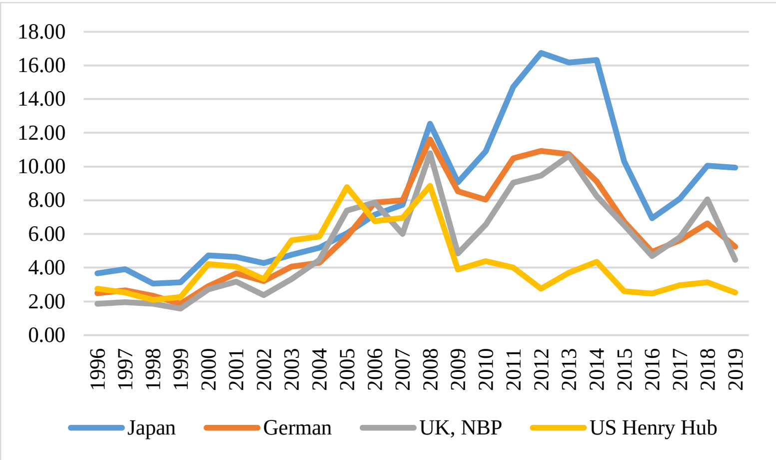

Figure 2. Evolution of regional gas prices, 1996–2019
Source: BP statistical review of world energy, 2020.

3.3 Information about South Pars Gas Field

As mentioned above, the South Pars gas field is located offshore, in the Persian Gulf, and together with the part of Qatar (North Dome) represents the largest natural gas deposit in the world (Figures 3, 4). At the end of 2013, the world's verified gas reserves were estimated at 185.7 trillion cubic meters. Iran has 33.8 trillion cubic meters of this amount, which is 18.2% of the world's gas deposits, making it the

1. Source: http://www.irna.ir/en/News/81478808/

largest gas reservoir in the world (BP Statistical Review of World Energy-June 2014).

The South Pars Gas Field contains about 50% of Iran's gas resources, and is considered the largest offshore gas field in the world. It is located 100 kilometers off the southern coast in Persian Gulf and is jointly owned by Iran and Qatar. The first excavations on this field were carried out in 1990, and seismic data and results confirmed the existence of gas there. Iran's share in this field covers an area of 3700 square kilometers and, according to conducted estimates, consists of 14.2 trillion cubic meters of gas (equivalent to 8% of the world's resources) and more than 18 billion barrels of condensates. The development costs for each phase of the South Pars Gas Field are estimated at about USD 1 billion.[1]

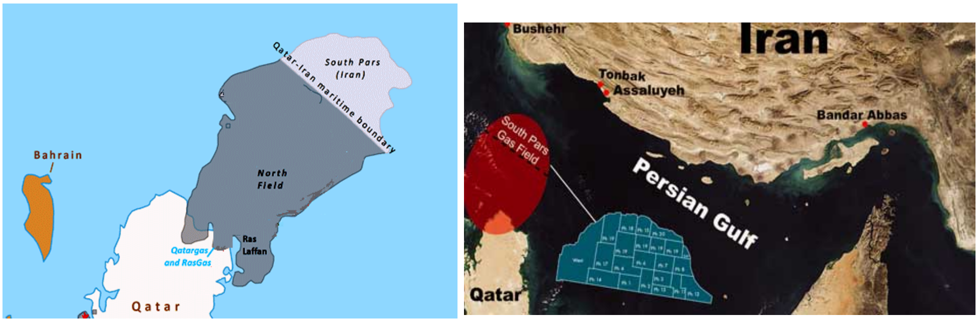

Figure 3. South Pars-North Dome Gas Field
Source: Adapted from EIA (left); Natural Gas Asia (right).

4. Optimal Policy for Qatar

We begin our consideration with the optimal policy for both countries if they do not interfere with each other. Iran and Qatar have very different populations and GDP per capita. Moreover, Iran's policy depends on sanctions.

1. http://en.wikipedia.org/wiki/South_Pars_/_North_Dome_Gas-Condensate_field

We present a highly stylized, simple theoretical model. Qatar is a resource-rich country, with a high per capita endowment[1] of natural gas and a high current income[2]. . Therefore, it does not need to extract much to meet domestic consumption and income demand from exports.

Suppose Qatar chooses the level of exploitation, considering only its preferences for the future. Let R0 be Qatar's initial gas reserves, while XQ be the gas product in a given year. Assume that the utility from gas exploitation has diminishing returns[3] and neglect extraction costs. Let us choose for simplicity:

$$U_Q = \ln(X_Q) + \delta(R_0 - X_Q) \qquad (1)$$

Here δ denotes the future discount. If it is close to one, the discount is small; the future is valued almost like the present. Qatar's optimization problem can be written as follows:

$$\text{Max}\,[\ln(X_Q) + \delta(R_0 - X_Q)] \qquad \text{w.r.t. } X_Q \qquad (2)$$

The optimal rate of extraction is then: XQ =1/δ. It is clear that the partial derivative of the optimal annual extraction rate with respect to the discount rate is negative. When the future is valued at a lower rate, today's extraction becomes higher. Analysis of the real rate in Qatar (which may be a proxy for the time discount rate) shows that it is close to 1%, implying a low rate of optimal extraction. Here, the model is not calibrated. If the scale of the mining unit is close to one, then the reserves should be approximately 100, giving a ratio R/P close to 100, as is the case in reality.

1. Qatar and Iran have comparable stock of natural gas resources, but Qatar's population in 2014 was 2.12 million people, much lower than Iran's (78.4 million). This gives much higher per capita resource endowment.
2. In 2014, Qatar's GDP per capita was $97.518; see: http://data.worldbank.org/indicator/NY.GDP.PCAP.CD
3. With high income per capita, decreasing returns are very pronounced. This was also pointed out in the works of Angus Deaton, the holder of Nobel Prize in economics in 2015.

Note that here Qatar's reserves are not affected by Iran's production policy, and this lack of feedback is a simplification made in this model.

5. Optimal Policy for Iran

Since such a policy depends on sanctions, we consider both cases with a very simple mathematical model.

5.1 The Case of Sanctions

Unlike Qatar, Iran has a large population of 78 million people. This implies both high domestic gas consumption and a much lower level of gas reserves per capita than Qatar.

As we know, Iran has faced economic sanctions until now and has not been able to access international resources for free to invest in gas fields and export its gas. Moreover, since Iran's domestic market is large, almost all of the gas produced is used for domestic consumption. The benefits from this gas consumption clearly have diminishing returns. On the other hand, Qatar has no restrictions on investment while the amount of gas consumption in the domestic market is negligible.[1] Unlike Qatar, Iran has high inflation and probably cares less about the future than Qatar. What can we assume about the cost of gas production? Let us first consider the case of linear (volume-based) extraction costs, c. When the benefit is logarithmic to domestic consumption, X,

$$U = \ln X - a X \tag{3}$$

then the optimal outcome is: *XI =1/a*. This is valid under the assumptions of embargo, neglection of gas value for future generations, and independent gas fields (not as South Pars).

5.2 The Case of No Sanctions

In a dynamic setup, this can be quite complicated, so we will focus on a static case. Let's assume that Iran can invest as much as it wants in

1. We can suggest that low gas prices and space limitation for installing new capacities are only that may decrease the extraction amount of joined gas field in Qatar.

the oil and gas industry and trade gas freely on the world market. Given the much lower per capita income compared to Qatar,[1] it is natural to assume a linear benefit component from export Y (there is a benefit from a set of goods that are imported[2]) and a log benefit from domestic consumption. This leads to the maximization problem for the following net benefit objective, NB, calculated as benefits minus costs:

$$\mathrm{NB} = \ln \mathrm{X} + \mathrm{bY} - \mathrm{c}\,(\mathrm{X} + \mathrm{Y}) - \mathrm{dY}^2 \tag{4}$$

Here *d* gives a nonlinear cost component that shows the technical difficulty of increasing exports rapidly. Then we can formally solve the model with two controls, extraction, *X+Y*, and domestic consumption volume, *X*. The first-order conditions for (1) give the following solution:

$$X = \frac{1}{c}, Y = \frac{(b-c)}{d} \tag{5}$$

The logarithmic utility for domestic consumption implies that the marginal cost of domestic gas consumption should be equal to the marginal utility, here inversely proportional to quantity. Since exporting yields a higher marginal benefit, Iran would prefer to export a higher share of its production, and only high costs of rapid development will set a limit. We see from (2) that *Y* increases when *d* decreases. This implies that Iran has an incentive to increase its gas production, but is limited only by sanctions, available capital, and finding buyers. Therefore, its optimal strategy for exploiting North Dome is likely to be less intensive than for Qatar (before sanctions are lifted and investment capital becomes available). Total extraction volumes will also depend on the discount rate[3], and will likely be higher than for Qatar. Therefore, in the absence of sanctions, we can expect Iran to likely favor faster exploitation of South Pars than Qatar.

---

1. Based on World Bank data, the GDP per capita for Iran in 2009, was $2161.
2. Given that the variety of commodities may grow and that income per capita is relatively small, we can assume no decreasing returns for imported consumption.
3. Not in this model.

5.3 Calibration

As we can see from Table 1, Iran produced 166.6 bcm of natural gas in 2014, and over 97% of it went for domestic consumption. If Iran were to aim for the consumption-to-production ratio typical of Qatar (25.9/158.5), it would need to increase its production to over 1000 bcm/year, a high volume even for Russia, one of world leaders in gas production. However, these figures are not realistic for three reasons: a) Iran does not want to reduce its R/P ratio to values as low as 40 years, b) it will incur too high investment costs, and c) this will have a negative impact on the global gas price.

The IEA (WEO, 2014) projects that Iran will produce 272 bcm of gas per year by 2040, slightly more than Qatar (237 bcm), with annual production growth of 2%. The low growth may reflect the nonlinear cost of increasing gas exports (see formulas 4, 5). However, even in the most optimistic scenario (if all development plans in Table 3 are implemented as planned), 300 bcm/year are not likely to be exceeded in the next two decades.

6. The Game between Iran and Qatar

There are both negative and positive externalities from the joint exploitation of a common gas field. The negative component is standard for the common pool problem and is related to faster depletion at higher exploitation intensities. The setup is based on two stylized facts: a) existence of multiple stages for exploitation, with the need to apply external pressure when the gas field is relatively depleted, b) migration of gas density across the field, which allows some free riding. This section complements sections 4 and 5 and shows the complexity of interactions between Iran and Qatar in joint field exploitation. Several cases of parameters are considered below. They can lead either to a pure common pool story or to a more complex interaction. In a very few cases, the social optimum may coincide with the Nash equilibrium. More often, however, the results are quite different.

We know that Qatar is already exploiting North Dome to a significant extent, while Iran is just beginning this activity. Therefore, we allow Iran to exploit this field at low and medium intensity, while Qatar can choose between medium and high intensity.

6.1 Assumptions of the Game

In the game between two players (i, q) there are two periods. In the first period, both decide on the number of wells to drill. Iran has a choice between 1 and 2 (stylized) wells, Qatar between 2 and 3 wells. These numbers are called w_i and w_q, and the total number of wells (W) can take the values 3, 4 and 5. Suppose that drilling a well has a cost of Cw = 2 for each unit. In the first period, we normalize the production from each well as Q1=3. The gas price in both periods is normalized to one, and no discount is assumed[1].

In the second period, the wells are partially depleted, and this depletion depends positively on the joint exploitation intensity:

$$X(W) = 1 - a(W - b) \tag{6}$$

where a and b are some positive parameters given later. The case $b=0$ corresponds to a linear field depletion, while $b>0$ can take place for a non-linear depletion (see Appendix2).

The output from each well in period 2 has two components: a) the residual, $Q_{2,0} = 3\,X(W)$, and b) the external pressure dependent, dQ. Both players can either apply zero pressure (strategy L), which costs nothing, or apply unit pressure (strategy H). Here there is an appositive externality for a rival. If one side plays H, then the pressure migrates and the rival's output is no longer zero. The values of the incremental output are given in Table 4. Later we will also consider the case of a lower positive externality, (1.2, 1.2) instead of (1.5, 1.5).

1. If the price increases at the discount, we will have the same mathematical problem.

Table 4. The Values of Incremental Output as the Function of Strategies in Period 2

dQ for the 2nd stage		Qatar	
		Strategy L (Cp=0)	Strategy H (Cp=1)
Iran	Strategy L (Cp=0)	0, 0	0.5, 0
	Strategy H (Cp=1)	1, 0.5	1.5, 1.5

Source: Research finding.

To begin, we set $a=0.5$ and $b=2$. The payoffs in each period are given by the profits (the difference between benefits and costs). Then we calculate the sum of the payoffs in both periods.

6.2 Game 1

For Game 1, we have dQ according to Table 4 and the following values for depreciation: $X(3) = 0.5$, $X(4) = 0$, $X(5) = -0.5$. We have the following game shown in Figure 4. There are three types of solutions: Efficient solution, commitment strategy and subgame perfect equilibrium.

For the efficient solutions, we use the Central Planner Approach. The maximum joint profit (JP) is obtained for several cases: JP=6 for (1, 2, H, H), (2, 2, H, H) and (1, 3, H, H). Note that for (2, 3) the joint gain is lower (5).

The highest payoff for binding strategies is obtained for Iran at (2, 2), while for Qatar it is (1, 3). Note that in both cases there is a decision to build only 4 wells (not 3 and not 5).

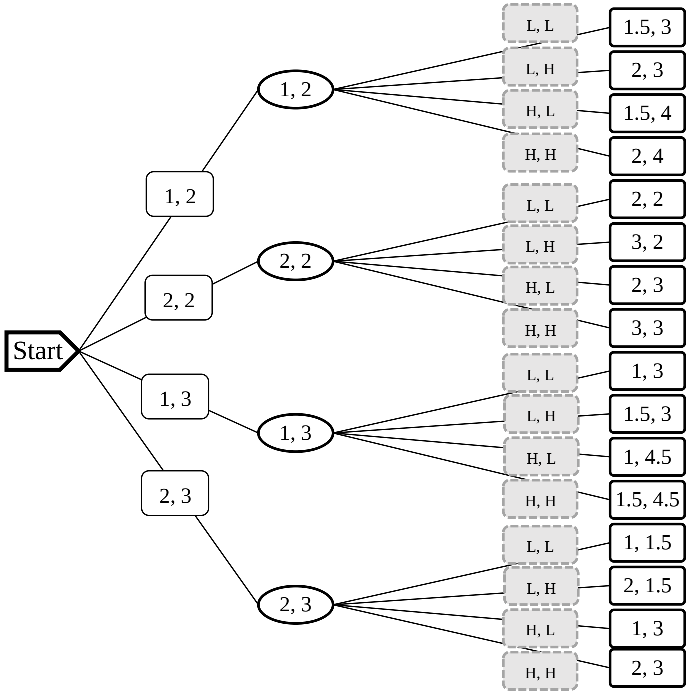

Figure 4. Version of the game for $X(W) = 1 - 0.5(W - 2)$ and high positive externality (1.5)

Source: Research finding.

Now we compute Nash equilibria based on subgame perfection. Note that for a high (1.5) positive externality *(H, H)*, a weakly dominant strategy is at level 2, which yields a higher payoff for both in all realizations of the first strategy. Considering this, it is easy to find optimal responses of both players to the strategies chosen in the first period.

Optimal response:

a) if wi=1, then wq=3 (since 4.5>4),
b) if wi=2, then wq=2 or 3 (Qatar is indifferent),
c) if wq=2, then wi=2 (since 3>2),
d) if wq=3, then wi=2 (since 2>1.5).

The answers agree only for $w_i = 2$ and $w_q = 2$ (efficient case A) and $w_i = 2$ and $w_q = 3$ (non-efficient case B). Therefore, we have two Nash equilibria: A- (2, 2, H, H) and B- (2, 3, H, H). In case B, Iran is worse off while Qatar is indifferent. Consequently, over-exploitation (W=5) leads to an inefficient Nash equilibrium.

In summary, we see the multiplicity of both Nash equilibria and socially optimal outcomes. They coincide with the payoffs (3, 3) under symmetric exploitation in only one case (2, 2, H, H). While asymmetric exploitation (1, 3, H, H) is socially efficient, it is not a Nash equilibrium because Iran will never adhere to it.

We also want to examine how robust these results are. In Game 2, we change the exhaustion formula to $X(W) = 1 - 0.2\,W$. In Game 3, we reduce the positive externality by changing 1.5 to 1.2 (see Table 4).

6.3 Game 2

For Game 2, we again have dQ given by Table 4 and the following values for depreciation $(W) = 1 - 0.2\,W$: $X(3) = 0.4$, $X(4) = 0.2$, $X(5) = 0$. We have the following game on Figure 6.

From Figure 1 we can see that the total payoff for Iran is highest in the choice (2, 2, H, H) and is 3.4. The best result for Qatar is 5.1, and is realized under (1, 3, H, H). The highest sum of payoffs is 7.5 (=3+4.5) under (2, 3, H, H). We see that Iran will tend to choose w_i=2 (hoping for w_q=2), while Qatar will tend to choose w_q=3 (hoping for w_i=1). Nevertheless, such a choice will lead to an efficient subgame Nash equilibrium (3, 4.5) that yields the highest sum of payoffs.

How did it happen that we get a “corner solution” with no properties of the common pool? Here we have both a negative externality from the common pool and a positive one from the pressure strategy in the second period. This positive externality is too high in this case and cancels the common pool property. We will continue to try to reduce it for Games 3 and 4.

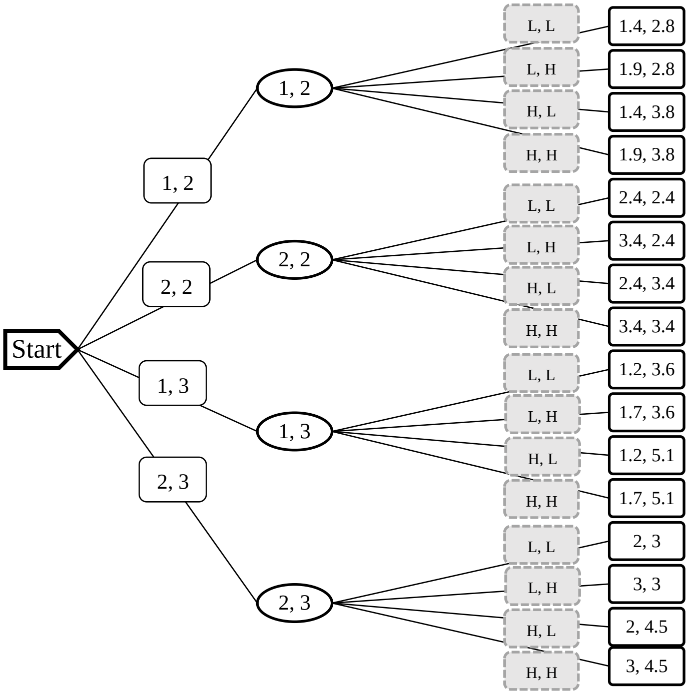

Figure 5. Game Tree with Final Payoff in the Form (Z_i,Z_q), where $\mathrm{Z} = \mathrm{U} + \mathrm{V}$

Source: Research finding.

Note: Each realization corresponds to 4 strategy choices – 2 by each player in each period (w_i, w_q,Y_i, Y_q), where w corresponds to the number of wells, and Y – to pressure in period2. The case $\mathrm{X(W)} = 1 - 0.2\ \mathrm{W}$.

6.4 Game 3

Here the only change from game 1 is the lower positive externality (1.2). The corresponding game is shown on Figure 6.

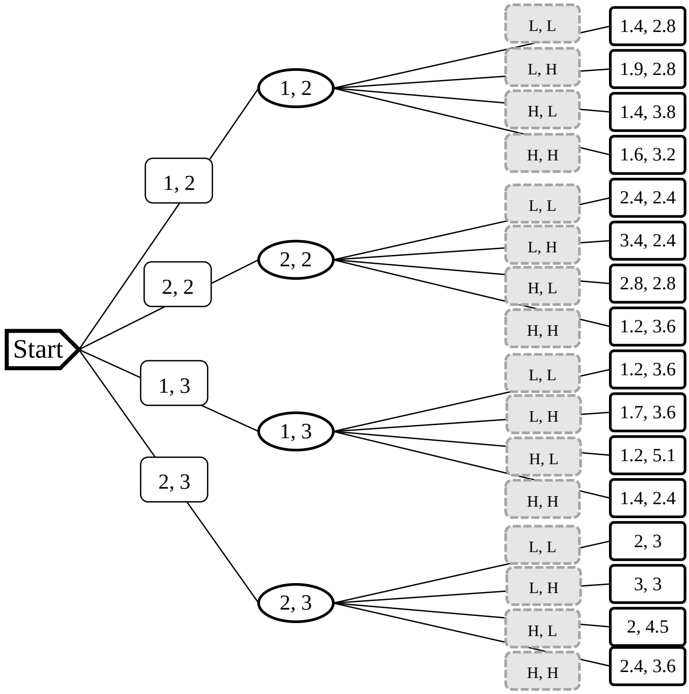

Figure 6. The Moderate Positive Externality (1.2) and X(W)=1-0.2W
Source: Research finding.

We can easily see that the maximal joint production (6.3=1.2+5.1) occurs for (1,3,H,L). It is possible to show (see Appendix) that there are two Nash equilibria here: a) (2,3,L,H) and b) (2,3,H,L). Iran would prefer to play L since it has a higher payoff; however, Qatar will prefer the same. However, they have no incentive to play both (L, L). Therefore, there can be equilibrium in mixed strategies.

6.5 Game 4

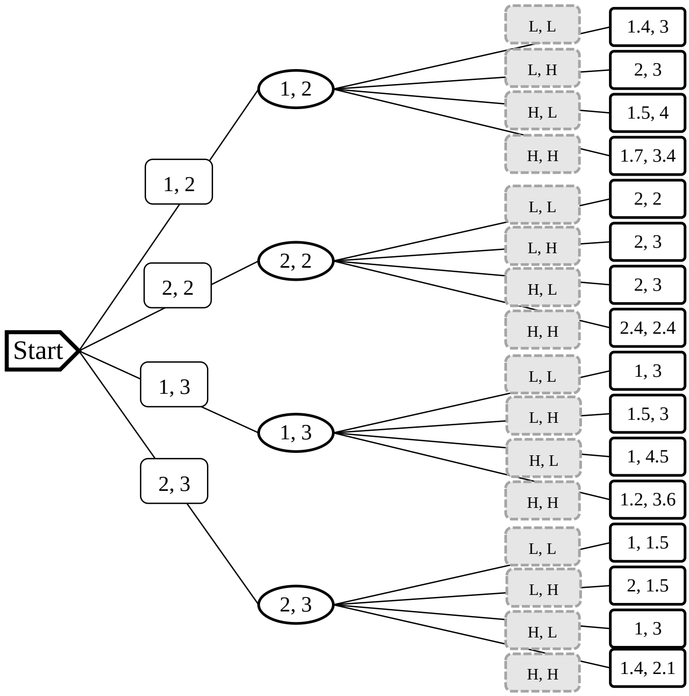

Figure 7. The Game for X*(W)=1-0.5(W-2)* and Moderate Positive Externality (1.2)
Source: Research finding.

As we can see in Figure 7, the highest joint payoff is 5.5, which is obtained for (1, 3, H, L) and (1, 2, H, L). In this case, we never have over-exploitation (W=5) as a joint optimal solution.

In terms of Nash equilibria, the second stage here brings many indifferences in the optimal answers. In the second stage, L is the weakly dominant strategy Iran in all cases, so she will never play H. The same is true for Qatar. Going back to Stage 1, we see that (2, 2) is the only equilibrium. Thus, (2, 2, L, L) is a Nash equilibrium.

Summarizing Games 1 to 4, we can see that the interaction of positive and negative externalities leads to a variety of different Pareto-optimal outcomes and Nash equilibria, depending on the relative strength of the joint pool and positive externality effects.

7. Efficient Joint Exploitation

If both countries were to pursue their short-sighted, policy-optimal extraction paths without regard to interaction, they would both suffer. If one of the countries has an extraction flow that exceeds its share of the common stock, it can punish the other country. Moreover, competition for more extraction will hurt both sides. Therefore, there is a room for cooperation.

If both countries would maximize the joint utility taking into account all externalities, they would reach the Pareto frontier. Then the only problem is to divide the pie among the participants. Again, equal either sharing or proportional to bargaining power can solve this. However, this solution will differ from the optimal extraction paths for both countries.

Another problem is that there is no perfect mechanism for accounting for the remaining share of gas for each country in the common reservoir. Predatory extraction can lower the gas pressure in the local field, making future extraction more expensive. However, the gas can migrate, and the lower pressure will also take place in the other owner's fields. Conversely, if country A has a lower production to reserves ratio than country B, it will be penalized by having tougher conditions to extract its gas because of B's actions.

Therefore, it is optimal for both countries to agree on an equal R/P ratio over the shared field. Nevertheless, what should that level be? Let us assume that $(R/P)_Q < (R/P)_I$. That is, Qatar wants to extract its gas faster than Iran, say in 50 years, while Iran wants to do it in 100 years. Then the effect of the common pool will be that both Qatar will do it slower and Iran will do it faster. If the only option was to choose a common rate, they would probably both choose $(R/P)_I$ =70. This gives both of them additional benefit by deviating from their optimal extraction path.

However, a small deviation from common R/P is not prohibitively expensive. A higher deviation, however, becomes more expensive.

Therefore, both countries, when optimizing and rationally accounting for the cost of deviating from the common R/P rate, are likely to arrive at a rational equilibrium where R/P is somewhere between an independently chosen and a jointly chosen one. Say, under certain assumptions, we could have:

$50\ (R/P)_Q < (R/P)^*_Q = 60 < (R/P)_J = 70 < (R/P)_I = 100.$

8. Impact of the Future Gas Market

8.1 Forecasting Future Gas Demand

Of the various fossil fuels, natural gas is expected to have the highest growth rate through 2030 (BP, Energy Outlook 2030). The share of fossil fuels in the world energy basket is projected to fall from 81% in 2008 to 74% in 2035. Nevertheless, gas demand will grow by an average of 2% per year over the same period, increasing from 3.1 tcm in 2008 to 2.1 tcm in 2035. The growth in gas demand will result in the share of natural gas in the world energy basket increasing from 21% to 25% over the period under study. Most experts have therefore referred to the present century as the “gas century” (IEA, World Energy Outlook, 2011). This means more energy for GECF. Moreover, according to the IEA special report published in 2011, “assuming the gas scenario, gas consumption will increase by more than 50% from 2010, and will account for more than 25% of world energy demand in 2035 - certainly a prospect that can be called Golden Age of gas”. Gas will therefore remain an important fossil fuel in the coming decades. Its share in the overall energy portfolio is expected to grow even in the scenario of partial replacement of fossil fuels by renewables, as it produces less carbon dioxide emissions than coal.

8.2 Optimal Development of Gas Fields

It is known that the owner of several gas fields optimally start developing the cheapest, and then move to more expensive ones. Given the positive trend in prices of non-renewable resources, it is always optimal not to do the opposite. Nevertheless, if there is no common owner of all fields, we have competition, and firms with different costs compete. As we know, for a given demand function, at a given time, only the group of firms with lower costs will exist. The rest will save their deposits for the future. The marginal firm in the market will operate with a profit of almost zero, while lower cost firms can make some positive profits.

If a firm has two or more deposits with different costs, it may exploit only one of them, the cheapest. Only in the case of a high future discount can it exploit both deposits, but only under the condition that the profit from the more expensive deposit is not negative.

Suppose two players in the market who have both cheap and expensive deposits and the market demand for today is such that exploitation of only one expensive deposit is sufficient to satisfy global demand. Then, the company with the higher discount for the future will put its deposit into exploitation today, making virtually no profit from it.

8.3 The Future Role of Qatar and Iran in Gas Markets

At present, both Qatar and Iran are underrepresented in world gas markets, considering the wealth of their resources. Qatar has a problem building pipelines, while there is little incentive to expand LNG capacity in the coming years (because the US discovery of economic extraction of shale gas acted as a negative shock to overall gas demand, and LNG in particular). Today, economic sanctions against Iran limit its presence in world gas markets. However, the country has significant capacity to export natural gas in the future, both as pipeline gas and in the form of LNG.

At present, global gas, exports are dominated by Russia, which has 26% of the world’s gas reserves. However, due to huge domestic demand, Russian exports are less than 30% of its production. Plans to increase production could see Russian gas production peak as early as 2040 at 930 bcm (Hartley & Medlock, 2009). Qatar's production will remain at a moderate 170 bcm. Yegorov and Wirl (2011) suggest a possible long-term scenario for natural gas extraction. If the EU's drive to diversify gas imports persists over the next decade, this will lead to a rapid drying up of the reserves of Norway, Algeria and Nigeria (which each hold less than 3% of world gas reserves). Then the dominant long-term gas suppliers (in the mid-21st century) will be Russia, Qatar and Iran.

9. Conclusion

The tragedy of the commons is a problem that arises from the situation in which several individuals act independently of each other and eventually deplete a shared, limited resource, even when it is clear that this is in no one's long-term interest. The concept was first described in the influential 1968 article "The Tragedy of the Commons" by Garrett Hardin. Since then, many scholars have expanded and applied the theory, but most of them focus on renewable resources, such as forests and fishponds. In this paper, we present a model of joint exploitation of a common gas field between Iran and Qatar. Competition to extract more gas from the joint field hurts both countries by decreasing pressure in the gas field and decreasing gas production rate, so they have an incentive to cooperate. In addition, selling gas at low prices is another negative effect of rapid production. According to Energy Outlook of the IEA, the demand for natural gas will increase significantly in the future. Therefore, there are enough reasons for both sides to cooperate to maximize their long-term revenues and ensure sustainable development.

Gas from Iran and Qatar will play a very important role in the middle of the 21st century, when the reserves of other gas producers with smaller supplies will dry up. Gas from Iran and Qatar will play a very important role in the middle of the 21st century when the reserves of other gas producers with smaller reserves will dry up. Therefore, the problem of optimal exploitation of the largest world gas field, South Pars-North Dome, plays a very important role not only for these countries, but also for the future world gas market.

The optimal dynamics of exploitation of this common gas field may look different from the perspective of Iran and Qatar. Moreover, for Iran, this dynamic also depends on the presence or absence of economic sanctions. We expect that in the sanctions environment, it would be optimal for Iran to exploit the field less intensively than Qatar. This effect is due to several reasons: a) lower limit of gas used domestically, b) lower resource requirement for investment in the field. However, after the sanctions are lifted, Iran has the opportunity to develop the field quickly because it needs more import revenues.

Unlike Iran, Qatar has a moderate need to accelerate the exploitation of this field. With a GDP per capita twice that of the US, the country does not need much money in the short term. In general, we expect Qatar to exploit its gas reserves more slowly than Iran and not reach its peak gas production before the end of the 21st century, if not later. It may be optimal for Iran to wait until sanctions are lifted and then develop its gas fields more rapidly, reaching its peak production in the middle of the 21st century, close to Russia. In order to deviate less from proportional exploitation of the common field South Pars-North Dome field, it could use additional resources more quickly. This is our idea of optimality, but in real life, not all decisions are optimal and are often influenced by politicians, both local and international.

Appendix 1. Backward Induction Solution for Game 3

Backward induction (optimal response):

In sub game (1, 2):

a) if wi=L, then wq=L/H (Qatar is indifferent),
b) if wi=H, then wq=L (as 3.8>3.2),
c) if wq=L, then wi=L/H (Iran is indifferent),
d) if wq=H, then wi=L (since 1.9>1.6).

Responses coincide for (L, H) and (H, L).

In sub game (2, 2):

a) if wi=L, then wq=L/H (Qatar is indifferent),
b) if wi=H, then wq=L (as 3.4>2.8),
c) if wq=L, then wi=L/H (Iran is indifferent),
d) if wq=H, then wi=L (since 3.4>2.8).

Responses coincide for (L, H) and (H, L).

In sub game (1, 3):

a) if wi=L, then wq=L/H (Qatar is indifferent),
b) if wi=H, then wq=L (as 5.1>4.2),
c) if wq=L, then wi=L/H (Iran is indifferent),
d) if wq=H, then wi=L (since 1.7>1.4).

Responses coincide for (L, H) and (H, L).

In sub game (2, 3):

a) if wi=L, then wq=L/H (Qatar is indifferent),
b) if wi=H, then wq=L (as 4.5>3.6),
c) if wq=L, then wi=L/H (Iran is indifferent),
d) if wq=H, then wi=L (since 3>2.4).

Responses coincide for (L, H) and (H, L).

Now we reduce the game tree to only the nodes corresponding to the best mutual answers in stage 2. We obtain the “sub”-game shown in Figure I.

Appendix 2. About Nonlinear Depletion

Field depletion can be linear or nonlinear with respect to the number of wells drilled. In Section 6, we gave two formulas for *X(W)*. The case $X(W)=1-0.2W$ is obviously linear. Here we show that the case $X=1-0.5(W-2)$ can be obtained as a linear Taylor approximation of the nonlinear dependence *X(W)*. Consider the quadratic formula for depletion: $X(W)=1-cW^2$ and its Taylor series in the neighborhood of $W=4$. Since $dX/dW=-2cW$, we obtain $X(W)=X(4)+dX/dW(4)(W-4)+O(W^2)$. Thus, to fit our formula with the coefficient -0.5, we get $c=1/16$ and $X(4)=0$. Then $X(W) = -0.5(W-4) +O_2 = 1-0.5(W-2)+O_2$, where O_2 stands for the second-order terms.

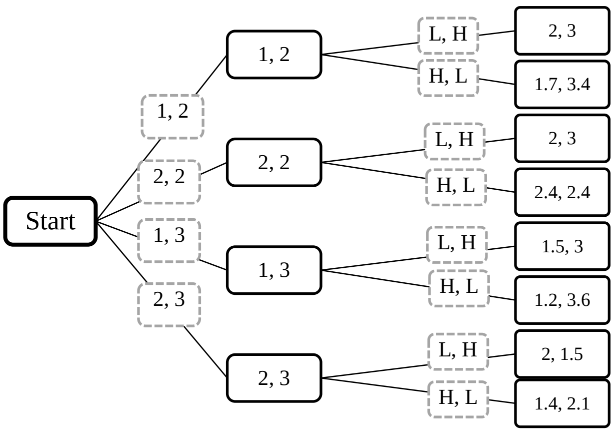

Figure I. The Subgame after Elimination of the Strategies that Are Never Best Replies
Source: Research finding.

Now we study the responses for commitment strategies:

If wi=1, L, then wq=3, H (as 3.6>2.8),

If wi=1, H, then wq=3, L (as 5.1>3.8),

If wi=2, L, then wq=3, H (as 3>2.4),

If wi=2, H, then wq=3, H (as 4.5>3.4),

If wq=2, L, then wi= 2, H (as 2.4>1.4),

If wq=2, H, then wi= 2, L (as 3.4>1.9),

If wq=3, L, then wi= 2, H (as 2>1.2),

If wq=3, H, then wi= 2, L (as 3>1.7),

Since Qatar's optimal response to Iran's strategies (2, L) is (3, H), it is a Nash equilibrium. We get the similar result only for (2, H) and (3, L), and never for any other bound strategies. In this case, there are again two Nash equilibria: (2, 3; L, H) and (2, 3, H, L).

References

Almeida, V., Filgueiras, F., & Gaetani, F. (2020). Digital Governance and the Tragedy of the Commons. *IEEE Internet Computing*, *24*(4), 41-46.

Andersson, D., Bratsberg, S., Ringsmuth, A. K., & de Wijn, A. S. (2021). Dynamics of Collective Action to Conserve a Large Common-Pool Resource. *Scientific Reports*, *11*(1), 1-11.

Azhar, R. A. (1993). Commons, Regulation, and Rent-Seeking Behavior: The Dilemma of Pakistan's "Guzara" Forests. *Economic Development and Cultural Change*, *42*(1), 115-129.

Baerlein, T., Kasymov, U., & Zikos, D. (2015). Self-governance and Sustainable Common Pool Resource Management in Kyrgyzstan. *Sustainability*, *7*(1), 496-521.

Bochet, O., Page, T., & Putterman, L. (2006). Communication and Punishment in Voluntary Contribution Experiments. *Journal of Economic Behavior & Organization*, *60*(1), 11-26.

Bolle, F. (1980). The Efficient Use of a Non-Renewable Common-Pool Resource is Possible but Unlikely. *Journal of Economics, 40*(3/4), 391-397.

BP Statistical Review. (2010; 2011). Retrieved from https://www.bp.com/

BP Energy Outlook 2030. (2013). Retrieved from https://www.bp.com/

Djiguemde, M. (2020). A Survey on Dynamic Common Pool Resources: Theory and Experiment. *Working Papers, 03022377*, 1-20.

Esmaeili, M., Bahrini, A., & Shayanrad, S. (2015). Using Game Theory Approach to Interpret Stable Policies for Iran's Oil and Gas Common Resources Conflicts with Iraq and Qatar. *Journal of Industrial Engineering International*, *11*(4), 543-554.

Gari, S. R., Newton, A., Icely, J. D., & Delgado-Serrano, M. M. (2017). An Analysis of the Global Applicability of Ostrom's Design Principles to Diagnose the Functionality of Common-Pool Resource Institutions. *Sustainability*, *9*(7), 1287-1295.

Grainger, C. A., & Costello, C. (2016). Distributional Effects of the Transition to Property Rights for a Common-Pool Resource. *Marine Resource Economics*, *31*(1), 1-26.

Gross, J., & De Dreu, C. K. (2019). Individual Solutions to Shared Problems Create A Modern Tragedy of The Commons. *Science Advances*, *5*(4), 21-33.

Hardin, G. (2009). The Tragedy of the Commons. *Journal of Natural Resources Policy Research*, *1*(3), 243-253.

Hartley, P. R., & Medlock III, K. B. (2009). Potential Futures for Russian Natural Gas Exports. *The Energy Journal*, *30*(Special Issue), 1-20.

IEA, World Energy Outlook. (2011). Retrieved from https://www.iea.org/reports/world-energy-outlook-2011

Kanai, M. (2011). Decoupling the Oil and Gas Prices. Natural Gas Pricing In the Post-Financial Crisis Market. Retrieved from https://www.ifri.org/sites/default/files/atoms/files/noteenergiemiharukanai.pdf

Lalehzari, R., & Kerachian, R. (2020). Developing a Framework for Daily Common Pool Groundwater Allocation to Demands in Agricultural Regions. *Agricultural Water Management*, *241*, 106278.

Libecap, G. D. (2010). Rights-based Management of Tuna Fisheries: Lessons from the Assignment of Property Rights on the Western US Frontier. *Conservation and Management of Transnational Tuna Fisheries*, *137*, 221-235.

---------- (1989). *Contracting for Property Rights* (20). Cambridge: Cambridge University Press.

Libecap, G. D., & Smith, J. L. (1999). The Self-Enforcing Provisions of Oil and Gas Unit Operating Agreements: Theory and Evidence. *Journal of Law, Economics, and Organization*, *15*(2), 526-548.

Libecap, G. D., & Wiggins, S. N. (1984). Contractual Responses to the Common Pool: Prorationing of Crude Oil Production. *The American Economic Review*, *74*(1), 87-98.

Oates, J. F. (1999). *Myth and Reality In The Rain Forest: How Conservation Strategies Are Failing in West Africa*. California: University of California Press.

Ostrom, E. (1998). A Behavioral Approach to the Rational Choice Theory of Collective Action: Presidential Address, American Political Science Association, 1997. *American Political Science Review*, *1*, 1-22.

---------- (1997). Self-governance of Common-Pool Resources. Workshop in Political Theory and Policy Analysis, Indiana University, Retrieved from https://www.iu.edu/index.html

Ostrom, E. E., Dietz, T. E., Dolšak, N. E., Stern, P. C., Stonich, S. E., & Weber, E. U. (2002). *The Drama of the Commons*. Washington, DC: National Academy Press.

Ostrom, E., Gardner, R., Walker, J., Walker, J. M., & Walker, J. (1994). *Rules, Games, and Common-Pool Resources*. Michigan: University of Michigan Press.

Parker, N. (2004). Using Natural Gas Transmission Pipeline Costs to Estimate Hydrogen Pipeline Costs. Retrieved from https://escholarship.org/content/qt9m40m75r/qt9m40m75r.pdf

Ridley-Duff, R., & Bull, M. (2021). Common Pool Resource Institutions: The Rise of Internet Platforms in the Social Solidarity Economy. *Business Strategy and the Environment*, *30*(3), 1436-1453.

Rose, C. (1986). The Comedy of the Commons: Custom, Commerce, and Inherently Public Property. *The University of Chicago Law Review*, *53*(3), 711-781.

Schitka, B. B. (2014). Applying Game Theory to Oil and Gas Unitization Agreements: How to Resolve Mutually Beneficial, Yet Competitive Situations. *The Journal of World Energy Law & Business*, *7*(6), 572-581.

Schlager, E., & Ostrom, E. (1992). Property-Rights Regimes and Natural Resources: A Conceptual Analysis. *Land Economics*, *1*, 249-262.

Sefton, M., Shupp, R., & Walker, J. M. (2007). The Effect of Rewards and Sanctions in Provision of Public Goods. *Economic Inquiry, 45*(4), 671-690.

Smyčka, J., & Herben, T. (2017). Phylogenetic Patterns of Tragedy of Commons in Intraspecific Root Competition. *Plant and Soil*, *417*(1), 87-97.

Squillace, M. (2015). Managing Unconventional Oil and Gas Development as If Communities Mattered. *Vermont Law Review*, *40*, 525-560.

Weaver, J. L. (2013). *Unitization of Oil and Gas Fields in Texas: A Study of Legislative, Administrative, and Judicial Policies*. New York: Routledge.

World Energy Outlook. (2011). Are We Entering a Golden Age of Gas? Retrieved from IEA, Special Report.

Yegorov, Y., & Wirl, F. (2011). Gas Transportation, Geopolitics and Future Market Structure. *Futures*, *43*(10), 1056-1068.