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External effects of shale gas hydrofracking: Risk and welfare considerations for water supply in Germany

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Abstract

In this paper, we investigate the externalities related to hydraulic fracturing ('hydrofracking') in Germany, based on a detailed analysis of hydrofracking risks and potentials, and a stylized social welfare analysis related to adverse impacts of unconventional gas production on both surface and ground water resources and water supply. Natural gas is extracted by a profit-maximizing monopolist. Society faces several kinds of negative externalities, including additional water purification costs. The results of our sensitivity analysis show that the maximized welfare is in any case higher than the welfare resulting from the profit-maximizing quantities, as is predicted by our model. Also, the regulator always has to pay a subsidy in order to maximize welfare, which shows that the monopolist has an incentive to exercise his market power in order to keep the prices up for profit maximization. The monopolist's profits are always non-negative, whereas the welfare-maximizing shale gas production generally reduces his profits. As profits do not drop below zero, however, there is no need to employ a second-best approach. We conclude that increasing costs and/or an increasing price sensitivity will lead to reduced profits and to reduced social welfare, while for an increasing choke price it is the other way around.

Key words: Natural gas; Fracking; Externalities; Water supply; Germany

JEL Classification Nos.: L71, Q31, Q34, Q42, Q53, Q58;

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1 Introduction

Compared to many other countries, Germany does not seem to have any major problems with water supply. Although especially in eastern federal states, like Saxony or Thuringia, the agricultural sector sometimes suffers from a shortage of rainfall, and even public warnings of forest fires occur, the quantity of water supply is not of major concern. Furthermore, the majority of German water supply systems relies on ground water rather than surface water. Still, the quality of drinking water supply does vary a lot by region. Because of agriculture and the manufacturing industry, for example, in some regions the nitrate and pesticide concentrations are much too high. This does not only concern surface water but also, increasingly, ground water reservoirs.

Extraction and processing of shale gas by hydraulic fracturing offers many opportunities for future energy supply, e.g., by promising lower prices and more self-sufficiency in the energy sector. Although the fracking technique is several decades old, only in recent years has shale gas extraction become cheaper and more efficient, and hence more widespread. Additionally, natural gas is less CO_2-intensive than coal or oil.

Hydraulic fracturing requires a considerable amount of water that is mixed with various chemicals. This mixture is then pressed through boreholes into layers of rock, some of them nearby or directly next to ground water layers. How harmful these effects of hydraulic fracturing on the quality and/or quantity of (drinking) water really are is still controversial, but some external effects seem likely, and thus regulatory and policy measures could be necessary for social welfare optimization.

Despite of an increasingly intense and polarized policy debate about the pros and cons of shale gas use, calling for responsible scientific analysis and public policy guidance, the academic literature on adverse environmental impacts of shale gas hydrofracking is still scarce, including Eaton (2013); Jenner & Lamadrid (2013); Popkin et al. (2013); Centner & O'Connell (2014), and often is not based on rigorous economic modeling. In interesting piece of research on the human right to drinking water, partly in the context of shale gas hydrofracking, includes Jeffords (2012) and Jeffords & Shah (2013). Shale gas reports are abound; recent ones include EPA (2012) and Reig et al. (2014).

In this paper, we investigate the potential risks for the German drinking water supply, whether existing regulations should be improved, and which mechanism yields the maximum social welfare. In section 2, we look at the current situation in Germany and discuss the expected shale gas reserves, the state of surface water and ground water bodies, and the legal framework. In section 3, we develop a simple economic model and explain two different policy instruments that can be used for internalizing the occurring external effects. Finally, we apply the model by using stylized figures, and perform a sensitivity analysis regarding the impact of key parameters on social welfare and profits.

2 Status quo of fracking in Germany

2.1 Shale gas reserves

Shale gas, once extracted, is exactly the same as ordinary natural gas. It develops as the result of the same geological and chemical processes that create natural gas and has the same consistency. The main component is methane and, once extracted from the ground, it can be treated like any other natural gas. The geological difference results from the fact that unconventional gas has not migrated out of its bedrock. Conventional natural gas, in contrast, has already migrated out of the rock layers into reservoirs and thus is far more easily accessible. Once opened up by drilling, natural gas is pressed out simply by the pressure of the surrounding rock or ground water layers. Shale gas, on the other hand, has to be pressed out artificially.

In other words, the difference between conventional and unconventional gas lies mainly in the extraction technique and this is where hydraulic fracturing comes into play. By means of 'hydrofracking', the reservoir rocks are broken up, and the shale gas can leak through the cracks created. To do this, a pressurized liquid is injected into the ground in order to keep the cracks open and press the bounded shale gas out of its bedrock.

This means that the crucial characteristic is the permeability of the rock layers, measured in millidarcy [mD]. While conventional natural gas is found in reservoir rocks with a high permeability of 1 mD or more, unconventional gas is defined as gas appearing in reservoir rocks with a low permeability of 0.001 mD or less. Gas from layers with a permeability lying inbetween those two is called tight gas. Although tight gas can geologically be seen as an intermediate resource, it still has to be extracted by fracking. As it is widely considered to be unconventional gas, we also regard it as such. Tight gas can be found in different kinds of reservoir rocks, such as sandstone or limestone. Besides tight gas, there are two other types of unconventional gas: coalbed and shale gas. They are both named after their bedrocks, i.e. shale gas is found in shale, whereas coalbed gas (or coalbed methane) is found in coalbeds. In this paper, the focus is solely on shale gas.

For first estimations of where to find shale gas, it is helpful to look at the circumstances under which hydrocarbons can emerge. Natural gas or oil develop only under very specific circumstances over long periods of time. Besides the amount and type of the enclosed organic matter, the pressure under which it is stored and the thermal maturity of the layers are important characteristics. The maturity can be seen as the ripeness of the layers and is crucial for the development of natural gas or oil reserves.

The content of organic carbon in the organic matter has to be higher than 2%. The prevailing pressure and temperature are a result of the thickness of the rock layers, which have to be thicker than 20 m, and how deep they are belowground, with typical values of between 1,000–5,000 m. The thermal maturity is reliant on age and temperature and

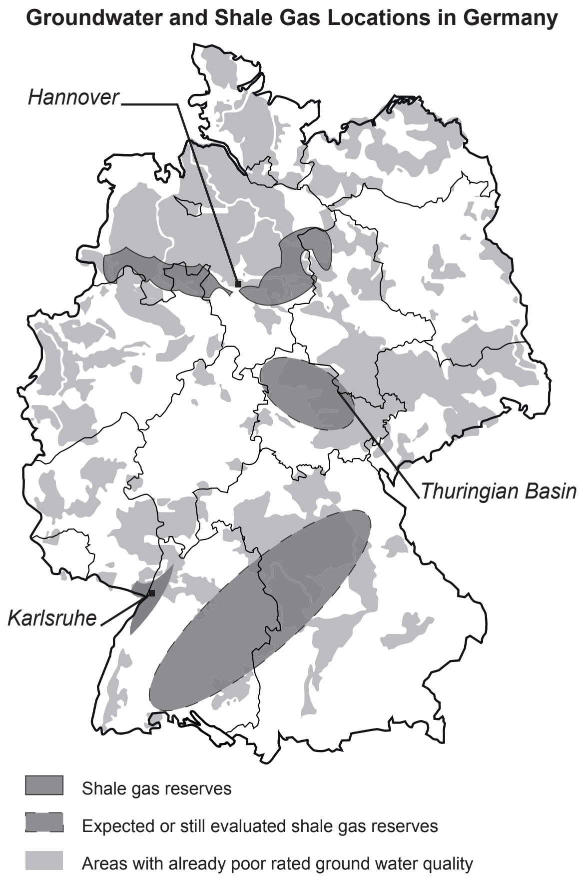

Figure 1: Spatial distribution of identified and speculative shale gas reserves in Germany and overlaps with groundwater reservoirs of already poor rated quality
Source: Andruleit et al. (2012)

has an influence on whether gas or oil is formed. It should be between 1.2% and 3.5% of porosity. In the following, we introduce these three areas, state their total amount of shale gas (gas-in-place, GIP), and how much of it might be technically extractable in Germany. We refer to an interim report published by the German Federal Institute for Geosciences and Natural Resources (BGR) (Andruleit et al., 2012). The estimated figures are provisional only, and other shale gas fields may be added to the report later, because measurements and evaluations delivering more data are still going on. This again illustrates that the idea of extracting shale gas for commercial use has only been considered in recent years. The release of the final report is scheduled for fall 2015.

Applying the explained selection criteria to suitable layers of rock narrows possible shale gas areas down to three that have been explored to date. There are two areas in Lower Saxony (Northwestern Germany), surrounding the city of Hannover, and one along the Rhine river near Karlsruhe in the federal state of Baden-Wuerttemberg.

In the absence of any commercial shale gas extraction in Germany to date, the estimation of the feasible amount of extractable shale gas relies on production data from the US. A quota of 10–35% of the GIP seems to be realistic. To be on the safe side, we continue our analysis by assuming a quota of just one tenth of the GIP.[1]

- The field east of Hannover is roughly 350 million years old and contains argillaceous rock, or clay rock, developed since the Lower Carboniferous period. The field covers an area of 2,700–6,300 km^2, and the shale gas layers are at a depth of between 1,000–5,000 m belowground. The GIP is between 2.5–17.7 trillion m^3, so that the 10% of extractable amount is computed at 0.25–1.77 trillion m^3. With an average estimate of 8 trillion m^3, this field contains probably the greatest reserves of the fields explored in Germany so far.

- West of Hannover and in the southwestern part of Germany, near the Franco-German border, along the Rhine river is a field with less than 200 million year old posidonia shale rock layers. It contains about 0.1–0.4 trillion m^3 of extractable shale gas. Both fields combined stretch over an area of 3,200–4,800 km^2, and the rock layers are found in depths of 1,500–2,200 m.

- The third shale gas deposit is located in another clay rock formation, again west of Hannover, but only 150 million years old and at a depth of approximately 1,300–1,700 m. With an area of no more than 280–420 km^2 a relatively small field, it probably contains about 0.1–0.4 trillion m^3 of extractable shale gas, and so almost the same amount of, or even slightly more, shale gas than in the layers in the posidonia shale rock west of Hannover.

The wide ranges in the estimated potentials give a good impression of the high uncertainty one is confronted with when trying to determine the amount of shale gas that there is. In summary, it means that in the aggregate, the currently expected shale gas reserves in Germany range between 6.8–22.6 trillion m^3. The median value, with a probability of more than 80%, is 13 trillion m^3. Still, according to the more conservative assumption, the technically extractable amount is considered to be just one tenth of these numbers (which is enough to cover Germany's gas consumption for a period of about 13 years). Compared to Germany's neighbors France and Poland, with 5 trillion m^3 extractable shale gas reserves each, that does not seem much. But considering a global natural gas consumption of 3.406 trillion m^3 in 2014 (BP (2015), 1 trillion m^3 = 900 Mtoe), again 1.3 trillion m^3 seems quite sizable. The estimated technically recoverable global shale gas resources worldwide amount to about 200 trillion m^3 (Reig et al., 2014).

Additionally, there are still other areas in eastern and southern Germany which have not yet been completely examined and form no part of the BGR interim report (Andruleit

[1]For the exact calculation method, see Andruleit et al. (2012), Ch. 3, p.21.

et al., 2012). The Thuringian Basin (see Figure 1) is an example of such an area that might increase the amount of extractable shale gas further.

2.2 Current water conditions

The recent floods that ran through the southern, eastern, and northern parts of Germany indicate that it is a water-rich country[2]. It has plenty of rainfall; for instance, 768 liters per square meter fell in 2012, which resulted in 274 bnm^3 of water.[3] Of course, a lot is lost through evapotranspiration or surface runoff. Due to the plentiful rainfall, the quantity of ground water is also of no concern.

Almost 5.1 bn m^3 of water were consumed in 2010, of which 79% came from below-ground (including spring water, ground water, and enriched ground water). The other sources are surface waters, such as reservoirs, lakes, or rivers. Compared to 2004, the share of ground water dropped by 3%, and the overall volume of consumed water declined by 290 million m^3 per year. Generally, ground water is preferred, as it needs less conditioning before being drinkable.

The 5.1 bn m^3 of water consumed can be broken down into water losses through leaks or self-consumption by the water companies (0.6 bn m^3), and water for end use by private households or industries (4.5 bn m^3). About 3.6 bn m^3 of the water for end use is delivered to private households and small businesses, which results in a new low of water consumption of 121 liters per day and resident – dropping from 147 l in 1990. The remaining 0.9 bn m^3 are used by the industrial sector.[4]

Although it seems that most people in our part of the world do not spend much time thinking about their water consumption and supply, these numbers indicate just how essential water is in the industrial sector, and even more so in everyday life. But besides the available water *quantity*, which seem to be no issue of concern in Germany, the water *quality* is at least as important. Hence, in the following, we look at the ground and surface water quality.

To evaluate the water conditions, each stretch of water is divided into one or more water bodies, and then each body is rated and categorized individually. Thereby, a body can be rated as "good" or "bad", and the European Water Framework Directive (EU-WFD) stated that a good qualitative and quantitative status of all water bodies had to be achieved by 2015.

[2]See Association of Drinking Water from Reservoirs (ATT) et al. (2011), p.8.

[3]See the press release by the German Meteorological Service (DWD), December 2012: http://www.dwd.de/ bvbw/generator/DWDWWW/Content/Presse/Pressemitteilungen/2012/20121227_ _Deutschlandwetter Jahr__2012,templateId=raw,property=publicationFile.pdf/20121227_ DeutschlandwetterJahr_2012.pdf.

[4]See Statistisches Bundesamt (2013) for further details.

2.2.1 Ground water conditions

Ground water is water found in the saturated zone of the soil. It can form reservoirs or streams belowground or fill up cracks and hollow spaces between rocks and layers. Characteristics of ground water are the slow flow velocity, the low replenishment rate, and its perfusion of layers of rock and soil. Because of this, many sediments can settle, impurities are filtered out, and minerals dissolve in the water. This means that the water quality should be steady, and most of the time there is only little or no conditioning needed, which leads to ground water being the main source of water supply overall. Once contaminated, though, these characteristics imply the drawback of the ground water remaining polluted for a longer time.

In order to ensure a good quantitative status, the EU-WFD stipulates that ground water withdrawal has to be significantly lower than the renewal rate of the specific water body. Furthermore, the ground water level should not be subject to anthropogenic influences, and any other influxes, such as salt water, have to be prevented. Otherwise, the water body cannot be rated as "good".

As can be seen from Figure 1, the overall quantitative status in Germany is sufficient. Exceptions can be found in small areas where the ground water level has to be lowered for open-cast mining. Other areas with a possibly poor ground water quantity can be found near the sea because of salt-water influx.

The ground water quality looks different, though. The distinction between good and poor ground water quality depends on the chemical status, which is measured by several threshold values. While some values are set by the EU-WFD, others are set by the EU member states themselves. Whenever one of the values is exceeded, the water quality is rated as "poor". In 2010, 37% of the German ground water was categorized as having poor quality. Besides other agricultural pesticides, the main problem is contamination by nitrates. Nitrates can cause cyanosis; they are highly water soluble, and contaminated water is hard to treat. The location of the poor water quality areas is shown in Figure 1. Comparing these locations with the expected shale gas reservoirs reveals that some of the locations overlap. Especially in the areas of the northern fields, the ground water quality is already rated as poor. This could lead to concerns about how fracking might further increase pollution of local ground water bodies. The expected influences are discussed in section 2.3 below.

2.2.2 Surface water conditions

Surface water includes rivers, lakes, reservoirs, and more. Surface waters are rarely also influenced by ground waters, but most of the water is replenished by rainfall. Because surface waters are in a more exposed position than ground waters, they are also subject to more influences and, owing to the higher replenishment rate, conditions change faster than in ground waters. This can be positive, as surface waters can recover faster than ground waters, but are also more affected by pollution. Especially private and industrial waste waters are of a major concern. Rivers are frequently used as receiving waters, sometimes even without the waste waters having passed through a water treatment facility.

Nevertheless, as soon as the treatment facilities are overburdened, for example after heavy rainfalls, the waste waters are disposed of directly into the receiving waters. This leads to a lot of pollutants ending up in the latter. Other impairments, like elevated temperatures through the use as cooling water in power plants, come along and also have a negative influence on surface water quality. Stricter rules apply for dams and reservoirs, but as these are exposed to polluted rain, some water treatment is necessary before it can be used as drinking water.

The evaluation of surface waters considers the ecological and the chemical state of the water bodies. By measuring characteristics like temperature, morphology, oxygen and nutrient content, fish stock or heavy metals concentration, the quality of each water body is rated. The ecological state is categorized in five categories, from "very good" (1) to "bad" (5); in contrast, the chemical state is again only rated as "good" or "not good".

As soon as one value breaches the reference values, the water bodies cannot be categorized as "good" anymore. The EU-WFD requires all water bodies on the ecological side to be rated at least as "good" (2). Unfortunately, only 10% of the German surface waters achieved this rating in 2010, while 90% were rated either as "modest" (3) or as "worse" (4 & 5). In contrast, 88% of the water bodies have a good chemical condition. An interesting exception is the river Rhine. It is the most important commercial waterway in Germany, accommodates many industries, and is an important receiving water. Its chemical and ecological conditions are almost completely rated as "bad".

Just like the results for ground water bodies, the current surface water conditions render concerns about the worsening of the conditions through the influence of fracking – and especially fracking fluids – understandable. While water *quantity* does not seem to be of a major concern, we can conclude that water *quality* definitely should be.

2.3 Impact of fracking on water resources

Although the fracking technique is several decades old, because of high costs and a relatively small reach, there have only been a small number of fracks to date in Germany. They were mostly exploration and testing fracks. In the following, we explain the effects on water that derive from the experience gained from these projects. This and the following subsection are based on Meiners et al. (2012).

To reach the shale gas layers, there have to be drillings through many different layers of rock, ground water, and soil. These disturbances could alter or accelerate the interactions between the ground water and rock layers and may also have an influence on surface waters. The flow velocities between the different layers are relatively slow and depend on the permeability, pressure, and differences in potentials. But they are measurable and are crucial for the ecosystem belowground.

In summary, there are several possibilities how ground or surface waters can be polluted by fracking. On the surface, fracking fluids and flow-backs may penetrate the soil. Pollution of deeper layers along the borehole is also possible. Cracks appearing between the layers or the penetration of layers through diffusion are further possibilities of how chemicals may pollute ground water bodies. The different impact pathways also depend on the structure of the rock and soil layers. In what follows, we differentiate between the pollution of ground water bodies, caused by fracking fluids pressed into the borehole, and a pollution of surface waters through the disposal of returning fracking flow-backs.

2.3.1 Fracking fluids

The fracking fluids are a mixture of different chemicals that are composed individually for every borehole and the surrounding soil and rock. There are different fluids available, but in Germany, only water- or foam-based fluids have been used to date. Others are based on oil or hydrochloric acid. These fluids carry out multiple tasks, like transferring the pressure to the rocks, cracking them, and making the shale gas extraction possible. Proppants are included as well, such as quartz sand, to keep the cracks and paths open against the pressure of the downwards-pushing rock masses. There are also other additives, which are used to minimize the friction in the system or to prevent unwanted sedimentations, corrosion, microbiological growths, and the development of hydrogen sulfides. While the latter additives usually have only a share of 0.2–10% of the overall fluid mass, they are the most problematic part of the fluids. Proppants take up to 30% of the mass, and the largest component is water with up to 80% or more. The quantity of the additives used depends on the fracking fluid and the conditions of the particular shale gas layers; in a multi-frack, up to 20 t are possible, with about 460 kg of biocides, 12,000 m^3 of water, and 588 t of proppants. Biocides also count as an additive and are used to avoid biofilms and to reduce hydrogen sulfides.

Next to the risk of (micro-)earthquakes caused by the drillings, the pollution of the water bodies through these additives is the biggest concern. It is not completely documented as to what kind of fracking fluids have been used in Germany up to now, but it seems that most have been toxic, caustic, detrimental to health, and water-polluting. By analyzing the available data, Meiners et al. (2012) conclude that additives with “worrying characteristics” have been used in past frackings and that the used fluids bear “middle to high human- and ecotoxicologic risks” (see also Chapter C3.2.13, p.C48 of that report).

Even more worrying is the fact that only a small fraction of these additives can be found in the flow-back, as the majority remain belowground. Although it is likely that some of them start to degrade once the biocides lose their effect, the lack of reliable data to verify what exactly happens to these activities is nevertheless unsettling.

In the end, the possible contamination of the rock and soil layers and the water supply depends a lot on the local circumstances and whether or not the remaining fluids can seep into the ground water layers.

2.3.2 Flow-back

Generally speaking, the term flow-back refers to everything that comes up through the boreholes besides shale gas. More specifically, next to a fraction of the used fracking fluids, some formation water and several other substances can come back to the surface. Formation water is water that, like shale gas, has been pressed out of the pores of the rocks. Other substances might be just sand or clay from the rock layers or from the proppants, or millions of years' old bacteria, other organic materials, gas, or naturally occurring radioactive substances. This reflux is called flow-back, the mixing ratio varies and lasts through the entire frack but in general decreases over time.

At the beginning of the fracking process, up to 1 m^3 of flow-back per minute is possible and roughly 60% of the flow-back occurs during the first four days of the frack. The variation of flow-back volumes is pretty large, depending again on the external circumstances and fracking methods used. Over 60 days, it stretches from less than 100 m^3 to more than 3,000 m^3. A comparison between the injected fracking fluids and the returning flow-backs is difficult, because of the proportion of formation water.

As these flow-backs include unhealthy fracking fluids and other possible harmful contents, they have to be disposed of properly. After some treatment, such as the separation of solids, hydrogen sulfides, or mercury, they are often disposed of belowground. This still leaves up to 0.5 million m^3 a year for further treatment, but the operators do not consider it economically feasible, and the results would not meet the requirements of the German water supply legislations anyhow. To date, exhausted crude oil or natural gas reservoirs have been used to store the flow-backs, but resulting dangers for the water supply and the environment have barely been investigated and lack supervision.

2.4 Legal framework

In this section, we provide an overview of the authorities and legislations involved in Germany in shale gas extraction permits, water supply protection, and flow-back disposal. Before turning to the regulations concerning fracking fluids and flow-back disposal, we first give an outline of the general legislative and regulatory structure.

In Germany, fracking is not regulated by a dedicated Act, but through several different legislations. Because Germany has a federal structure, jurisdiction is split between state law and federal law. On top of that, guidelines by the European Union need to be considered as well. Because the procedure involves deep drilling and huge amounts of water, both water and mining legislations apply.

The requirements for water usage result from the European Water Framework Directive (EU-WFD), which is implemented into national jurisdiction by the Federal Water Resources Act, federal ground water regulations, and the different state laws for using water-polluting substances. For any water usage, permission has to be granted by the authorities, and any action that causes harmful changes to water conditions should be avoided to the extent possible. The waste water has to be disposed of without harming the general public and subject to generally accepted engineering standards. Quantity and noxiousness have to be minimized, and the disposal must be approved by the authorities.

German federal mining laws are again supported by state laws and cover the ownership, accessibility, search, and extraction of natural resources to secure the raw material supply and to evaluate their importance compared to other public benefits. Here, the European guidelines focus more on the environmental aspects of mining projects. If different natural resources overlap, it will be decided by the authority which one is to be prioritized.

Jurisdiction for the mining sector always lies with the individual state's mining authorities, which are subject either to the state ministries of the economy or departments of the environment. Matters related to water are more complicated, because in some states, the water authorities are organized as a part of the mining authority, whereas in others they are separated, and so the jurisdiction differs.

Depending on the size of the project, the general environmental impact may have to be additionally explored and approved. Furthermore, several other laws, such as the Chemicals Act, the Federal Nature Conservation Act, and the Waste Management Act, have to be taken into account as well.

Some of the mining legislations also require water-related permissions. Sometimes, these overlap, and since there is no delimitation law, both legislations remain valid and in force. As a result, the authorities responsible for the planning permissions have to grant two permissions separately: one for water-related legislations and the other one for the remaining mining operations. In some cases, these permissions also refer to each other. A new act aimed at somewhat unraveling the legislations concerning fracking, while setting higher requirements for obtaining authorization, and calming down the increasing concerns of the public, is in the process of being passed through the German Parliament[5].

[5]BMUB (2014); for further information see also the press release of the Ministry of the Economy and Energy (April 1, 2015): bmwi.de/DE/Presse/pressemitteilungen,did=699322.html; The Wall Street Journal (April 1, 2015): "German Cabinet Approves Anti-Fracking Draft Law" www.wsj.com/articles/german-cabinet-approves-anti-fracking-draft-law-1427896555; and "Shale gas in Germany – the current status (April 2015): www.shale-gas-information-platform.org/areas/the-debate/shale-gas-in-germany-the-current-status.html.

2.4.1 Regulation of fracking fluids

Withdrawal of surface and ground water has to be approved by the authorities, except when an old permission exists, or where small quantities for a temporary purpose are taken. Guidance on the quantities that should be considered as small, and what purposes can still be considered as temporary, is quite vague. Landmarks for quantities can be drawn from the Environmental Impact Assessment Act (UVPG), which states that a small withdrawal has to to be less than 100,000 m^3 per annum, in sensitive areas less than 5,000 m^3 annually. In any case, the particular state law and circumstances have to be considered. If the water withdrawal threatens the public water supply, permission has to be denied by the authorities. A deterioration of the quantitative or qualitative state of the water bodies has to be prevented as well.

The additives might be subject to the EU-REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) legislation and Germany's Chemicals Prohibition Act. This means that substances or mixtures that are to be used as an additive have to be checked as to whether there are any restrictions or prohibitions. Some substances can only be used after having been approved by the authorities, and all applications have to be reported. Also, mining and water laws have regulations for the usage of dangerous goods, the protection of the workforce, and the internal and external storage and transportation of fracking fluids.

Biocides are among the more noted groups of substances that fracking fluids contain. As of September 2013, these fall under the new European Biocidal Products Regulation and can only be used if approved by the German authority for safety at work or by a corresponding European authority.

2.4.2 Flow-back disposal

As explained in section 2.3 above, the flow-back contains parts of harmful additives and these are mostly disposed of belowground in old boreholes. Flow-back can be classified as waste water or just as waste. When classified as waste, it has to be treated according to the mining laws – unless it is left to a third party who is not subject to the mining authorities. In this case, the flow-back falls under standard waste legislation. Transportation of the flow-back by road to a waste disposal facility would be such a case.

Any discharge into a water body or a waste water treatment facility must be classified as waste water, and the treatment falls under standard federal water resources legislation. Even if no additives were used for fracking, because of the formation water that mixes with the fracking fluids and returns with the flow-back, it has to be classified as waste water. This implies that the flow-back disposal and storage of flow-back in old boreholes is regulated by water resources legislation. It also seems to be the most practical way, but some requirements still need to be met. The quantity and harmfulness of the flow-backs need to be as small as possible when using state-of-the-art extraction techniques, and no lasting ground water pollution may be expected. Finally, the disposer must not be obliged to hand the waste water over to the municipal waste water treatment facilities.

In general, all waste waters do have to be handed over to waste water treatment facilities maintained by the municipalities. Exceptions are waste waters that are excluded by the facilities themselves or a special case of authorization by the state that the flow-back does not have to be handed over. These facilities are generally well suited to treat the flow-back, and an authorization could be refused if a proper flow-back treatment could only be ensured in this way. A direct disposal into surface or ground water can only be permitted under stricter requirements. So, depending on how the flow-back should be discharged, different legislations apply, and this also has an influence on how high the requirements are. Additionally, all possible radioactive parts, which are mostly filtered out of the flow-back through sieving, fall under the Radiation Protection Act.

Due to this mix of regulations and jurisdiction, loopholes seem likely, and thus simplifying the fracking fluids and flow-back regulations could be helpful in avoiding these.

2.4.3 Water protection areas

Water protection areas are subject to particularly stringent regulation. In general, there are three protection zones, ranging from Zone I, which is the most strictly regulated zone, to Zone III, which has the largest expansion around the well or any other water body that needs protection. Jurisdiction is in the hands of the local water authority, which can grant special authorizations for protected areas or can set higher requirements than the usual conditions. Although drilling is permitted in Zone III, each individual drill has to be granted by the authorities. This also includes drills that reach only vertically into the protected area. In Zones I and II, there are any facilities that treat water-polluting substances are prohibited, whereas for Zone III, special permission by the authorities is needed to establish such a facility. In all three zones, it is prohibited to discharge any substance that is harmful to water. So flow-back cannot be disposed of underground, in ground waters, or in surface waters located in a protected area. Finally, if fracking fluids are categorized as harmful, fracking in a water protection area requires a special permit.

3 Welfare analysis

3.1 Model specification

In our study, we focus on shale gas extraction and the external effects on water resources. As described in section 2.3, to extract shale gas, water is mixed with fracking fluids before it is pressed into the borehole. After this procedure, the water in the flow-back is polluted and has to be treated. Assuming that the shale gas producer takes the water from belowground, adds fracking fluids, and discharges the water afterwards without having to pay for the negative production externalities, every unit of extracted shale gas causes a certain amount of social cost of pollution. The waste water has to be treated and stored or disposed of afterwards, because if the polluted water were to enter the water cycle, humans and nature would be endangered. But water treatment incurs costs. Hence, we want to develop an economic model that represents these processes of shale gas extraction and water purification. Of course, compared to reality, our model is a gross simplification, but as our goal is to show the general connections of the main factors and not to reflect reality entirely, it will suffice our research goal.

First, we lay down the framework of our model. We consider a free market, with the gas supplier (a monopolist) and an infinite number of buyers. There is only one production output: the amount of extracted shale gas. Actors are assumed to always act strategically and economically rationally maximizing their own benefit. The monopolist maximizes profit, which means in our model revenue minus aggregated costs. The shale gas producer disposes of the waste waters by leaving them for the public waste water treatment facilities, thus ignoring the purification costs.

These external costs for the waste water treatment then have to be borne by the general public. The monopolist only considers the shale gas demand and his own extraction costs when calculating profits.

Next, we consider water and shale gas as private goods. When the available amount of water or shale gas is finite, then the polluting of water resources and the producing of shale gas reduces their availability, because they cannot be used by someone else in the same manner anymore. Also, if there is a price for both, an exclusion is possible. This means that both characteristics for the definition of a private good, i.e. rivalry and excludability, apply.

Basically, we see our market as a Cournot monopoly, and a single-staged static game, where all parties make their decision about the supplied or demanded shale gas amount simultaneously. The market price for shale gas then adjusts endogenously through the aggregated demand, while all other values, including the prices for water and water purification, are considered to be exogenous constants.

The model also assumes perfect information, i.e. all participants have perfect knowledge of prices, costs, quality, and quantity. There are no transaction costs or any entry or exit barrier costs. Finally, to avoid any mathematical inconveniences, we presume that any constants or values are greater than zero.

So, in general we need an equation for the monopolist's extraction costs, one that describes the external effects occurring while extracting shale gas, and one for the shale gas demand of consumers. To achieve a solution that optimizes social welfare, the purification costs then have to be somehow internalized, but first we need to specify the economic functions:

- **Extraction costs** $C_E(x)$. For the gas supplier, we include fixed costs f_c [€] and variable costs; the latter are directly correlated to the extracted amount of shale gas, while fixed costs are independent and are assumed to remain constant no matter how much gas is extracted. In reality, fixed costs might be drilling permissions or exploration costs, whereas variable costs could be manpower or the required fracking fluids. The distinction can sometimes be blurred, so in our model the variable costs only represent costs for the water required for shale gas extraction. All other costs are considered as fixed costs, f_c, i.e.

$$C_E(x) = f_c + p_w \cdot q \cdot x, \tag{1}$$

  where p_w [€$/m^3$ $water$] the exogenous price of water, q [m^3 $water/m^3$ $shalegas$] is the quantity of water needed for one unit of extracted shale gas, and x [m^3 $shalegas$] the amount of shale gas extracted. Note that q can also be interpreted as a description of the efficiency of the shale gas extraction technique. As shown above, this depends both on external circumstances, for example the nature of the rock layers, and on the techniques used to extract shale gas. So a lower q implies a higher water efficiency, less fracking fluid needed, and thus lower extraction costs accruing. We refer to q as the technology and environmental coefficient (TEC) and, when it is multiplied by the amount of extracted shale gas x, we obtain the total quantity of water used. The dependencies of the other constants and the variable extraction quantities x on the extraction costs are observable, too. With higher fixed costs or a higher price of water, the extraction cost would rise. These values are positively correlated with the extraction costs.

- **Water purification costs** $C_P(x)$. These naturally correlate with the amount of shale gas extracted. The more water is needed, the more fracking fluids are needed, and so the purification costs increase. Again, to obtain the total amount of water used, we need to multiply the TEC by x. Regarding the treatment facilities, we assume that waste water treatment plants already exist, so there are no costs for building new ones. They are also assumed to be suited to treating fracking flow-back waste waters without any technical upgrades, their capacity is unlimited, and transportation costs do not accrue either. So we make sure that the external costs in our model depend only on the exogenous purification costs of water p_p

[€/m^3 *wastewater*] and the amount that needs to be treated:

$$C_P(x) = p_p \cdot q \cdot x. \tag{2}$$

The dependencies are, as with the extraction costs, positively correlated. With rising purification prices or a higher TEC and/or a higher amount of extracted shale gas, the costs will also rise.

- **Demand for natural gas** $D(p)$. This model equation represents the consumer side; demand depends on the market price for shale gas p [€/m^3 *shalegas*]. Its inverse function $p(x)$ describes the market price that sets according to the extracted shale gas amount x by the supply, i.e.

$$D(p) = x = \frac{1}{m}[Q - p(x)] \Longleftrightarrow p(x) = Q - m \cdot x. \tag{3}$$

Both equations have a negative slope, because with every marginal value of the demand that is met, it has to get smaller (the more shale gas is extracted, the lower the price). The sensitivity (and thus the slope) by which the price responses on changing extraction amounts is shown by the parameter m [(€/m^3)/m^3]; the reciprocal value also represents the slope of the demand curve. Then Q [€/m^3] is the maximum price that the consumers are willing to pay if the extraction amount is approaching zero (choke price). At that price, the sales would be zero (for $p(x) = Q \Rightarrow x = 0$). This time, the dependency of the extracted shale gas amount has a negative correlation, while the maximum price that consumers are willing to pay has a positive correlation. With a drop in the amount of shale gas extracted, x, or a drop in m, the price of shale gas can be expected to rise.

3.2 Unregulated market

3.2.1 Profit maximization

Now that we have a framework to work with, we can develop the model further. The first step is to illustrate how the participants of our market would behave in an unregulated market. For the monopolist, this means that he wants to maximize his benefit, which is in our case just his profit. It results from his revenues, computed as extraction quantities multiplied by the market price for shale gas minus extraction costs (eq. (1)):

$$\Pi = x \cdot p(x) - C_E(x). \tag{4}$$

Note that at this point, the producer does not have to deal with any purification costs because these accrue to the public as negative production externalities. To compute his profit, the monopolist needs to know his profit-maximizing extraction output and, since the price adjusts depending on the output level, he does not know the profit-maximizing price yet. However, he does know the inverse demand function (eq. (3)), which calculates the price. He can use this equation, plug it in the profit equation, and then compute the maximizing amount, i.e.

$$\Pi = x \cdot (Q - m \cdot x) - C_E \rightarrow max : \frac{\delta \Pi}{\delta x} \stackrel{!}{=} 0, \tag{5}$$

which gives:

$$Q - 2m \cdot x - p_w \cdot q = 0, \tag{6}$$

and then after solving it we can compute the monopolist's profit-maximizing production output as:

$$x^{M*} = \frac{1}{2} \cdot \frac{1}{m}(Q - p_w \cdot q). \tag{7}$$

In our model, by providing exactly this amount, the monopolist will always maximize his profit. Another interesting observation might be the missing fixed costs, f_c, in both equations. This means that although they affect the profit, the extraction amount and the adjusting market price for shale gas remain untouched, increasing or decreasing the fixed costs.

Next, we can read off the correlations between the constants and the extraction amount. While rising costs ($p_w \uparrow$ and/or $q \uparrow$) lead to a smaller extraction amount, an increased maximum price that demanders are ready to pay (Q) or a higher price sensitivity (m) cause a higher amount. Compared to reality, this makes sense, as higher production costs will commonly lead to a smaller production output.

Having determined the output, the monopolist has to set his profit-optimizing price at which he will provide the shale gas. As he has no competitors, he has to consider only the demand function and his extraction amount. So he includes the optimal output (x^{M*}) in our inverse demand function $p(x)$ and calculates the price as:

$$p^{M*} = \frac{1}{2}(Q + p_w \cdot q). \tag{8}$$

This time, we see that raising both the choke price (Q) and the costs would lead to an increasing price ($Q \uparrow, p_w \uparrow, q \uparrow \Longrightarrow p(x) \uparrow$). This results from the producer allocating his production costs to the buyer. Also, the willingness to pay higher prices encourages the producer to charge higher prices. Including these two profit-optimizing values (p^{M*} and x^{M*}) in the original profit function (eq. (4)) calculates the maximum achievable profit Π^{M*}. Notice that this does not necessarily mean that the profit is always below or equal to zero. Because of the costs, especially the fixed costs, which are not reflected in the optimizing amount or price, it is possible that the highest reachable profit might still be negative. In that case, the monopolist would compare the negative profit to his reservation benefit (RB), which in our case would be zero.

The reservation benefit is defined as the monopolist's benefit (profit) if he chooses not to supply any shale gas at all. There are two possible consequences. When the fixed costs (f_c) are thought of as costs that occur only when the producer decides to supply, then the reservation benefit for zero production is zero as well ($RB = 0$).

The other possibility would be that fixed costs occur independently from the supplier's decision to provide shale gas or not. He would have to bear the fixed costs anyway. Then, the reservation benefit would be the negative value of the fixed costs ($RB = -f_c$) because he would make a loss if choosing not to supply any shale gas. In other words, this would lower the reference value for his decision to enter the market. In our model, though, we assume that if the monopolist does not supply, he has no costs to bear, and the reservation benefit is zero.

However, our focus is on optimizing the overall welfare and not so much on the supplier's profit maximization. But to make a comparison and to see how the welfare in this case compares to the maximized welfare, we need to calculate it first under these conditions. For social welfare considerations, the problem is that only extraction costs are considered by the monopolist, while purification costs remain to be borne by the public and thus also have a (negative) effect on social welfare.

Generally speaking, to determine the social welfare, we need to add up the consumer surplus (CS) and the producer surplus (PS). The consumer surplus describes the benefit of the demanders, whereas the producer surplus displays the benefit of the shale gas supplier. The producer surplus includes already the extraction costs, because in our model, the monopolist's profit is the same as the producer surplus:

$$PS = \Pi = x \cdot p - C_E(x). \tag{9}$$

Due to the design of our model, and specifically the linear inverse demand function, the consumer surplus resembles the area of a triangle. It is half the difference between the choke price (Q) and the actual market price multiplied by the extraction amount:

$$CS = \frac{1}{2}x(Q - p). \tag{10}$$

Welfare is defined as the sum of consumer and producer surplus, but as can be seen, we have not considered the purification costs yet and we know that they reduce welfare, so we need to subtract them accordingly:

$$W = CS + PS - C_P(x). \tag{11}$$

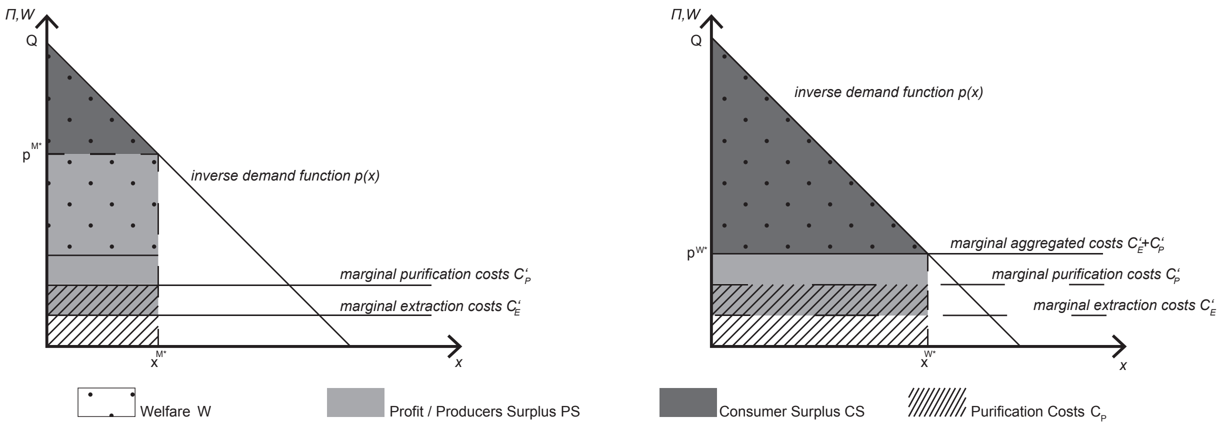

Figure 2: Welfare, consumer surplus, producer surplus, price and extraction quantity for the profit-maximization (left plot) and for the welfare-maximization (right plot) in a Cournot monopoly

Figure 2 shows a graphical representation describing the welfare and helps to clarify the structures. We have pictured the marginal extraction and purification costs, $C_E'(x)$ and $C_P'(x)$, the inverse demand function $p(x)$, and the profit-maximizing price and quantity. The function of the consumer surplus resembles the space of the triangle above the price, p^{M*}. It adjusts according to the extraction quantity chosen by the monopolist, and below the inverse demand function $p(x)$. The producer surplus is the space of the rectangle formed by the extraction amount x^{M*} and the price p^{M*} minus the extraction costs $C_E(x)$. They are displayed by the rectangle beneath the marginal extraction costs line and left of the profit-maximizing amount x^{M*}. Then, as explained before, to compute the social welfare, we also have to subtract the purification costs $C_P(x)$, which are computed analogously to the extraction costs.

From the welfare specification, we get the same equation as we would have had if we included the discussed functions (eqs. (9) and (10) in eq. (11)):

$$W = \frac{1}{2}x(Q - p) + x \cdot p - C_E(x) - C_P(x). \tag{12}$$

3.2.2 Welfare maximization

The next step is to calculate the welfare-optimizing amount instead of the profit-maximizing amount that the monopolist would choose. After calculating it, we can derive the corresponding market price, as we did in the previous section 3.2.1.

Considering the graphical approach from Figure 2 (left plot), we can see that the social welfare can also be determined by computing the area beneath the inverse demand function and above the aggregated marginal cost functions. Mathematically speaking, the area beneath a curve is the integral of the corresponding function, so the welfare can be described as:

$$W = \int p(x)dx - C_E(x) - C_P(x). \tag{13}$$

In contrast to the profit-maximizing approach, the upside of this approach is having the purification costs already included from the beginning. This way, we make sure that we will not end up with an inefficient extraction amount. Including the inverse demand function and both cost functions ($C_E(x)$, $C_P(x)$) in the equation, calculating the integral and solving the result, yields the following welfare function:

$$W = Q \cdot x - \frac{1}{2} \cdot m \cdot x^2 - q \cdot p_w \cdot x - q \cdot p_p \cdot x. \tag{14}$$

For determining the welfare-optimizing amount we need to differentiate the welfare equation over x:

$$\frac{\delta W}{\delta x} = Q - m \cdot x - q \cdot p_w - q \cdot p_p \stackrel{!}{=} 0. \tag{15}$$

Solving this equation for x yields the welfare-maximizing quantity:

$$x^{W*} = \frac{1}{m}[Q - (p_w + p_p) \cdot q]. \tag{16}$$

As we can see, the price for water treatment p_p, and thus the marginal purification costs $(p_p \cdot q)$, are considered now, while the general structure remains very similar to the profit-maximizing quantity from the previous section. The correlation also remains the same; only the aggregated cost value is increased because of the included marginal purification costs.

Next, by including the amount again in our inverse demand function, we derive the corresponding price:

$$p^{W*} = p_w \cdot q + p_p \cdot q. \tag{17}$$

This equation shows the welfare-optimizing price equal to the marginal aggregated costs $(\frac{\delta(C_E+C_P)}{\delta x} = p_w \cdot q + p_p \cdot q)$. Note that this is a nice shortcut, because it means every time we want to define our welfare-maximizing amount, we can just set the price equal to the aggregated marginal costs $(p^{M*} = \frac{\delta \sum C_i}{\delta x})$. By using these two welfare-maximizing values, we can compute the maximum welfare. Again, fixed costs have no effect on the amount extracted or the market price.

Inspection of Figure 2 (right plot) confirms that the aggregated marginal costs and price are equal in an optimized welfare case. The consumer surplus is again represented by the triangle between the inverse demand function and the welfare-maximizing price p^{W*}. However, this time, the area of the producer surplus is equal to the area of the purification costs. Producer surplus is drawn as the rectangle that results from multiplying the welfare-maximizing price p^{W*} by the quantity x^{W*}, and the purification costs are again

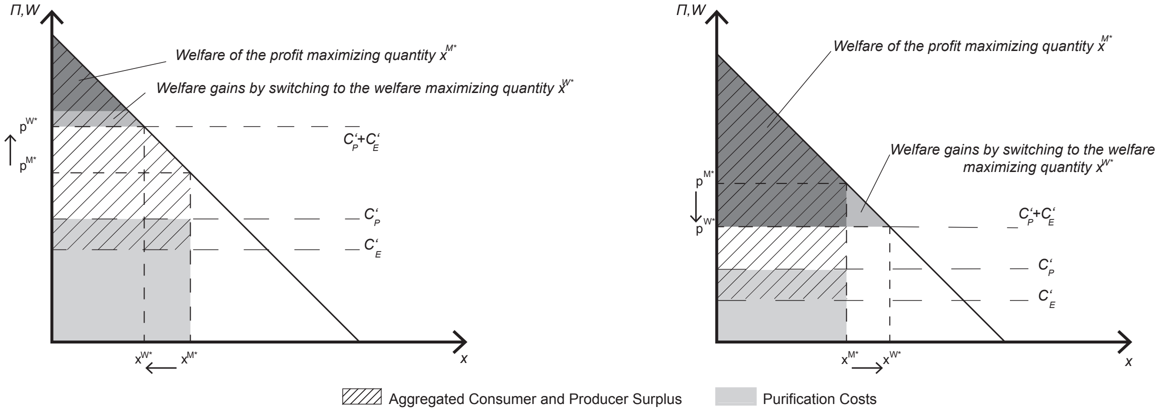

Figure 3: Comparison welfare- and profit-maximizing shale gas production: The monopolist may extract more (left plot, Scenario A) or less (right plot, Scenario B) than the welfare-maximizing amount of shale gas

the rectangle beneath the marginal purification cost curve $C'_P(x)$ and are limited by the extraction amount.

In other words, the monopolist's profit, i.e. again, revenue minus extraction costs, is canceled out by the purification costs, leaving the welfare equal to the consumer surplus. Still, in every case this is the highest achievable social welfare. The amount extracted and the price that leads to this welfare is the benchmark at which we want the monopolist to provide his extracted shale gas.

3.2.3 Comparison of results

So far, we have derived two different amounts: one amount that tells the monopolist how much shale gas extraction would maximize his profit, and then another one that tells us what the proper amount for a maximized welfare would be. In the following, our goal is to incentivize the monopolist somehow to choose the welfare-maximizing amount instead of his profit-maximizing one, meaning that both amounts are equal. But before that, we want to compare the two amounts with each other.

There are two possible scenarios as to how the two amounts relate to each other – excluding the situation where they equal each other. The first one, Scenario A, has the welfare-optimal extraction quantity, x^{W*} (which is lower than the profit-maximizing quantity, x^{M*}) It is shown in Figure 3 (left plot), where we see the two states resulting from these amounts compared to each other. The maximized welfare is displayed as the light grey triangle above the aggregated marginal costs, and the welfare resulting from the profit-maximizing amounts is displayed as the darker grey triangle. The latter is smaller than the maximized welfare and covers the upper part of the maximized welfare up, so we only see the small stripe that resembles the welfare gains resulting from switching to the welfare-maximizing amount.

The triangle that represents the welfare from the profit-maximizing amount results from subtracting the rectangle of the purification costs from the added up consumer and producers surplus, shown by the dashed area.

As in this scenario, the welfare-optimizing quantity, x^{W*}, is smaller than the amount the monopolist would choose by himself to maximize his profit, x^{M*}. Thus the regulator has to increase the monopolist's costs somehow, up to the point that the monopolist will decrease his extraction amount down to the point where it is equal to the welfare-maximizing amount. As a consequence, *cet. par.*, the market price for shale gas will rise.

In Scenario B, it is the other way around. Because there is no competition in this market, the monopolist might choose an extraction amount that is lower than needed for a maximized welfare. Thus, the regulator might want to encourage the shale gas extractor somehow to supply more shale gas than his profit maximizing amount until it reaches the welfare maximizing amount.

As we can see in Figure 3 (right plot), the welfare gains still exist, even if the difference between the two quantities ($x^{W*} - x^{M*}$) now has another sign compared to Scenario A. This means that as long as the monopolist does not extract the welfare-maximizing amount, there will always be a loss in social welfare, irrespective of whether he extracts too much or not enough shale gas.

Starting with the profit-maximizing amount from Scenario B, an increasing output ($x \uparrow$) would result in an increasing welfare. But as soon as the output exceeds the welfare-maximizing amount, the influence of the also increasing purification costs would kick in and start decreasing welfare again.

Exactly how the two amounts relate to each other is always dependent on the exogenous circumstance and cannot be determined before the inclusion of some values in the equations. Because of this, our aim was to show that irrespective of how the two amounts compare to each other, the welfare-maximizing quantity does just this: it maximizes welfare under all conditions.

3.2.4 Second-best solution

Before we finally get into internalizing the external effects caused by water pollution, for the sake of completeness, we first want to discuss a special case that might raise a problem. From the viewpoint of welfare maximization, we want the monopolist to extract the welfare-maximizing quantity, so this amount would be our first choice. But as we have discussed previously, the shale gas operator will refuse to extract and supply shale gas when he expects to realize a loss through his business. When we consider the possibility that the welfare-maximizing amount might lead to a negative profit, the optimal welfare cannot be reached. To ensure the desired shale gas supply in this case, we would have to maximize the welfare function

$$W = \frac{1}{2}x(Q - p) + x \cdot p - C_E - C_P \tag{18}$$

under the side condition that the profit would be at least zero:

$$\Pi = x \cdot p(x) - C_E \overset{!}{=} 0. \tag{19}$$

The resulting extraction quantity is called second-best quantity because, although it does not maximize welfare, it ensures the highest welfare possible subject to the constraint that the monopolist does not make a loss. As this is only an addition to our main objective, we will only describe this approach roughly.

In a monopoly, the second-best quantity always results from equating the inverse demand function, which sets the price, and the average costs of the supplier. In our case, the average costs ($\overline{C}$) are the extraction costs divided by the extracted quantity:

$$\overline{C} = \frac{C_E}{x} = \frac{q \cdot p_w \cdot x + f_c}{x}. \tag{20}$$

When equating the average costs with the inverse demand function, which determines the price (eq. (3)), and solving it, we get our second-best extraction quantity:

$$x_{1,2} = -\frac{1}{2} \cdot \frac{q \cdot p_w - Q}{m} \pm \sqrt{(\frac{1}{2} \cdot \frac{q \cdot p_w - Q}{m})^2 - f_c}. \tag{21}$$

As can be seen in Figure 4, there are two quantities that fulfill this condition. Because the average cost function is convex and intersects the inverse demand function twice, there are two possible candidates for second-best welfare amounts. Which one really maximizes social welfare depends on the exogenous variable. However, in all cases the resulting welfare will be smaller than the maximized welfare from the first-best approach and higher than the welfare resulting from the monopolist's decision to maximize his profit.

3.3 Internalizing the external effects

Now that we have seen how negative external effects create inefficient outputs, we have to think about internalizing them. The general thought is to force the shale gas operator to produce less or more shale gas than his profit-optimizing intentions demand that he does. We are going to discuss two different approaches on internalizing these external effects.

The first approach is a very direct and static way. The regulator obliges the shale gas extractor through regulation regarding how much shale gas he has to extract, and any

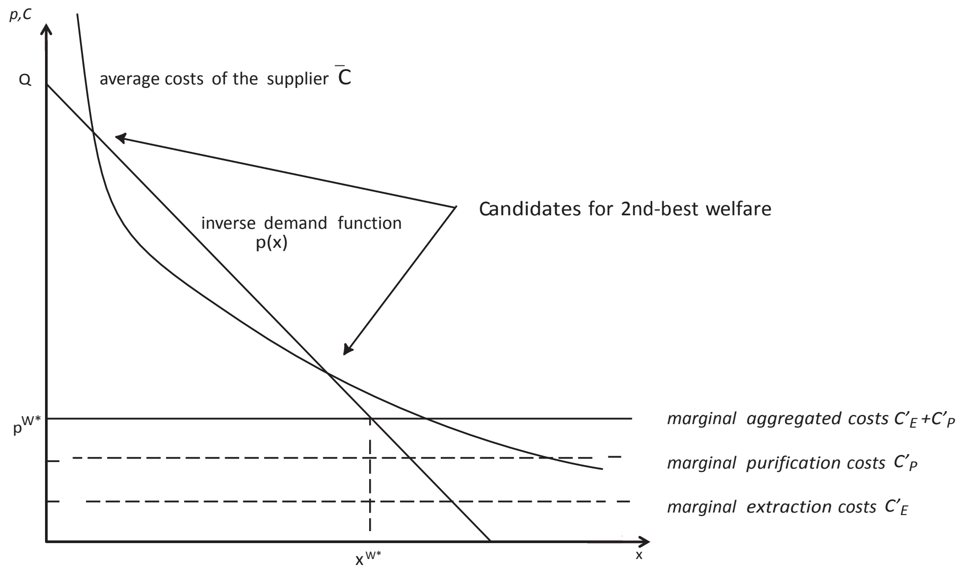

Figure 4: Determination of the extraction quantities that lead to a second-best welfare level

violation will result in a fine. For a strictly ecologically-thinking regulator, this is the way to go, as the amount of pollution permitted can be exactly defined and the incentive to violate the extraction limits decreases the higher the penalty is set.

The second approach is more market-based and sets a monetary incentive through a tax or a subsidy on shale gas. By increasing (tax) or decreasing (subsidy) the shale gas producer's costs to the point where his profit-optimizing extraction amounts are equal to the welfare-optimizing amounts, the regulator tries to reach the welfare optimum. Another option could be to tax the water, because it is needed for shale gas extraction. We will show that through our assumed cost structure, this solution would be very similar to a tax on shale gas but has other disadvantages.

Obviously, both approaches have their up- and downsides, and while we compare them we try to explain them and investigate possible implications when implementing these instruments in reality.

3.3.1 Implementing standards

In general, there are two ways to implement a standard. The first one is that the regulator defines a certain amount of pollutant that a producer is allowed to emit. The second possibility is to conduct an upper limit for the emissions into a medium. Both have a standard value in common and the difference is just to what it applies, and where the damage is measured.

- **Emission command-and-control.** The first method, controlling the emissions of the producer on the source, would need the authorities to control the outlet where the producer's waste, waste water, or exhaust air escapes. If he violates the emission standard, he would have to pay a fine that depends on how much he exceeded the standard. When there is more than one producer, each one of them would have to be monitored, which implies that the effort increases when the number of suppliers in the market increases. In our shale gas extraction model, the regulator first had to set the amount of shale gas that each supplier is allowed to extract, because that sets the amount of waste water that he would dispose of. This should be the welfare-maximizing quantity. The next step would be to implement an effective control system, in order to see if they extract the right amount, and to choose a sufficiently high fine that prevents a producer from violating the standard.
- **Emission standard.** The second method would be an emission standard. This means limiting the concentration of damaging substances in a medium like air or water. Generally speaking, monitoring just the polluted medium, in our case the surface and ground waters, if any boundary values are exceeded, promises less effort than controlling all producers all the time. With an increasing number of suppliers though, the trade-off would be reducing the effort of monitoring all possible sources of pollution to open up opportunities for slipping through the controls. In our case, there is just one source of pollution (the monopolist), but in reality there might be more. As the authority only measures the environmental pollution data, if an actual violation were to be discovered, it would be difficult to allocate who exactly had caused the exceeded amounts. Aside from monitoring the emissions, also spot tests would be necessary, but the risk of being caught while exceeding the allowed amounts would remain smaller than in the first approach. From a legal perspective, this is problematic as well. When we consider constitutional states with more than one possible source of pollution, where anyone has to be proven guilty before being punished, and punishment of potential offenders - without being able to prove it - is unlawful, we have to assume that a producer might get away with exceeding the limits.

In reality, there might be more than just one location in Germany where shale gas will be extracted. But as fracking has already received a lot public of attention, the authorities might take controls very seriously. Hence, trying to dispose of fracking flow-back covertly might be risky. But then again, surveillance of emissions in surface waters is easy, but in ground waters much harder, so that the costs of monitoring them have also to be considered. Additionally, the problem arises of how to prove who has caused the damage, especially if the used waste waters contain chemicals with more areas of application than

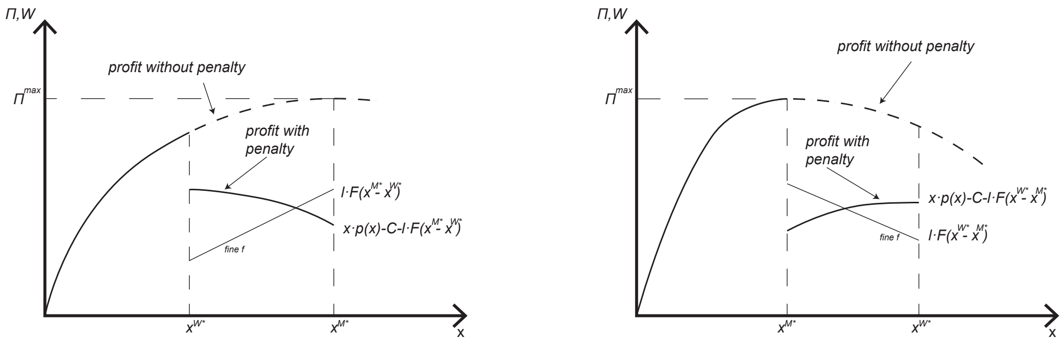

Figure 5: Profit function and function of the fine with standards when (a) the monopolist extracts too much shale gas (left plot) and (b) not enough shale gas (right plot) compared to the welfare-optimizing amount

just shale gas extraction.

In the end, humans and the environment are affected by the actual amount of dangerous goods they are exposed to, so the second method of measuring the emissions seems more effective. As fracking fluids have to be considered detrimental to both human health and nature, setting a limit can definitely prevent damage. But for pollution through fracking fluids, the approach to monitor either one, emissions or emissions, will not be sufficient, as we also have to identify the polluter. In terms of ecological thinking or focusing on public health, only the combination of both measurements will lead to a very high safety level. Of course, only if the limits are chosen well and all participants keep them, can a high safety level be ensured. To allocate the pollution to the true polluter, the amount of pollution that each shale gas extraction emits has to be monitored.

Returning now to our model, this means that the regulator has to set a certain amount of extracted shale gas as a benchmark. As we want to force the supplier to produce the welfare-maximizing amount, this has to be the target value. The monopolist is still only maximizing his own profit and would chose his output accordingly. As noted before, there are two possibilities: The profit-maximizing quantity will either be higher or lower than the welfare-maximizing quantity.

First, we look at the scenario where the monopolist's extracted amount is too high (Scenario A in section 3.2.3 and Figure 5, left plot). With implemented standards and a fine for deviations from the mandatory amount, the monopolist's profit function is:

$$\Pi \begin{cases} x \cdot p(x) - C_E & for \quad x = x^{W*} \\ x_i \cdot p(x) - C_E - l \cdot F(x - x^{W*}) & for \quad x > x^{W*}. \end{cases} \tag{22}$$

The lower part of the equation expresses the costs of deviating from the welfare-optimizing amount, x^{W*}. As long as the actually extracted quantity is higher than the welfare-optimizing amount, the penalty kicks in, and the monopolist has to pay a fine F. The fine gets smaller by reducing his production and approaching x^{W*}. The parameter l is the probability of being caught, defined as $0 \leq l \leq 1$.

We assume that the chances of discovering a violation, on the one hand, depend on the number of checks that the authorities execute and, on the other hand, on the amount by which the monopolist deviates from the target value. The higher the difference between the actually produced quantity, x, and the welfare-maximizing quantity, x^{W*}, the more likely the violation will be discovered and result in a fine.

In reality, where it is almost impossible to monitor all possible sources at all times, a low chance of discovering a violation can be compensated by the fine. We define the fine as a linear function: $F(\triangle x) = \triangle x \cdot f \cdot l$. Considering a constant deviation, the fine rises with either an increasing l or an increasing fine rate f, because both are multiplied by the difference between the actual extraction and the target value, expressed as: $\triangle x = x - x^{W*}$. This means that as long as the fine rate is high enough, a low detection rate can be compensated or even neglected. The costs for supervision also have to be considered when setting the fine rate.

As shown in Figure 5 (left plot), applying a penalty on violating the allowed extraction quantities reduces the profit instantly. The monopolist can only gain the maximized profit without the fine, and he will not extract less shale gas than the welfare-maximizing quantity, because this would also reduce his profits. As all costs for the monopolist resulting from the fine are paid to the public, this solution has no effect on the optimal social welfare level.

Scenario B implies that the monopolist has to extract more shale gas than his profit-maximizing amount to achieve an optimized social welfare level. This might happen because the monopolist uses his market power, resulting from a lack of competition, to keep the price for shale gas up. The procedure of fining him is similar, though. As long as the monopolist does not extract the mandatory amount, he has to pay a fine and will not exceed the welfare-maximizing quantity, because that also means a negative impact on his profit.

This can be seen in Figure 5 (right plot) and also in the profit function, which looks only slightly different. This time, the difference between the actually extracted quantity and the target value is computed as $\triangle x = (x^{W*} - x)$, and the resulting profit equation is:

$$\Pi \begin{cases} x \cdot p(x) - C_E & for \quad x = x^{W*} \\ x_i \cdot p(x) - C_E - l \cdot F(x^{W*} - x) & for \quad x < x^{W*}. \end{cases} \tag{23}$$

Of course, if the main policy goal is trying to contain the damage caused by shale gas extraction, it seems a little weird to force the monopolist to increase his production. But this has to be seen as welfare-maximizing behavior and thereby it is possible that there is not enough shale gas extraction.

The problem with implementing emission standards in reality is that a lot of information is needed to achieve an optimized level of welfare. When there is more than one supplier, with different cost structures for shale gas extraction, the result would be different extraction quantities. While we know in our model the exact welfare-optimizing quantities and can set them as a boundary value, in reality knowing every single cost function of each participant and the demand function is very unlikely, or even impossible.

To protect humans and the environment from harmful fracking fluids and flow-back, while accepting that, because of a paucity of information, an optimized welfare is not achievable, setting a standard on emissions might be useful. This explains why this approach is very widespread in reality and especially in water legislation. Although it secures the quality of water very well, from an economic point of view there might still be potential for further improvement.

3.3.2 Pigouvian tax on shale gas

Another instrument to internalize external costs that we want to discuss is the implementation of a Pigouvian tax on each unit of produced shale gas. The tax would be levied as soon as someone started supplying the market with shale gas, so there would be no "unpunished" shale gas extraction, unlike in the approach presented in the previous subsection. The intention is again to push the monopolist to extract the welfare-optimizing quantity instead of the one that maximizes his own profit when there is no tax.

Because we consider again two scenarios with our model, where the monopolist either extracts too much or extracts insufficient shale gas, this tax can also be interpreted as a subsidy. We will see at the end that the calculation is, in both cases, the same and that only the interpretation and the sign of the result differ.

First, we want to look at the situation with the monopolist extracting too much shale gas, compared to the welfare-maximizing extraction amount (Scenario A). When the regulator or the authorities decide to impose a tax, the market participants will anticipate this and try to maximize their own profit given the included tax burden. As we do not know the value of the tax rate at this point, we determine our tax burden as:

$$T(x) = t \cdot x \tag{24}$$

In other words, to keep it simple, we calculate the tax just by multiplying the amount of shale gas produced, x, by the actual tax rate t.

Another idea could be to impose a tax on water, because this is the medium we actually want to protect from too much pollution. The tax then would be $T(x) = t \cdot q \cdot x$, so only extended by the TEC. But as water is also used by participants who do not extract shale gas, a tax on water would allocate the external costs of shale gas extraction to them also. Yet this is exactly what we want to avoid, because when internalizing the external effects, it should only be on the actual polluter.

Back to the tax on shale gas: the general idea is to increase the shale gas extraction costs further, the higher the output is. With the tax considered, the new profit function would be determined by the monopolist as

$$\Pi^T = x \cdot p(x) - C_E(x) - T(x). \tag{25}$$

With the profit equation determined, the monopolist now wants to know the extraction amount that would maximize this profit. We see that the costs increase by about the value of the tax burden. A negative tax rate would increase the profit, and this means that this is a subsidy, because the authority would pay money to the monopolist instead of receiving it from him. But we will come back to this interpretation later on.

Now, the monopolist does exactly the same as he did in section 3.2.1. To calculate his maximized profit, after differentiating the profit function over x, equating it to zero ($\frac{\delta \Pi^T}{\delta x} \overset{!}{=} 0$), and solving the resulting equation to x, he determines the profit-maximizing extraction quantity. Note that the tax rate is also considered in the following equation:

$$x^{T*} = \frac{1}{2} \cdot \frac{1}{m}(Q - p_w \cdot q - t). \tag{26}$$

Recalling the profit-maximizing extraction quantity in the absence of regulation (eq. (7)), we see that when the tax rate is zero ($t = 0$), those two equations are the same. As the monopolist considers for his profit the expected (marginal) costs, it is obvious that additional costs would also be reflected in his profit-maximizing extraction quantity. So the only difference is the tax rate and, as with any other cost burden, an increase decreases the output ($t \uparrow \Rightarrow x \downarrow$).

Now we have again two amounts, the welfare-maximizing quantity x^{W*} as our benchmark, and the profit-maximizing one – with considered tax rate – as a starting point. Because we still want the monopolist to extract the welfare-maximizing amount, we have to set the tax rate exactly the same as the difference between those two amounts in order to push him there. So, to compute the tax rate, we simply have to equate:

$$x^{W*} = x^{T*}. \tag{27}$$

We want to find their intersection point and get to it by solving it with respect to t:

$$t = q(p_w + 2p_p) - Q. \tag{28}$$

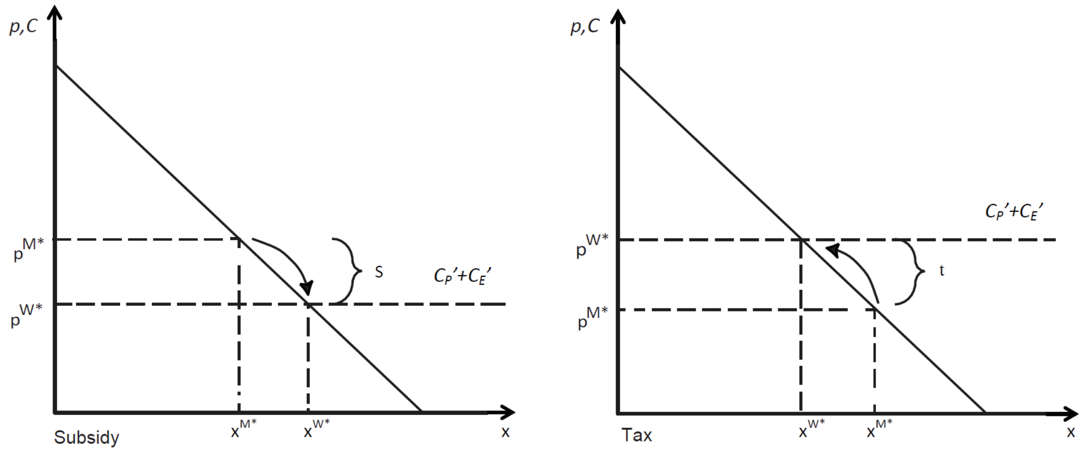

Figure 6: The effect of a subsidy with subsidy rate (s) (left plot) and a tax with tax rate (t) (right plot) on the extracted quantity

Notice that this is exactly the tax rate that pushes the monopolist to extract the welfare-maximizing shale gas amount. When we look at it, we see that we cannot say unambiguously whether it always has a positive value. This leads us back to a subsidy, because a negative tax rate in its effect is just that. As we have explained before, the regulator then pays the monopolist to extract more than his profit-maximizing amount.

The problem with the tax is that as soon as the number of suppliers increases, we need for every single one the exact welfare-maximizing amount. We can derive this amount only from their cost structures and, just as with the emission standards, figuring them out seems highly unlikely. Turning back to our model, the next step is to test whether this tax rate really is expedient. We include it in the profit equation, denoted Π^T, which now considers the tax:

$$\Pi^T = x \cdot p(x) - C_E - x \cdot [(p_w + 2p_p)q - Q]. \tag{29}$$

Repeating the steps that compute the profit-maximizing amount, differentiating the profit function over x and then solving it, we can compute the welfare-maximizing amounts as (cf. section 3.2.2):

$$x^{T**} = x^{W*} = \frac{1}{m}[Q - (p_w + p_p)q]. \tag{30}$$

It is the implementation of the tax (or subsidy) that moves the monopolist's costs exactly to the right amount in order to reach x^{W*}. At least from a mathematical point of view, an implementation like this means that we do not have to make an explicit distinction between cases, unlike how we did in the last section.

Now we need to look at the effects of the taxation or the subsidy on social welfare. Apart from the extraction costs, the monopolist also has to pay the tax burden or, in the case that he is receiving a subsidy, his costs diminish. Both cases have implications for the producer's surplus, and also have an influence on the public budget. Thus we can state that the welfare is computed differently but reaches the same maximum. The monopolist's profit changes by the amount of the tax burden or subsidy (see eq. (25)), but the welfare is compensated by the same tax revenue or amount of subsidy. Algebraically, this means that we subtract the tax burden $t \cdot x$ in the monopolist's profit but add it again in the welfare equation at the end, i.e.

$$W^{T*} = \Pi^T + CS - C_p + T(x). \tag{31}$$

In other words, we then have a redistribution of the external costs on the polluter without changing the optimized welfare.

3.4 Comparison of internalization methods

So far, we have developed a model of a shale gas extractor in a closed market and have shown two methods of internalizing the external effects on water caused by fracking. However, there are some limitations to our model.

First of all, our market is a closed economic area. While this assumption might be applicable to a few states that are very sealed off from the rest of the world, most countries do have an open market economy. Our Cournot game is run for only one round, with no possibilities for the participants to learn from their own behavior and that of others. Our only source for natural gas and energy is the shale gas extracting monopolist who has no competition to fear, and the connection between shale gas extraction and water pollution is very explicit. This makes our model even more conceptional. Our view on welfare is then purely limited to the monopolist's profit and the benefit of the demanders, expressed by their consumer surplus. But in reality there are many more factors that might influence social welfare. Another point is that we have only two states: the monopolist extracts the welfare-maximizing amount or he extracts the amount that optimizes only his own profit. Also, to achieve an optimized welfare, we need the shale gas producer's cost structures and exactly the resulting damage that fracking fluids cause. We cover them through the purification costs, but in reality many influences cannot be described in monetary units, and companies have generally a very secretive manner about their internal structures.

We can still derive a few implications from our analysis. The tax or subsidy seems to be more easily to implement, whereas the emission standard is definitely more secure. Specifically, since the amount of the penalty to be paid can increase, the incentive to abide by the rules is very good, even where the likelihood of being caught is low. Because fracking fluids can contaminate ground and surface water, and can be very unhealthy to humans, a strict policy seems legitimate. These pollutants used for shale gas extraction are not comparable with emissions like CO_2, which spread very widely and where it does not matter so much from where they were emitted. A local solution has to be favored in order to control fracking fluids to protect residents and their water supply. Of course, this means high control costs, but considering the amount of expected shale gas, it might be worth the trouble – if implemented correctly. Then, again, a tax might have the benefit of forcing the shale gas extractors to develop techniques that need less water.

Generally speaking, a unified legislation and a unified authority for water and mining affairs for special cases like fracking should be a main objective for the German lawmaker. This way, we can benefit from profits that shale gas promises while avoiding the risks.

4 Empirical analysis

We now want to parameterize our model, and to see what implications we get and what we can learn from the results. As explained in the previous section, because of the limited approach to welfare analysis, we do not expect that all results will make sense. Also, the data for some values are hard to verify and for others the range is very wide. But we have included this part in order to elaborate the correlations between the different constants and the extraction amounts further. We will also see the influence on social welfare.

4.1 The data

In the following, we explain step by step where we gathered the data and how we prepared them to make them fit in our model. In general, we explain the more directly measurable data first and then move more and more to abstract (less available) data, before we get to actually including the values. After discussing the data sources, we provide a summary and then include these numbers in our model in section 4.2.

4.1.1 Water and water treatment prices

The water and water treatment prices are set by the municipal water treatment facilities themselves. The prices are different for bulk buyers or large-scale industries and for small businesses or ordinary citizens. This depends on the required amounts of water, so the higher they are, the lower the prices. In our study, the shale gas extractor is assumed to be one of these bulk buyers of water, and also a bulk buyer of water treatment services, as he needs to properly dispose of the flow-backs generated.

The price range and the average price of water in Germany for industrial customers in 2010 and 2011 can be seen in Table 1. The prices reported are average values for Germany. However, since they are set by the municipalities or their water treatment facilities, respectively, they can vary substantially from region to region. In our model, the influence of the water price is reflected by the parameter p_w.

Table 1: Price of water (p_w) [€/m^3] for bulk buyers in Germany, 2010 and 2011.

Year	For 7500 m^3 of water	For 100,000 m^3 of water	Average	Rate of increase
2010	1.797	1.714	1.720	—
2011	1.807	1.723	1.729	0.5%

Source: Bröker (2011, pp.54–55)

We will compute social welfare later with the average price for all of Germany. Then, we define a bandwidth and use the values of the upper and lower limit to also compute it. For the water prices, the bandwidth in which we conduct our sensitivity analysis is determined by the highest and lowest local price of water. The values range from 0.922–2.374 €/m^3 (cf. Bröker, 2011, pp.54–55), equivalent to a bandwidth of 53%–134% of the average price.

Another distinction is made between the requested amount of water, where a very high water demand gives the buyer a quantity discount. But as the water demand for shale gas extraction varies a lot, depending on external circumstances, we will use the average value. Additionally, we have added the prices of 2010 and see that the water price had increased by about 0.5%, whereas the inflation rate in Germany was 2.5% in 2011 (HICP for Germany in 2011 by Eurostat). So the water prices remain, in nominal terms, relatively stable, while the price adjusted for inflation actually sank.

The price of water treatment – or water purification – in our model is represented by the parameter p_p. As a reminder: this was the parameter that we needed the monopolist to consider in his extraction amount in order to reach the welfare-maximizing amount, or otherwise the result would be an inefficiently high or low welfare. The price remained the same between 2010 and 2011 at 2.14 €/m^3 (cf. Bröker, 2011, pp.54–55), which can be explained, as water prices also had only a very small increase, and purification might have even less price fluctuation. As we have no exact range, we decided to assume a similar bandwidth as we have seen for the water prices. Because water supply and water treatment facilities are often run by the same municipal authority, this seems plausible. So our boundaries would be at 53% and 134% of the water treatment price, i.e. at 1.13 €/m^3 and 2.87 €/m^3, respectively.

4.1.2 Water efficiency in fracking

In this section we try to compute the TEC parameter (q), which resembles basically the water efficiency of the frack. Reliable information about how much water per cubic meter of extracted gas is hard to compute. The reason is that both the amount of water needed varies from borehole to borehole, as does the amount that can be extracted in one frack. The estimates reach up to 20,000 m^3 water per frack. Thus, we assume 20,000 m^3 to be the worst case and as little as 5,000 m^3 to be the best case. Because the less water has to be used, the better it is for the water cycle. But again, these amounts are extremely dependent on external circumstances.

Then we need to assume an extracted shale gas amount per frack. Remembering the expected technically extractable shale gas amounts from section 2.1, varying from 0.1–1.77 trillion m^3 per shale gas field, we set three amounts. Next to 0.1 trillion m^3 as the lower limit and 1.77 trillion m^3 as the upper limit, we define 0.4 trillion m^3 as a mid-range value, because it is the maximum expected amount in two of the three examined fields (see section 2.1). Combined with our best and worst case scenarios for the water needed, we get a TEC between $3 \cdot 10^{-6}$ $[m^3\ water/m^3\ shale\ gas]$ as best case and 0.0002 $[m^3\ water/m^3\ shalegas]$ as worst case.

To quickly verify these very abstract numbers, we compare them to enquiries from the interim report that we quoted earlier[6]. From there, we calculated a bandwidth ranging from $5.7 \cdot 10^{-5}$ $[m^3\ water/m^3\ shale\ gas]$ (best case) to 0.013 $[m^3\ water/m^3\ shale\ gas]$ (worst case) by dividing the amount of water used through the extracted shale gas. For the sensitivity analysis, we use a combination of those two bandwidths, and as a starting point the average TEC from the enquiries, which is $5.7 \cdot 10^{-3}$ $[m^3\ water/m^3\ shale\ gas]$.

4.1.3 Price sensitivity, choke price, and fixed costs

Now we turn to values that are much harder to estimate. First, we want to discuss the fixed costs. Their components vary a lot, depending on how they are defined. In reality, licenses or permission fees for drilling could be included, or some of the machines needed to bore the holes could be considered as part of the fixed costs. Although they have a huge influence on profits and welfare, it is always within the exact same scope. But since they have no influence on the extraction amounts or prices, we start by assuming they are zero.

Next, we look at the choke price. It is defined as the price that consumers would pay at most if the extracted amount reaches zero. Graphically, it is the intersection point of the inverse demand function and the vertical axis. We are going to derive it from the normal price for gas or liquified natural gas (LNG).

LNG is traded at the European Energy Exchange (EEX) in Leipzig, and we chose data from the spot market of the first hundred trading days in 2011[7]. This way, we stay consistent because we have already used data from that year. From there, we calculated the average price as 0.0231 $€/kWh$. As natural gas has a heating value of between 8–12 kWh/m^3, this results in a price of natural gas between 0.19–0.27 $€/m^3$. The heating value is determined by the quality of the conventional or shale gas and differs depends on its origin. But we want to find a price that is too high to find a buyer. We want to cover a wide range and so we are going to consider three scenarios as well.

[6] See also Meiners et al. (2012), pp.A69–A70.

[7] See https://www.eex.com/de/Downloads/Marktdaten/Erdgas/ .

Table 2: Overview of the values for the sensitivity analysis

Parameter	Symbol	Unit	Lower limit	Standard case	Upper limit
Price of water	p_w	[€$/m^3$]	0.922	1.729	2.374
Purification costs	p_p	[€$/m^3$]	1.13	2.14	2.87
Water efficiency/TEC	q	[m^3/m^3]	$3 \cdot 10^{-6}$	0.0057	0.013
Choke price	Q	[€$/m^3$]	19	43.25	67.5
Price sensitivity	m	[(€$/m^3$)$/m^3$]	0.1	1	10

For the lower limit of our bandwidth, we assume that there are alternatives for shale gas in energy supply, so that the choke price is a hundred times the lower price of natural gas ($Q = 0.19 \cdot 100 = 19$ €$/m^3$). The upper limit is then set as two hundred and fifty times the higher price, because we assume that the consumers are willing to pay higher prices since there is no alternative to (domestic) shale gas in energy supply ($Q = 0.27 \cdot 250 = 67.5$ €$/m^3$). To complete the bandwidth, we set the third choke price exactly in the middle of the upper and the lower limits ($Q = 43.25$ €$/m^3$). The wide range also resembles the uncertainty in the determination of the choke price.

Finally, the price sensitivity (m) is left. It is measured in [(€$/m^3$)$/m^3$] and expresses the reaction of the demand on changes of the market price of shale gas. The higher the price sensitivity, the stronger demand decreases when the price increases by a marginal unit, and thus the flatter the slope of the inverse demand function. As the price sensitivity has a strong influence on the extraction quantities, we also want to cover a wide range and set the bandwidth from 0.1–10 [(€$/m^3$)$/m^3$].

4.2 Welfare analysis

The numbers displayed in Table 2 are now inserted into the economic model described in section 3. The standard case can be considered as a fixed point from which we can compare the changes caused by varying the other values.

First, we want to discuss this summary. Noticeable are the values of the cost side (q, p_w, p_p), which are considerably lower than the demand side (Q, m) of our model. Especially because of the TEC (q), the extraction and purification costs might have an inferior influence on profits and social welfare than the demand side of the equations.

In Table 3 we have listed the worst case with the lowest possible welfare, the standard case, and the best case with the highest possible welfare. The worst and best case scenarios are the limits that social welfare can reach; no combination of our values can compute a value that is outside the interval between 17.921 and 22,781.246. To calculate them, we put together the lowest (highest) choke price on the demand side and combine it with the highest (lowest) costs to compute the worst (best) case. We use eqs. (4), (14), (16), and (17). When plotting these three welfare functions, we can see that their course is similar, but that the scale changes (see Figure 7).

Table 3: Worst, Standard and Best Case (top-down) of welfare maximization

Q	p_w	p_p	q	m	x^{W*}	p^{W*}	Π^M	W
19	2.374	2.87	0.013	10	1.893	0.068	0.071	17.921
43.25	1.729	2.14	0.0057	1	43.228	0.022	0.527	934.328
67.5	0.922	1.13	$3 \cdot 10^{-6}$	0.1	675	~0	0.002	22,781.246

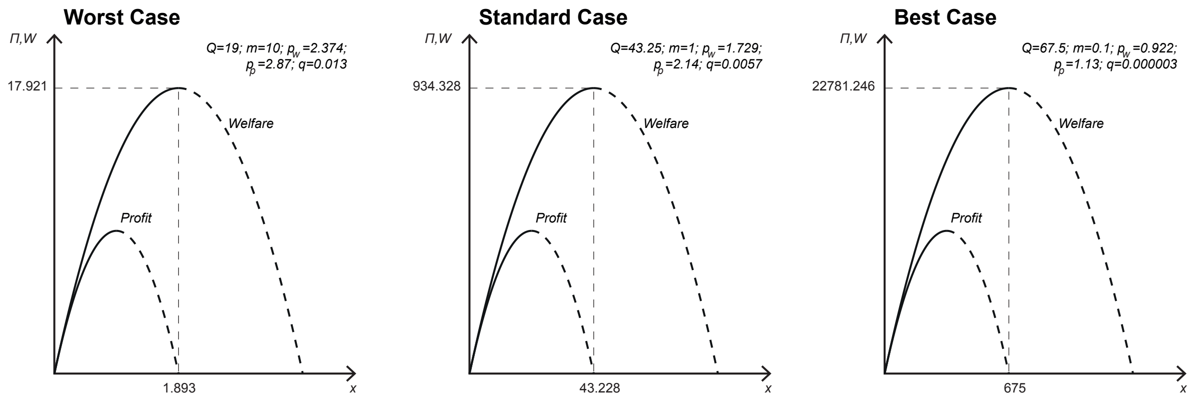

Figure 7: Welfare and profit functions for the Standard, Best, and Worst Case

We have also added the profit function to show that the amounts maximizing the monopolist's profit or the welfare are in fact different. Otherwise, they should be on the same vertical line. We notice that the monopolist's profit always stays above zero, so we do not need to follow the second-best approach. On the other hand, we find that the monopolist's profits in Table 3 are just above zero, and we have not considered any fixed costs yet. Therefore, the margin for fixed costs is very small.

Now we want to vary the values individually in order to see their influence on the monopolist's maximized profit and the maximized social welfare. We have grouped our parameters into two classes: the demand side (section 4.2.1) and the cost side (section 4.2.2). In addition, we explain the tax or subsidy rate that would push the monopolist to produce the welfare-maximizing amounts. Note that we have not included values for the emission standard approach, because it relies a lot on the amount of the fine and the likelihood of being discovered.

4.2.1 Varying the choke price and the price sensitivity

On the demand side, we have the choke price Q and the price sensitivity m. Both have a relatively large influence on welfare, but while the choke price has a positive correlation, the price sensitivity has a negative one.

As can be seen, a rising Q increases welfare. Notice further that the maximized welfare for every iteration of Q is higher than the corresponding welfare resulting from profit-maximizing quantities. This is a very good sign, because that is the essence of our entire economic model described in section 3. We also notice that the profit-maximizing

Table 4: Sensitivity analysis for the profit maximization (varying Q, p_w, p_p, q, and m; parameters varied in boldface

Q	p_w	p_p	q	m	x^{M*}	p^{M*}	$\Pi^{M,*}$	W
19	1.729	2.14	0.0057	1	9.495	9.505	90.156	135.119
43.25	1.729	2.14	0.0057	1	21.620	21.630	467.428	700.878
67.5	1.729	2.14	0.0057	1	33.745	33.755	1138.730	1707.683
43.25	**0.922**	2.14	0.0057	1	21.622	21.628	467.527	701.027
43.25	**1.729**	2.14	0.0057	1	21.620	21.630	467.428	700.878
43.25	**2.374**	2.14	0.0057	1	21.618	21.632	467.348	700.758
43.25	1.729	**1.13**	0.0057	1	21.620	21.630	467.428	701.002
43.25	1.729	**2.14**	0.0057	1	21.620	21.630	467.428	700.878
43.25	1.729	**2.87**	0.0057	1	21.620	21.630	467.428	700.788
43.25	1.729	2.14	$3 \cdot 10^{-6}$	1	21.625	21.625	467.641	701.461
43.25	1.729	2.14	**0.0057**	1	21.620	21.630	467.428	700.878
43.25	1.729	2.14	**0.013**	1	21.614	21.636	467.155	700.131
43.25	1.729	2.14	0.0057	**0.1**	216.201	21.630	4674.275	7008.776
43.25	1.729	2.14	0.0057	**1**	21.620	21.630	467.428	700.878
43.25	1.729	2.14	0.0057	**10**	2.162	21.630	46.743	70.088

quantities are always smaller than the welfare-maximizing amounts, so we need the regulator to pay a subsidy in order to make the monopolist extract more shale gas. Next to the amounts we have also displayed the resulting subsidy rate (Table 6).

Inspecting a similar table for the price sensitivity, we notice that an increasing sensitivity decreases both welfare and profit. This means that the more sensitively buyers react to rising shale gas prices, the more profits and social welfare will decrease. Due to the way in which we chose our iteration steps (multiplication by a factor of 10), the results also decrease by a factor of 10. Again, the maximized welfare is higher than for the profit-maximizing quantities. Recalling eq. (28), which describes the tax or subsidy rate, we know that the price sensitivity has no influence on the rate, so it would be the same in all iterations of m, and thus we do not need to report those values.

4.2.2 Varying the price of water, the purification price, and the TEC

Last, we look at the parameters on the cost side. This includes the price of water (p_w), the purification price (p_p), and the TEC (q). As can be seen from Table 2, the values are relatively small, and we will see later that the impact on the profits and welfare are small as well. But they are consistent and visible. We begin with the water prices. Notice that both welfare and the monopolist's profits are decreasing in small steps, whereas the price of water is increasing. Table 5 again confirms that the welfare-maximizing amounts in fact lead to a higher welfare than the profit-maximizing quantities. Also, as the profit-maximizing quantities are again smaller than the welfare-maximizing quantities, the regulator again has to pay a subsidy in order to achieve the optimal welfare level.

Looking at the profits and welfare while varying the price for water treatment in Table 4, we can see that neither the profit-maximizing quantities nor the maximized profit

Table 5: Sensitivity analysis for the welfare maximization (varying Q, p_w, p_p, q), and m, parameters varied in boldface

Q	p_w	p_p	q	m	x^{W*}	p^{W*}	Π^M	W^*
19	1.729	2.14	0.0057	1	18.978	0.068	0.231	180.081
43.25	1.729	2.14	0.0057	1	43.228	0.022	0.527	934.328
67.5	1.729	2.14	0.0057	1	67.478	0.022	0.823	2276.637
43.25	**0.922**	2.14	0.0057	1	43.233	0.017	0.527	934.527
43.25	**1.729**	2.14	0.0057	1	43.228	0.022	0.527	934.328
43.25	**2.374**	2.14	0.0057	1	43.224	0.026	0.527	934.169
43.25	1.729	**1.13**	0.0057	1	43.234	0.016	0.278	934.577
43.25	1.729	**2.14**	0.0057	1	43.228	0.022	0.527	934.328
43.25	1.729	**2.87**	0.0057	1	43.224	0.026	0.707	934.148
43.25	1.729	2.14	$3 \cdot 10^{-6}$	1	43.250	~0	~0	935.281
43.25	1.729	2.14	**0.0057**	1	43.228	0.022	0.527	934.328
43.25	1.729	2.14	**0.013**	1	43.200	0.050	1.202	933.107
43.25	1.729	2.14	0.0057	**0.1**	432.279	0.022	5.273	9343.277
43.25	1.729	2.14	0.0057	**1**	43.228	0.022	0.527	934.328
43.25	1.729	2.14	0.0057	**10**	4.323	0.022	0.053	93.433

Table 6: Sensitivity analysis for the subsidy rate s (varying Q, p_w, p_p, and q)

	x^{M*}	x^{W*}	s
Q=19	9.495	18.978	18.966
Q=43.25	21.620	43.228	43.216
Q=67.5	33.745	67.478	67.466
p_w=0.922	21.622	43.233	43.220
p_w=1.729	21.620	43.228	43.216
p_w=2.374	21.618	43.224	43.212
p_p=1.13	21.620	43.234	43.227
p_p=2.14	21.620	43.228	43.216
p_p=2.87	21.620	43.224	43.207
q=$3 \cdot 10^{-6}$	21.625	43.250	43.250
q=0.0057	21.620	43.228	43.216
q=0.013	21.614	43.200	43.172

are influenced by them. Of course, social welfare is affected, because the purification costs are covered by the general public if they are not internalized by the monopolist.

It is interesting, though, that when the monopolist is forced to produce the welfare-maximizing quantities, his profit increases when the purification costs increase, while the maximized welfare decreases naturally with rising costs. This is because of the increasing prices resulting of the decreasing amounts. As the changes compared to the variation of the price for water are small, we already expect that the regulator will have to pay a subsidy again. This is confirmed by the data depicted in Table 6.

The third and last cost parameter considered is the TEC. It has a similar effect on profits as does the price for water purification, so that the results are similarly structured (Table 4).

4.3 Discussion of results

The results of our sensitivity analysis show that the maximized welfare is in any case higher than the welfare resulting from the profit-maximizing quantities. This was predicted by our model. Also, the regulator always has to pay a subsidy in order to achieve the maximum welfare, which shows that the monopolist tries to exercise his market power in order to keep the prices up for profit maximization. The monopolist's profits are always non-negative, whereas the welfare-maximizing quantities generally reduce his profits. As profits do not drop below zero, however, there is no need to use the second-best approach. However, there are many situations where the monopolist's profits would fall below zero as soon as there are positive fixed costs, and he would extract the welfare-maximizing amounts. Compared to the real world, the assumption of zero fixed costs is a strong one; but as explained before, we nevertheless wanted to show the interrelatedness of the different influences. The strong influence on the amounts, profits, and welfare of the choke price (Q) and the price sensitivity (m) is due to the slightly arbitrary way in which we defined their bandwidth. In reality, these are hard to determine and have a large influence, calling for sensitivity analysis. Overall, we can conclude that increasing costs and/or an increasing price sensitivity will lead to smaller profits and reduced social welfare, while an increasing choke price will also increase profits and social welfare.

5 Conclusions

In this paper we have investigated the potential for shale gas in Germany and potential conflicts with water supply. The perspectives taken are those of a profit-maximizing monopolist engaged in shale gas production who is able to shift the cost burden of water pollution treatment to society versus the welfare-maximizing regulator. The water-related risks inherent in hydrofracking and the prevailing legislation have been discussed in detail. Despite of the significant economic potential of shale gas production in Germany, however, both low social acceptance and the recently introduced, very restrictive fracking law render it quite unlikely that the trade-offs inherent in the costs and benefits of shale gas production will have to be balanced against each other in real world policy-making in Germany in the coming years. Still, our model can provide useful for the further discussion both in Germany, where the shale gas potential has recently been estimated, but also in other countries contemplating the exploitation of this unconventional fossil fuel resource that has seen a remarkable boom in the US in recent years, and that at least for the time being is of great geopolitical relevance.

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