Can hydraulic fracturing make Poland self-sufficient in natural gas?

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Abstract

The International Energy Agency (IEA) has highlighted hydraulic fracturing (fracking) as the key to a “Golden Age of Gas”, but to reach this age the world must drill a million new wells. Within the European Union (EU), Poland appears to have the greatest shale resource and test drilling has started there. Poland hopes to be able to replace gas from Russia with domestic natural gas production and eventually to become self-sufficient. Poland currently imports 12.4 billion cubic meters of natural gas per year. Our analysis shows the need to drill at least 400 new shale gas wells per year for Poland to become self-sufficient. If it is judged to be very important that Poland reach self-sufficiency, then the EU should assist in importing 40 to 50 drilling rigs and hydrofracturing equipment from the U.S.A. With 400 new gas wells drilled per year over 30 years, one obtains 12,000 shale gas wells in Poland, which is less than the current number of wells in the Barnett Shale.
Introduction

Since 1963, when the giant natural gas fields off Groningen [1] started producing natural gas, energy security changed significantly for the then six nations of the European Union (EU). Natural gas began to be an important component of the Union’s energy security. In 1970, consumption had increased to 60 billion cubic meters (bcm) per year with 99% of that gas was produced within the six EU nations. Today, the Union has expanded to include 28 nations, and natural gas consumption in today’s EU nations has increased to around 450 bcm/y [2]. The fact that only 32 percent of the consumed natural gas is produced within the EU suggests that the Union’s energy security has radically deteriorated.

Today, 25% of the EU’s imports come from Norway and 29% from Russia [2]. Through its membership in the European Economic Area (EEA), Norway is closely connected with the EU, and if one treats Norwegian gas production as production occurring within EU, then gas energy security is increased to 57 % of the consumption produced within EU. Nevertheless, there remains a huge demand for gas imports. As much as 50% of that demand is for the Russian natural gas [2].

In the article “European energy security: An analysis of future Russian natural gas production and exports” Söderbergh, Jakobsson and Aleklett studied Russia's ability to export natural gas until 2050. Critical to the long-term exports to Europe in 2009 was that production from the Stockman and Yamal peninsula would start as planned [3]. We now know that the start of this gas production is delayed, with negative impacts on Russia’s ability to produce natural gas in the future.

In order to improve energy security in the EU, hydraulic fracturing or “fracking,” as it commonly is called, is now stated as a possibility. Fracking is discussed in a "Special Report on Unconventional Gas", released by the International Energy Agency, IEA, in May 2012. This report, titled the "Golden Rules for a Golden Age of Gas" [4], highlights several points of importance for future unconventional gas production:

- Unconventional gas production (UGP) is an intensive process, generally requiring hydraulic fracturing and more wells than conventional gas.
- Many nations are lining up to emulate the successful UGP in the U.S.A. These nations include China, Australia, Poland and Latin America.
- Concerns remain that UGP might involve unacceptable environmental and social risks.
- UGP has major implications for local communities, land use and water resources.
- Serious hazards include the potential for air and groundwater pollution.

In the report, the IEA estimates that UGP will increase to about 1,200 bcm per year, and that the number of new wells around the world must increase from the current approximately 100,000 wells in the U.S.A. to some one million new wells.

The IEA report and other decisions within the EU regarding hydraulic fracturing have resulted in recommendations on the "minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing." These recommendations were adopted in January 2014, and they delineate in twelve bullets points the relationship between fracking and the Treaty on the Functioning on the European Union (TEU) [5]. Here is our summary:

- Member States have the right to determine the conditions for exploiting their energy resources, as long as they respect the need to preserve, protect and improve the quality of the environment.
- There is a need for a recommendation that lays down minimum principles that support Member States in the exploration and production of natural gas from shale formations and
ensure that the climate and environment are safeguarded, resources are used efficiently, and the public is informed.

- The Union’s environmental legislation was developed at a time when high-volume hydraulic fracturing was not used in Europe. Therefore, certain environmental aspects associated with the exploration and production of hydrocarbons involving this practice are not comprehensively addressed in current Union legislation, in particular on strategic planning, subsurface risk assessment, well integrity, baseline and operational monitoring, capturing methane emissions, and disclosure of information on chemicals used on a well-by-well basis.

- Therefore, there is a need to lay down minimum principles, which should be followed by the Member States when applying or adapting their regulations related to activities involving the high-volume hydraulic fracturing. A set of rules would level the playing field for operators; improve investors’ confidence and the functioning of the single EU energy market. Clear and transparent rules would also help alleviate public concerns, and possibly opposition to shale gas development.

The EU member nations have the right to decide whether or not to exploit their shale-gas basins or not. The IEA has compiled the current outlook for Europe. Four nations, France, Luxembourg, the Netherlands, and Bulgaria, have said no to fracking, while others said yes. In November 2013, the new government in Germany agreed to a temporary ban on exploration for unconventional natural gas until environmental issues were resolved. In southern Sweden, Shell drilled for shale gas but did not find commercial volumes [6].

Two nations that have been discussing future exploration and production of shale gas are Poland and the UK. The uncertain political situation in Ukraine, which is a major transit nation for Russian natural gas, has made the question of Poland’s self-sufficiency in natural gas even more important. As of May 2014, the Ministry of the Environment has granted 84 concessions for prospecting and/or exploration of hydrocarbon deposits, including shale gas. These concessions have been granted to 32 Polish and foreign entities (concessionaires). Up to May 5, 2014, the concessionaires have drilled 63 exploratory wells, of which 17 are vertical hydrofractured wells and 8 are horizontal hydrofractured wells. Until 2021 an additional 309 exploratory wells are planned. The number of exploratory wells planned in Poland in the next 7 years is less than the 400 new wells that must be drilled each year if Poland is to become self-sufficient in natural gas.

Hydraulic fracturing to produce natural gas [7] began in the Barnett shale west of Dallas in Texas, U.S.A. In this report, we will study gas production per average well in the Barnett shale and then apply this production function to future gas production in Poland. The goal of our study is to examine the number of wells that must be drilled to make Poland self-sufficient in natural gas. The area referred to as the most promising is the Baltic basin in northern Poland. We will discuss how close the spacing of new wells must be in this basin west of Gdansk.
**Methodology**

Future production of unconventional natural gas in Poland was simulated as three scenarios that require, respectively, the drilling of 300, 400 and 500 wells per year. In all scenarios, it is assumed that it takes two years to ramp up to the respective required drilling rate. First month's production is assumed to be 2.0 million cubic meters per month (mcm), a volume that is expected to be representative for the Barnett Shale in Texas. Gas production from each new well in Poland follows the average production from a Barnett Shale well. Under these assumptions, the scenario with 400 wells per year attains a level of production corresponding to Poland’s current natural gas imports after a period of six years.

The average production per well in the various shale gas fields in the United States varies considerably [8, 9]. For the scenario with 400 wells per year, we also calculate the total gas production in Poland when the first month's production volumes are respectively 1.5 and 2.5 mcm per well. For 1.5 mcm per well, even after 7 years of production the total production is less than Poland’s current import volume.

**Results**

As mentioned above, our simulations are based on the production history of shale gas in the Barnett Shale. A simple model of gas production consistent with the basic physics of the extraction process has been published by Patzek et al. [9]. Their model reproduces the production decline of each well in the Barnett Shale and predicts future production from those wells. Here, however, we use a simpler production decline model based only on actual well production data.

**Production Profile for Shale Gas Production at the Barnett Shale**

To calculate possible future production of shale gas in Poland, we choose to use the average producing gas well in the Barnett Shale. The Texas Railroad Commission (RRC) has designated the productive portion of the Barnett Shale as the Newark East Field. The productive part of the formation extends west and south of Dallas, covering 13,000 km² (5,000 square miles) and 18 counties [10]. The RRC states that the Barnett Shale is the largest onshore natural gas field in the United States.
Figure 1: Using DrillingInfo [11], we have generated a map of all gas wells west of Dallas. This map includes old vertical gas wells drilled in the area before the introduction of horizontal drilling. The large square covers approximately 12,500 km², roughly the area described in Table 1. This area contains about 80% of the horizontal hydraulically fractured wells in the Barnett Shale. The small square, discussed in Figure 7, has 178 wells. Note the large number of wells drilled previously in the area which is an important insight when discussing acceptance of hydraulic fracturing in the Barnett Shale.

Mitchell Energy, a small independent oil company, first drilled vertical hydrofractured wells in the region west of Dallas. Only when they started to drill horizontal wells in the Barnett Shale and hydrofractured them was the potential of the field realized. Significant drilling activity did not begin until natural gas prices increased in the late 1990’s [10]. At the turn of the century, different operators had drilled 534 horizontal wells in the Barnett. As of March 1, 2014, the number of wells drilled was 17,546. The number of wells drilled per month is reported by RRC [10].

Tarrant County with Fort Worth is the center of the Barnett Shale field. In Tarrant and the five surrounding producing counties one can find 14,406 wells in the Barnett Shale (82% of all wells) [11]. In Table 1 we have calculated the areal well density in these six counties. Note that a large part of Tarrant County is covered by the city of Fort Worth.
Table 1: Number of wells [11] in the central counties of Barnett shale, the numbers of wells per km², and population [12].

<table>
<thead>
<tr>
<th>County</th>
<th>Land area (km²)</th>
<th>Number of wells</th>
<th>Wells per km²</th>
<th>Population</th>
<th>Population per km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tarrant</td>
<td>2323</td>
<td>4134</td>
<td>1.78</td>
<td>1,880,153</td>
<td>809</td>
</tr>
<tr>
<td>Wise</td>
<td>2391</td>
<td>1620</td>
<td>0.68</td>
<td>60,432</td>
<td>25</td>
</tr>
<tr>
<td>Denton</td>
<td>2481</td>
<td>1524</td>
<td>0.61</td>
<td>707,304</td>
<td>285</td>
</tr>
<tr>
<td>Parker</td>
<td>2357</td>
<td>1443</td>
<td>0.61</td>
<td>119,712</td>
<td>51</td>
</tr>
<tr>
<td>Hood</td>
<td>1132</td>
<td>1401</td>
<td>1.24</td>
<td>51,182</td>
<td>45</td>
</tr>
<tr>
<td>Johnson</td>
<td>1901</td>
<td>4284</td>
<td>225</td>
<td>153,441</td>
<td>81</td>
</tr>
</tbody>
</table>

Producing natural gas from a field can be compared to opening a tap in a gas bottle. If you turn off the tap for a while and then open it again, the flow continues as if the tap had never been closed. The production profile for what will be called “a typical horizontal gas well in the Barnett Shale” should have a production without interruptions for maintenance and other disruptions. Tarrant County is in the center of Barnett Shales, and is also the county with the highest density of wells and population (Table 1). Wells in Tarrant County are chosen for the analysis, as well as wells in Parker County, west of Tarrant County, with fewer wells per square kilometer.

Table 2: Production profile for a typical well in Tarrant County, where production for the first month is normalized to one. Production for month 50 is 0.1722 and production for subsequent months is reduced by 1.5% per month. As discussed in the text, the production factor after 10 years is 6%.

<table>
<thead>
<tr>
<th>Month</th>
<th>Factor</th>
<th>Month</th>
<th>Factor</th>
<th>Month</th>
<th>Factor</th>
<th>Month</th>
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<th>Factor</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>1.000</td>
<td>13</td>
<td>0.390</td>
<td>25</td>
<td>0.274</td>
<td>37</td>
<td>0.220</td>
<td>49</td>
<td>0.175</td>
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<td></td>
</tr>
<tr>
<td>2</td>
<td>0.801</td>
<td>14</td>
<td>0.376</td>
<td>26</td>
<td>0.266</td>
<td>38</td>
<td>0.213</td>
<td>50</td>
<td>0.172</td>
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<td></td>
</tr>
<tr>
<td>3</td>
<td>0.712</td>
<td>15</td>
<td>0.359</td>
<td>27</td>
<td>0.263</td>
<td>39</td>
<td>0.208</td>
<td>51</td>
<td>0.170*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.649</td>
<td>16</td>
<td>0.352</td>
<td>28</td>
<td>0.260</td>
<td>40</td>
<td>0.204</td>
<td>52</td>
<td>0.167*</td>
<td></td>
<td></td>
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<tr>
<td>5</td>
<td>0.605</td>
<td>17</td>
<td>0.337</td>
<td>29</td>
<td>0.251</td>
<td>41</td>
<td>0.199</td>
<td>53</td>
<td>0.165*</td>
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<tr>
<td>6</td>
<td>0.546</td>
<td>18</td>
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<td>30</td>
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<tr>
<td>7</td>
<td>0.514</td>
<td>19</td>
<td>0.320</td>
<td>31</td>
<td>0.239</td>
<td>43</td>
<td>0.192</td>
<td>55</td>
<td>0.160*</td>
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<td></td>
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<tr>
<td>8</td>
<td>0.481</td>
<td>20</td>
<td>0.314</td>
<td>32</td>
<td>0.234</td>
<td>44</td>
<td>0.190</td>
<td>56</td>
<td>0.157*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.458</td>
<td>21</td>
<td>0.302</td>
<td>33</td>
<td>0.226</td>
<td>45</td>
<td>0.187</td>
<td>57</td>
<td>0.155*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.438</td>
<td>22</td>
<td>0.299</td>
<td>34</td>
<td>0.223</td>
<td>46</td>
<td>0.182</td>
<td>58</td>
<td>0.153*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.419</td>
<td>23</td>
<td>0.287</td>
<td>35</td>
<td>0.221</td>
<td>47</td>
<td>0.181</td>
<td>59</td>
<td>0.150*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.403</td>
<td>24</td>
<td>0.280</td>
<td>36</td>
<td>0.218</td>
<td>48</td>
<td>0.179</td>
<td>60</td>
<td>0.148*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(*) Calculated production factor.

To get a production profile that spans over 50 months, the data set is limited to the newer wells drilled in the years 2007 - 2009. In total, we found 958 wells without major disruptions in production. In total, these wells had 68,413 production months of which 2736 were months with zero production. These zero-months were removed and production moved forward as appropriate to obtain the continuous production history of a typical well in the Barnett Shale. The production from all the 9585 wells was aggregated and the production for the first month was normalized to one. The resulting production profile is presented in Table 2 and Figure 2.
Using the same method as for Tarrant County we have deduced the production profile of the 489 wells in Parker County (see Figure 2). Their decline has the similar shape and after 36 months (three years) of decline we get for both curves the same factor, 0.22. Using the production factors for the months 36 to 50 we can extrapolate the production factor up until month 120. For the production profile of a typical well of Parker County we get around 0.07 and for Tarrant County 0.05. For the average production profile of a new gas well in Poland we choose the factor 0.06 in month 120, corresponding to a decline rate of 1.5% per month for years 5 to 10.

The Texas Railroad Commission has published the total number of wells drilled in the Barnett Shale [10]. There were 11,774 new wells drilled in the years 2007 – 2013 (2007: 1,591, 2008: 2,835, 2009: 3,594, 2010: 1,146, 2011: 984, 2012: 840, and 2013: 784). In a test of our model, we calculate the output of the Barnett Shale for the years 2007 to 2013 by assuming that the new wells are evenly distributed throughout the year, and that each new well produces according to our decline model, with the average production for the first month equal to 1.87 mcm (66 million cubic feet, mcf per month), the number deduced from our analysis. As real production also has months with zero production we introduced a zero production month every 6th month. In Figure 3 the calculated production is presented and compared with the actual production in the Barnett Shale. For 2009 and 2010, the calculated production is significantly larger than the real one. The real production growth for 2009 was less than for 2008 even though more wells were drilled in 2009 than in 2008. Therefore most wells drilled in 2009 were not completed because the price of natural gas collapsed; making it profitable to deliver the gas to the market. These wells were completed at a later date. The low price
of natural gas is also one reason why the number of new wells drilled in the Barnett Shale has declined [13]. Our simple model shows how a decline in drilling activity affects production of natural gas in the Barnett Shale. It is impossible to say that the production decline observed in 2013 is an indicator that the overall gas production rate in the Barnett shale has already peaked, even though the U.S. Energy Information Administration (EIA) has stated that “some of the production declines in these fields (including Barnett) are also partially attributable to the normal decline or maturity of their existing wells” [13].

![Modeled and real shale gas production in Barnett Shale](image)

**Figure 3**: Annual production of shale gas in the Barnett Shale and the simulated production based on the decline profile of an average well. The calculation is based on the number of wells drilled each year, assuming that all wells drilled in a year are put into production that year. The difference between actual and calculated production, particularly for 2009 and 2010, can be explained by the fact that natural gas prices collapsed in 2009 and producers delayed the start-up of new wells.

**Future production of shale gas in Poland**

The area referred to as the most suitable for hydraulic fracturing in Poland is the Baltic Basin. The shale formation is at a depth of several kilometers along a belt that extends north from the central Pomerania district south towards the Lublin area. After few years of shale gas exploration, better knowledge has been gained on how to characterize the Basin. The Paleozoic shale formation has been
identified as containing significant hydrocarbon bearing rocks. Three potential intervals have been identified including the Lower Silurian, Ordovician, and Upper Cambrian. The Upper Cambrian shale is developed only in the northern part of the onshore Baltic Basin and in its offshore part, while the Upper Ordovician shale mainly is developed in the central and western part of the Baltic Basin [14]. The targeted intervals for drilling contain a package of thick, laterally extensive, organic rich source rocks in a relatively quiet tectonic setting between 2,000 – 5,000 meters depth. Comparing this with 40 historical wells drilled mainly from 1960s and 1970s, this most recent activities have brought about a breakthrough in the knowledge of the Lower Paleozoic play. Now it is clear that the Baltic Basin is not static.

There is still not enough understanding in terms of oil and gas quality of the reservoir and its future commercial potential. For now, the Upper Cambrian Alum shale is getting more attention in the northwestern part of Baltic Basin, while the Lower Llandovery shale appeared surprisingly rich in total organic content in some locations in the Eastern Baltic Basin [15]. An important outcome of new wells drilled in this part of Poland is the confirmation of the presence of gas and/or oil saturation in shale reservoirs, allowing for high expectations for the basin’s future commercial production.

In 2011, in the northern part of the basin (in the Pomeranian Voivodeship County) Lane Energy Company drilled the first full-scale exploratory well. The fact that a team coordinated by the Polish Geological Institute studied the environmental impact of the fracking means that we have a detailed description of the fracking of the well. The well close to Łebień is named "Łebień LE-2H", and is 4075 meters deep. The hydraulic fracturing was performed by Schlumberger in 13 clusters along the 1000 meter-long horizontal section of the well. About 17,322 m³ of water, 1,271 tons of quartz sand and 462 m³ of chemicals were mixed and injected in the well during the fracking. The report of the fracking is an environmental report and nothing is mentioned regarding gas production from the well [16]. Elsewhere, however, it was reported [17] that the initial gas production from this well was 8000 cubic meters per day (282000 scf/day), the first non-negligible production from a shale gas well in Europe, but still 8 times less than an average well in the Barnett shale.

![Production, Import, Consumption and Changes in Storage Volume for Poland](image)

**Figure 4:** Production, import, consumption and changed volume of natural gas reserves in Poland. *Source: Data is extracted from Figure 1 in reference [18].*
In 2012, Poland consumed on average 16.6 billion cubic meters of natural gas per year (bcm/y) or 1.6 billion cubic feet of natural gas per day (bcf/d) [2]. Gas production in Poland was 4.2 bcm/y and this leaves an import demand of 12.4 bcm/y. In Figure 4 the production, importation, consumption and variable volume of natural gas storage in Poland is presented for the years 2010 to 2013 [18]. Storage capacity in Poland makes it possible to have a rather constant import volume, and in our analysis the import volume is set constant at 12.4 bcm/y.

Most of the gas is imported from Russia and there are limited options to import natural gas from other nations. The Polish Oil & Gas Company (PGNiG) imports under the Yamal contract the most expensive stream of natural gas in Poland. The minimal Yamal gas reception provided for by PGNiG in Poland is approximately 9 bcm/y, which is almost 60% of current Polish demand [18, page 20].

Since Poland joined the European Union, there is a clear political desire to become less dependent on imported natural gas from Russia. The troubled political situation in Ukraine strengthens this desire and Poland is now highlighting domestic production of shale gas as an alternative.

In this report we examine what it would take for Poland to become self-sufficient in the provision of natural gas by using hydraulic fracturing of shale deposits. In our calculations we use the production profile listed in Table 2, i.e., we assume that the production profile of a typical gas well in Poland is the same as the production from an average well in the Barnett Shale. This may be somewhat optimistic assumption as no hydraulic fractured well in Poland has been reported to have flow rates that could be profitable. From this assumption it follows that production after three years declines by 78%. As a comparison, in his book "Drill, Baby, Drill", David Hughes has calculated the decline rates in four other U.S. shale formations where gas production is underway. The production decline after three years varies from 77 to 89 percent. A mean decline in individual wells for all U.S. shale gas production after three years is 81% [8]. This comparison shows that the decline of our model well is close to the mean.

We note that the Pomeranian Voivodeship County that includes Gdansk has a surface area of 18,300 km², which means that the Barnett Shale with its 13,000 km² could fit within it. There is a common perception that fracking in the U.S.A. occurs in areas of lesser population density than in Europe. However, examining the population density in the 6 counties listed in Table 1, we find that the average population density over that area of the Barnett Shale is 230 persons per square kilometer, while that in the Pomeranian Voivodeship County is 120 persons per square kilometer. Therefore this perception may be incorrect. With a total of 17,400 wells drilled in the Barnett Shale, the field produced more than 150 million cubic meter per day (mcm/d) or 5.0 billion cubic feet per day (bcf/d) in 2013, which is more than three times as much as Poland requires to be self-sufficient. A major difference between the U.S.A. and Poland is that there were already over 1,500 drilling rigs in the United States when the shale boom began. Soon thereafter, in early 2006, production in the Barnett Shale exceeded Poland’s needs. Using a range of assumptions regarding the number of future drilling rigs in Poland, we want to estimate how long it will take to make Poland self-sufficient in natural gas and how many wells it will be necessary to drill.
Figure 5: Production buildup of shale gas production in Poland under the assumption that the rig capacity after two years is sufficient to drill respectively 300, 400 and 500 wells per year. First month production for individual wells is 2.0 million cubic meters (mcm).

There are no conclusive data on the expected production from hydraulically fractured wells in Poland, but some data indicate that it may be less than in the Barnett Shale [17]. Despite that, we will use the production volume from the reference well in Table 2. A comparison of the five largest natural gas-producing shale formations in the United States shows that a well in the Barnett Shale has the lowest production volume during the first month [8]. It is therefore realistic to assume that a well in Poland at least should have the same volume of production as wells in the Barnett. Production for the first month is about 1.9 mcm (66 million standard cubic feet Mcf), and 2.0 mcm is used in the analysis. We assume that it takes 2 years to build the rigs needed to drill respectively 300, 400 and 500 wells per year. Further we assume that for each well there are months when production is zero because of maintenance requirements and other issues, as observed in production data [11]. We introduced a zero production month every 6th month. In Figure 5 we show production buildup under the various assumptions. With 300 new wells per year, i.e., 1800 wells after 7 years, Poland would not have a production volume enough to make it self-sufficient. To assure self-sufficiency within 7 years, up to 400 wells should be drilled per year. With 500 wells a year, there might be some volume of gas available for export. When self-sufficiency is reached it appears that 300 wells per year are needed to maintain the production at that level (see Figure 5).

The first month’s production for individual wells in the Barnett Shale may vary greatly, and in *Drill, Baby, Drill* [8], we can see that there is wide variation in the first month’s average production between various shale gas fields. For the case of 400 new gas wells per year in Poland, we have studied how different production volumes affect the structure of annual shale gas production. We have chosen 2.0 ± 0.5 million cubic meters for the first month’s production. A production rate of 1.5 mcm for the first month may be the lower limit in order for a well to repay investment costs. From Figure 6 we can see that the lower level of production volume obtained with 300 wells per year is not enough to make Poland self-sufficient for natural gas.
Figure 6: Production buildup of shale gas production in Poland under the assumption that 400 wells are drilled per year and that first month production (f.m.p.) for individual wells is 2.0 ±0.5 mcm.

Discussion

Assuming that an average shale gas well in Poland is as productive as an average Barnett shale well, 400 hydraulically fractured wells per year are needed for a shale gas boom that could make Poland self-sufficient in natural gas. For comparison we should mention that 840 wells were drilled in the Barnett Shale in 2013 and that this number was insufficient to maintain the 2012 production rate. In 2009, the peak drilling year in the Barnett Shale, 3,594 wells were drilled [10]. To assess whether or not a gas production boom in Poland is possible, we will discuss the factors that were crucial to the shale gas boom in the U.S.A.

Shale gas producing companies must make a profit. Normally, this profit is generated by the sale of natural gas and this sale should cover all production costs. However, in the initial stages or during critical periods, governments can subsidize operations.

Some of the important factors supporting the U.S.A. shale gas boom are:

• **Technological innovation:** Horizontal well drilling technology and improved technology for hydraulic fracturing were combined so that each drilled well accessed a reservoir volume large enough to drain natural gas at a rate sufficient to make the well profitable. Poland does not need to develop new technologies, but can apply approaches already used in the United States.
• **Landowner own mineral rights under their land [19]:** This fact has created increased interest from landowners to sell exploration rights to companies and to sign contracts that gives royalties from the sale of gas. The companies do not have to negotiate with the state and this creates opportunities for small companies to become actors side-by-side with major players. In Poland, state owns mineral rights and compensation to land owners will need to be generous. There may be potential for conflicts.

• **Government passed laws that facilitated extraction of shale gas:** In 2005, at the urging of Vice President Dick Cheney, Congress created the so-called “Halliburton loophole” to clean water protections in federal law to prevent the U.S. Environmental Protection Agency from regulating hydraulic fracturing, despite serious concerns that were raised about the chemicals used in the process and its demonstrated contamination of drinking water [20]. It is difficult to imagine that Poland and the EU will enact such a law.

• **The price of natural gas was high in the early 2000s:** Compared with today’s price, the price of natural gas was approximately double when the shale gas boom started. Today, the gas price in the EU is approximately twice the price in the U.S.A. Therefore, gas prices should be a positive factor for shale gas development in Poland.

• **Favorable geology for the production of shale gas:** We know that the geology is favorable for production of shale gas in the U.S.A. Our estimate of future shale gas production in Poland assumes similar conditions to those in the U.S.A. This assumption has resulted in, theoretically, very favorable circumstances for Poland, but we do not yet know its validity.

• **Access to water and sand:** Extrapolating from the reported volumes used for Poland’s first hydraulic fractured well [16,17], we find that 400 wells per year would use at least 6.7 million cubic meters of water and with somewhat longer fracking zones, over a million tons of sand. Drilling and completion of 400 wells would also generate large amounts of produced water that must be disposed of.

• **An extended pipeline system for natural gas is needed:** Poland already has a pipeline system for natural gas. New production regions would need to be linked to this system. Obtaining the money to fund this linkage should be possible through the sale of exploration rights that is already occurring.

The main issue for decision makers, in this case the EU, is to create market conditions and laws that encourage companies to invest and produce profitably the natural gas needed by the community. One can consider the EU Commission’s decision on recommendations for shale gas [5] as one step in this direction.

The key factor determining profitability is the volume of gas a well produces per year. Gas prices and potential/possible subsidies are also important. The detailed study we made of the production profile of wells in the Barnett Shale, and the fact that wells in other shale formations decline in similar ways, allows us to present simple rules to calculate the profitability of a shale gas well. If Q is the first month’s production in our model well, after 4 years this well produces 16.2Q. The total production after 10 years is 23.5Q. (Using q, production per day at startup, we get 700q as cumulative production after 10 years.) This means that after 4 years our well has produced 2/3 of the cumulative 10-year production.

First month production for our model well is 66,000 mcf (1 mcf=1000 standard cubic feet) and that means that the integrated production after four years is 1,069,200 mcf (1 bcf) and after 10 years 1,584,000 mcf (1.6 bcf). With the current low price of natural gas in the U.S.A., $ 4.5 per mcf, this means that the revenue after 10 years of production will be about $ 7,000,000. The American Oil &
Gas Reporter has published costs for natural gas production in the Barnett Shale and the well costs a minimum of $3 million, royalties of 22%, and operating costs of 0.7 $/Mcf [21]. For our model well, this would mean that one breaks even after 4 years and achieves a profit of $1.4 million after 10 years. A comparable well in the Haynesville shale, where the well cost is $8 million, royalties are 25%, and operating costs are 2.5 $/mcf, is not profitable.

Assuming a gas price in the EU of $9 per mcf, results in revenue of around $14 million after 10 years of production from our average well. A realistic operating cost is $2 million, and the fee to the state for permission to extract shale gas could be around $2 million. This means that the well cost and the profit can be $10 million. The fact that several of the big oil and gas companies have left Poland may indicate that the expected production per well is not large enough or that the cost of drilling a well is higher than in the U.S.A. On the other hand, Chevron and ConocoPhillips recently decided to stay and this gives a positive signal from the industry [22].

In addition to the fact that hydraulic fracturing must be profitable, there must also be acceptance by the general public in the areas where hydraulic fracturing is conducted. In Figure 1, we show that the entire area west of Dallas had many vertical hydrofractured wells before the transition to horizontal wells. This meant that one did not need new social acceptance for drilling horizontal wells, and there was little discussion of any environmental effects. Drilling and hydrofracturing new gas wells in Poland will be a completely different situation.

The Polish government’s decision to make a detailed environmental study in connection with the first full-scale fracturing in Poland is commendable. For details of the results, we refer to the report “Environmental impact of hydraulic fracturing treatment performed on the Łebień LE-2H well” [16]. The report includes the following summary:

“The hydraulic fracturing treatment did not generate any air pollution. Some increases of noise level were noted in time of hydraulic fracturing. The studies did not show any impact of the treatment on quality of surface and ground water nor decrease in ground water resources in the well site which would result from water consumption for the needs of the operation. The treatment also did not result in any ground vibrations or shaking which could create risk of damage for buildings or infrastructure.”

The most difficult issue for the people who will live in the area with fracking may be to imagine how gas wells will impact their surroundings. If fracking becomes reality, one must be aware that the activity will last for many years. At a rate of 400 wells per year, 4000 wells will be drilled after 10 years, and 12,000 after 30 years. After 30 years, the well density in some areas in Poland will be similar to that of the existing well density in the Barnett Shale with 17,400 wells. This density is less than one well per square kilometer. The well density that the IEA discusses in their report is one well per square kilometer [4].
Figure 7: The area east of Eagle Mountain Lake in Tarrant County is an area with high well density. The marked area in the figure is 25 square kilometers (note the scale at the bottom to the right) and the number of sites for fracture is 102 (4.1/km²). The number 2, 3, 4 etc. to the right of each site is the number of wells drilled at that site. In total, the number of wells is 178 (7.1 per km²). A and B are photo spots for respectively Figure 8 and Figure 9. In the middle to the right there is also a residential area. The number of sites and wells are deduced from DrillingInfo [11] and Google Map [24].

According to the Polish Geological Institute’s environmental report a fracking site is 3.74 acres (0.0374 km²) [16]. That means that 10 years of operation will occupy 225 km², which is a little over one percent of the area of the Pomeranian Voivodeship County. In areas that have favorable conditions for production, well density might be higher. To show how this might look, in Figure 7 we show an area in Tarrant County where the density is much greater than one well per square kilometer.

By using the Google map of the area in Figure 7 [24] one can get an idea what it looks like when one has a greater density than one well per square kilometer. The marked area is 25 km² and the number of fracking sites within this area is 102. From DrillingInfo [11] we find that the number of wells is 178 or 7.1 wells per km². Note that there is also a residential area within the marked area.
One of us, KA, has visited the Barnett Shale region to get a personal view of how one experiences such intensive production. While the wells and the infrastructure for gas production are, indeed, part of the visual landscape, each production unit is quite small and they do not dominate the landscape.

Natural gas compressors are at the heart of natural gas production. When production from the shale gas wells declines, gas pressure from these wells also declines. Gas compressors must be deployed to boost gas pressure to a high enough value for injection into the pipelines. In Figure 8, we show a compressor system that serves four wells. When planning a compressor station one must be aware that gas compressors are not noiseless. In densely populated areas, it may be necessary to place them in soundproof buildings. Compression of the produced shale gas so that it can be injected into the national gas grid is part of the operating cost.

Although the total land area occupied by production sites is small, these sites may interfere with the priorities of a landowner. In Figure 9 we show that shale gas production and livestock can coexist. Figure 10 shows that a production well may be in the middle of a corn field.
To facilitate public acceptance of fracking it might be important that production/exploration contracts contain a clause stating that as large a surface as possible should be restored to the previous condition after production ends. Another clause should direct what should be done with the well itself when production ends. To ensure that wells are abandoned according to prevailing regulations, companies could pay a plug-and-abandon fee up front and a state agency could be given responsibility for plugging of the well. This would ensure that, in the event that a gas production company goes bankrupt, the well will still be abandoned properly.

Conclusion

The recommendations of the European Commission highlight importance of keeping the public informed [5]. In order to rapidly scale up operations in Poland, it is very important that there are opportunities to quickly access enough drilling rigs and equipment for hydraulic fracturing. If it is important for the EU’s energy security that Poland becomes self-sufficient in natural gas, then EU should cooperate with operators in the U.S.A., to rapidly move equipment from the United States sufficient to drill 400 wells a year.

Poland should undertake an ambitious exploration/production program to quickly delineate its production potential for shale gas. Without completion of such a program, all talk of Polish energy independence is moot.

In the report "Golden Rules for a Golden Age of Gas" [4], the International Energy Agency states that the number of new shale gas wells must increase from the current 100,000 wells in the U.S.A. to about one million wells worldwide. Poland is one of the potentially most favorable areas for hydraulic fracturing. We showed that 30 years of natural gas supply with today's Polish consumption would generate about 12,000 of the 1,000,000 new wells that the IEA needs for a "Golden Age of Gas". The question is where the remaining 988,000 wells will be drilled.
We understand how important it is for the energy security of Poland and EU that Poland succeeds in fracking. We have performed our current analysis with a positive view, and have tried to make a realistic estimate of the conditions necessary to make Poland self-sufficient in natural gas. We are aware of that there is a public concern for the environmental consequences of hydraulic fracturing and we share the European Commission's view that information is required. However, it is also important for the general public to understand that modern societies cannot exist without ample cheap energy.

**Computational Methods**

The calculations were done with Excel in a matrix where the production for a number of new wells was calculated for up to 120 months. After the contributions of all new wells are added, the field’s total production for each month of the 120 months is calculated. For a production profile for each well, we chose the average well profile from the Barnett Shale. Further we assume that for each well there are months when production is zero because of maintenance requirements and other issues, as observed in production data, and we introduced a zero production month every 6th month. Production for the first month and the number of wells per month can vary.

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**Keywords:**

Hydraulic fracturing, Barnett Shale, shale gas, Poland, decline profile,

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