An assessment of the footprint and carrying capacity of oil and gas well sites: The implications for limiting hydrocarbon reserves.

Clancy, S. A. [1*], Worrall, F. [1], Davies, R. J. [2], & Gluyas, J. G.[1]

[1.] Department of Earth Sciences, Durham University, Science Labs, Durham, DH1 3LE, UK.

[2.] School of Civil Engineering and Geosciences, Newcastle University, Newcastle, NE1 7RU, UK.

[*] Corresponding author: sarah.a.clancy@durham.ac.uk

Abstract

We estimate the likely physical footprint of well pads if shale gas or oil developments were to go forward in Europe and used these estimates to understand their impact upon existing infrastructure (e.g. roads, buildings etc), the carrying capacity of the environment, and how the proportion of extractable resources maybe limited. Using visual imagery, we calculate the average conventional well site footprints to be 10800 m^2 in the UK, 44600 m^2 in The Netherlands and 3000 m^2 in Poland. The average area per well is 541 m^2/well in the UK, 6370 m^2/well in The Netherlands, and 2870 m^2/well in Poland. Average access road lengths are 230 m in the UK, 310 m in The Netherlands and 250 m in Poland.

To assess the carrying capacity of the land surface, well pads of the average footprint, with recommended setbacks, were placed randomly into the licensed blocks covering the Bowland Shale, UK. The extent to which they interacted or disrupted existing infrastructure was then assessed. For the UK, the direct footprint would have a 33% probability of interacting with immovable infrastructure, but this would rise to 73% if a 152 m setback was used, and 91% for a 609 m setback. The minimum setbacks from a currently producing well in the UK were calculated to be 21 m and 46 m from a non-residential and residential property respectively, with mean setbacks of 329 m and 447 m, respectively. When the surface and sub-surface footprints were considered, the carrying capacity within the licensed blocks was between 5 and 42%, with a mean of 26%. Using previously predicted technically recoverable reserves of 8.5 x 10^{11} m^3 for the Bowland Basin and a recovery factor of 26%, the likely maximum accessible gas reserves would be limited by the surface carrying capacity to 2.21 x 10^{11} m^3.

Key words: Fracking, Shale gas, Setbacks, Infrastructure, Bowland Shale, Well pad.

1.0 Introduction

The rapid growth of shale gas developments within the United States (US) and the possibility of developments within Europe have raised concerns about the potential environmental impact (McGowan, 2014; Bomberg, 2013). Landscape disturbance from shale gas developments is inevitable (Drohan et al., 2012) as numerous wells (10 wells each with multiple laterals) from many well pads are required to intersect the gas bearing formation(s) for the resource to be economically viable (Baranzilli et al., 2015). Land disturbance will vary depending on, amongst other considerations, the number of wells per pad, the well pad size, the well pad density (pads per area), and the specifics of the shale play that is being developed (Baranzelli et al., 2015). Furthermore, the pattern of land ownership, public engagement and development regulations may cause higher or lower densities of well pads.

The spatial footprint of shale gas developments consists of the well pad and the area required for access roads. In part, the number of wells on each pad defines the size of the well pad. In recent years the mean and maximum number of wells per site has been increasing, this trend has been attributed to advancements in technology and an understanding that greater consolidation of infrastructure is more efficient and economical (Drohan et al., 2012). In Pennsylvania, Johnson et al. (2010) document a mean of two producing wells per pad, Drohan et al. (2012) reported over 75% of pads to have just one or two wells per pad, whilst Jantz et al. (2014) found a mean of 2.45 wells per pad. When including producing and permitted wells there was a higher mean of 4.67 wells per pad. Jantz et al. (2014) focused on the more recently developed Bradford County, Pennsylvania, thereby giving a more recent picture of current development patterns and consolidation of infrastructure. In the UK, Cuadrilla Resource Ltd., herein termed Cuadrilla, who are currently investigating potential shale gas production from the Bowland Shale in Lancashire, have stated that they intend to have 10 wells per pad (Regeneris Consulting, 2011). The UK's Institute of Directors (IoD) suggested several potential development scenarios, one of which was based on the development of pads with 10 vertical wells and 40 laterals (four laterals per vertical well – Taylor et al., 2013). The US Inner City Fund (2009) summarised planning information requested by the New York Department of Environmental Conservation from three active Marcellus Shale operators and showed that a multi-well pad with six to eight wells would be between 10000 m^2 to 23000 m^2 (1 ha to 2.3 ha), with a typical site being 19000 m^2 (1.9 ha). The US Inner City Fund has suggested a 'rule-of-thumb', based on discussions with operators: assume an initial single-well pad size of 13000 m^2 (1.3 ha) that increases by approximately 1600 m^2 (0.16 ha) per well, i.e. according to these guidelines, a six well pad would have a footprint of 21000 m^2 (2.1 ha) (US Inner City Fund, 2009). In the UK, Cuadrilla is planning to develop 10 wells on a 7000 m^2 (0.7 ha) well pad (Broderick et al., 2011). However, Taylor et al. (2013) suggest future scenarios with shale gas pads of 20000 m^2 (2 ha).

It is difficult to review the additional footprint required for well site access roads as many researchers have not distinguished between the area required for general infrastructure (e.g. pipelines and storage ponds etc.) and the area specifically required for roads. However, Jantz et al. (2014) made this distinction and found the mean additional area for access roads to be 12000 m^2 (1.2 ha), with a range of 200 m^2 to 68000 m^2 (0.02 ha to 6.8 ha). Jiang et al. (2011) recorded a lower average of 5800 m^2 (0.58 ha), with a range of 400 m^2 to 11100 m^2 (0.04 ha to 1.11 ha). Access road widths generally range from 6 m to 12 m during the drilling and fracturing phase and from 3 m to 6 m during the production phase (NYS DEC, 2015). Calculations show that for every 46 m by 9 m access road, ~400 m^2 (0.04 ha) is added to the total well site surface acreage (NYS DEC, 2015). Permit applications for Marcellus horizontal wells prior to 2009 recorded road lengths ranging from 40 m to approximately 900 m (NYS DEC, 2015).

The physical footprint of the well pads and access roads do not necessarily represent the entire surface area as many regulatory bodies have proposed setbacks from the edge of the physical well pad. Setbacks are defined as the distance that well pads have to be away from existing infrastructure, they are enforced to provide additional protection to water resources, personal and public property, and the health and safety of the public (Eshleman & Elmore, 2013). The UK and several other European countries have no legislative or planning policy requirements on minimum setback distances; they are designated on a site to site basis (Cave, 2015). In the US, restrictions vary from state to state and are often based on local conditions such as population density (Richardson et al., 2013). Of the 20 sites surveyed in Richardson et al. (2013), 65% have building setback restrictions ranging from 30 m to 305 m from the wellbore, with an average of 94 m.

Surface footprint should be considered alongside the subsurface footprint. Geology, planning permits and legal requirements, along with the current onshore drilling technology, limits lateral well extent and therefore the well pad spacing (NYS DEC, 2015). Currently maximum lateral length cannot greatly exceed the depth of the well, however as drilling technology evolves this is likely to change (NYS DEC, 2015). In the UK, Broderick et al. (2011) and Hardy, (2014) note that typical horizontal wellbores extend 1 km to 1.5 km laterally, but agree it can be more. The Maryland Department of the Environment indicates that spacing multi-well pads in dense clusters located as far apart as is technically feasible makes maximum use of horizontal drilling technology and could minimise the surface footprint (Eshleman & Elmore, 2013). Composite Energy (cited in Broderick et al., 2011) estimates laterals of 1 to 1.5 pads per 1 km^2 (100 ha) should be sufficient in a UK setting. However, even spacing of well pads is often impossible, as it does not account for geology and above ground constraints, such as existing infrastructure (Broderick et al., 2011).

At the time of writing, few shale gas wells have been drilled in Europe. However, the 'big four' plays (the Barnett, the Fayetteville, the Hayneville, and Marcellus Shale) in the US host more than 30000 wells, consequently the literature is based mostly on US experiences (Inman, 2014). With a nascent shale gas industry in the UK and the rest of Europe, resource estimates are beginning to be published (e.g. Andrews, 2013; The Geological Society, 2012). However, accessible resource estimates around the world have not considered the carrying capacity (total area required) of the surface or subsurface footprint and how well site placements are restricted by the current surface environment, e.g. proximity to domestic housing. It will not be possible to drill where these are located without substantial and potentially unacceptable disruption. The limit on accessible surface locations and how this impacts recoverable resources has not been included in any resource evaluation. This study aims to determine the likely physical footprint of well pads if shale gas developments were to go forward in Europe. Using these estimates, we hope to better understand the carrying capacity of the environment and the associated limitations on recoverable resources.

2.0 Approach and method

To estimate the likely footprint of any shale gas development and the likely restriction this would cause to recoverable resources we considered the likely size of well pads and the size of potential setbacks. Without a shale gas industry currently operating within Europe, information has been drawn from the US and analogues within Europe (conventional wells in the UK, The Netherlands and Poland). The assessment of carrying capacity based on the well pad footprints was applied to the Bowland Shale, UK. The surface area above the Bowland Shale is split into blocks which are generally 100 km^2 (10000 ha) (Fig. 1). The UK government grants licences for designated blocks and invites exploration companies to bid for the right to explore that block for hydrocarbon resources. At the time of writing, 127 blocks over the Bowland Shale are licenced to various operators (Fig. 1). To assess whether the likely footprint from well pads represents an impact unique to shale gas extraction, comparisons to other types of currently operating comparator industries such as wastewater treatment works and petrol stations has been undertaken.

2.1 Footprint of conventional onshore hydrocarbon operations within Europe

The onshore, conventional well pads of the UK, The Netherlands and Poland were selected for study as the data were comprehensive and publicly accessible. Additionally, they represent a range of conventional onshore development styles in countries at varying stages of shale gas exploration. All 2193 wells drilled onshore in the UK were analysed (Oil and Gas Authority (a), 2016).

For The Netherlands, 426 of the 4307 onshore wells have been studied (Geological Survey of the Netherlands, 2016). To ensure an unbiased selection, wells sites were selected using the stratified random sampling technique; they were split into the 12 Dutch provinces and listed in order of spud date (the date drilling of the well began) before a proportional number from each province with varying spud dates was randomly selected. Of Poland's 8076 onshore wells, 802 have been analysed (Polish Geological Survey, 2016). However, due to less readily accessible data, a different selection process was used; the first 802 onshore wells that were listed on the Polish Geological Survey database were selected.

The direct well site footprint has been defined as the land required for the borehole, drilling and fracturing equipment, storage facilities and the additional land required for noise and visual barriers, such as hedges. For each country, we used aerial photography and the Google Earth polygon and ruler tool to measure the perimeter and area of each site in order to obtain the direct footprint. The measurements were then divided by the number of wells per pad to calculate the average area required per well. Additional access road measurements were included where possible (existing roads were not). Access roads were defined as purpose built extensions to existing roads which were solely built to allow for well sites access.

The majority of the Google Earth imagery was taken between 2005 and 2015 and was of good quality. Where ambiguity in the well site measurements did arise (due to issues such as photographic resolution, seasonal cover etc.), they were categorised by reliability. A quality classification system was not used for the access road measurements. In cases where identification was ambiguous, measurements were not taken.

Strong indication: Very clear indication of well site location, no or little ambiguity in defining well site boundaries (Fig. 1a).

Poor indication: Fairly good indication of well site located. One was relatively confident on defining an accurate perimeter.

Very poor indication: Some indication of a well site being present at some point, e.g. (1) well shape patches of field discolouration (Fig. 1b); (2) a clear patch of woodland or a pond in dense woodland the same shape and size of a well site (Fig. 1c).

No indication: No well site present and no evidence of having been present.

To ensure a sufficient number of well sites were measured from Poland and The Netherlands the results were bootstrapped. This random sampling technique allowed us to assess the confidence in the sample number. The bootstrap approach re-samples the current sample and measures how summary statistics vary upon re-sampling as a means of judging the adequacy of the overall sample. By re-sampling 100 measured well sites in groups of 10 we have evaluated the properties of variance and have been able to determine the level of confidence in the sample size.

2.2 Impact of well sites and setbacks on the land in the UK

For the purpose of this analysis, the setbacks defined for the State of Maryland developments were used; a setback of 152 m from the well pad for private wells, and a 609 m setback from upstream public surface water supply intakes and public system wells. These values were deemed suitable as they were vigorously scrutinized before being recommended for use in the State of Maryland. Whilst states such as Pennsylvania went ahead with the exploration and production of the Marcellus Shale, Maryland had an unofficial moratorium on shale gas development and during this time carefully considered whether exploration could go forward safely (Eshleman & Elmore, 2013). After much assessment of neighbouring states, reviews of current unconventional shale gas development regulations and best management practises, visits to well sites and an assessment of the available literature, the setback values suggested were determined to be acceptable (Eshleman & Elmore, 2013).

To assess the impact of well pads developed on the UK landscape; this study employed a variant of the Buffon’s needle approach (Ramaley, 1969). A well pad (as measured above) and its associated setbacks (as taken from State of Maryland developments) were randomly placed into the currently licensed blocks covering the Bowland Shale, and the probability that the direct and indirect footprint enclosed or crossed a feature of interest was calculated (Fig. 2). We considered 100 randomly placed well pads, based upon the suggested size of the UK industry (Taylor et al., 2013). The license block and the x and y coordinates within that block were randomly generated. The impact on different land types and existing infrastructure were recorded based on their importance as ranked below:

- **Mild (easily movable)**: fields, hedgerows and footpaths.

- **Moderate (movable but with some challenges)**: woodland and tracks.
- **Considerable (movable but extremely challenging)**: roads, railway lines and buildings.
- **Immovable (impossible to move)**: protected ponds, streams and rivers.

To assess if our sample of 100 well sites was an adequate sample size, a bootstrap analysis was performed on the results.

2.3 Wells per licence block

To determine the carrying capacity of an area for shale gas development, the number of well pads and associated setbacks it would be possible to place within a licence block without impacting existing infrastructure and without compromising access to the resource was assessed. A licensed block covering the Bowland Shale (Fig. 1) was selected using the uniform random distribution technique, and then the number of well pads that could be placed into that block with the recommended setbacks was calculated. The recommended setback of 152 m from the borehole determines the physical footprint on the land; it generates a total surface footprint of ~92400 m^2 (9.2 ha).

The subsurface footprint together with the surface footprint was included in the assessment of carrying capacity. The former was determined by the lateral extent of the horizontal wells: this study deemed a 500 m lateral a realistic projection for new UK developments, thus generating a subsurface footprint of 1 km^2 (100 ha). To assess the carrying capacity with respect to the subsurface the number of 1 km^2 (100 ha) sites that could fit into 20 of the 100 km^2 (10000 ha) licence blocks without overlap or disruption of surface infrastructure was counted. Of these 20 license blocks, 15 were randomly selected using the uniform random distribution technique, whilst five were chosen on the basis that they represented end members of the number of sites that could be located within a licence block. To assess if 20 random sites were sufficient to characterise the population, a bootstrap analysis was performed on all of the results, resampling in groups of five. From these results, a number of shale gas development scenarios were generated based on the physical number of well sites each block can sustain, assuming all 127 currently leased licenced blocks were developed.

2.4 Conventional well setbacks

Eshleman and Elmore (2013) recommended setbacks were used. To determine if these were realistic current acceptable setbacks from producing conventional well sites within the UK were measured. Using aerial photographs, the setback distances of 121 producing well sites were measured. Measurements were taken from the borehole to the edge of the nearest building (e.g. house, barn, farm etc.). Where more than one borehole was located on a well site, a central borehole was selected. Where the nearest building was not a house, the setback from the borehole to the nearest house was also measured. Setbacks from the nearest train line, pond, flowing water system (e.g. dyke, stream, river, sea) were also measured. If the setback was greater than 650 m from these additional infrastructures, it was not considered further.

2.5 Footprint of currently operating comparator industries in the UK

To assess whether the footprints from unconventional well sites represent an impact unique to shale gas extraction, comparisons to other types of currently operating industries was undertaken. Petrol stations being of roughly a similar size are a good comparison to shale gas well sites; both are often located in rural settings; and need to manage hazardous chemicals and hydrocarbons. There were 8494 petrol stations in the UK in 2015 (UK Petroleum Industry Association, 2016). We randomly selected and measured the direct physical footprint of 50. Our study excludes those attached to super markets, or with additional shops or car washes attached. All measurements were bootstrapped in groups of ten to ensure the sample size was sufficient and a fair representation of petrol stations overall.

Wastewater treatment works were also compared to shale gas developments: they too manage hazardous waste and chemicals, and are often located in rural settings. Site selection was determined based on data availability from searches carried out online. A search for wastewater treatment works with corresponding Population Equivalent (PE) was completed; those sites that recorded PE had their physical footprint measured. An assessment of 21 sites with PE varying from 1019 to 1.9 million was performed.

3.0 Results

3.1 Footprint of conventional onshore hydrocarbon operations within Europe

3.1.1 UK

Well pad size was compared against spud date, well location, and the company that drilled the well. Visual inspection of the results showed no variation between the different factors, thus we determined that these factors did not influence the overall footprint size and discarded these potential inputs, instead focusing on the independent well site measurements. The status of the 2193 wells analysed in the UK are given in Table 1: 30 were reported as 'void' as their footprints could not be measured; 21 were drilled too recently to appear on the available aerial images; 9 were actually located offshore; 1280 had no surface indication, leaving 883 wells with sufficient indication for a measurement. The average perimeter and area for the 883 wells measured was 422 m and 10800 m^2 (1.08 ha), with a range of between 21 m and 914 m for the perimeter and 27 m^2 (0.0027 ha) and 35400 m^2 (3.54 ha) for the area (Table 2). The abandoned Poxwell 1 well (Dorset) had the smallest footprint, whilst the producing Welton well pad (Lincolnshire) had the largest: at the time of writing 41 conventional wells were located on this site. The average perimeter and area for the 780 wells with a 'strong indication' was 450 m and 11800 m^2 (1.18 ha) (Table 2). The UK averages 20 wells per site, using the average area calculated for all the wells this generates 541 m^2/well (0.05 ha/well). The average perimeter and area for the 738 access roads measured was 460 m and 1520 m^2 (0.152 ha), with an average road length of 230 m. The maximum access road length was 2040 m; however, some wells had no additional access road.

3.1.2 The Netherlands

Of the 426 wells studied, 218 indicated current or past drilling: 179 recorded a 'strong indication' of well site footprint; 9 a 'poor'; and 30 a 'very poor' (Table 1). The average well pad perimeter and area was calculated at 692 m and 44600 m^2 (4.46 ha). The average footprint for wells with a 'strong indication' was 808 m and 53800 m^2 (5.38 ha), whereas for 'poor' and 'very poor' they were 173 m and 2220 m^2 (0.22 ha) and 152 m and 2630 m^2 (0.26 ha), respectively. Well sites in The Netherlands average 7 wells per site, giving an average of 6370 m^2/well (0.64 ha/well). There were 145 well pads with defined access roads; the average perimeter and area was 620 m and 1950 m^2 (0.2 ha). The maximum access road length was 1410 m, whilst the average was 310 m.

3.1.3 Poland

Well analysis showed 160 of 802 wells indicated the location of the well pad footprint. Of these, 54 were recorded as showing a 'strong', 25 a 'poor' and 81 a 'very poor' indication of the well site footprint (Table 1). The average well pad perimeter and area were 176 m and 2960 m^2 (0.30 ha). The average area and perimeter for wells with a 'strong indication' of the well site footprint was 194 m and 2940 m^2 (0.29 ha) (Table 2). The average footprint with a 'poor indication' was 59 m and 352 m^2 (0.04 ha), whereas the average with 'very poor indication' was 205 m and 3770 m^2 (0.38 ha) (Table 2). Poland averages 1.03 wells per site, thus has an average area of 2870 m^2/well (0.29 ha/well). The average access road perimeter and area for the 90 sites measured was 499 m and 1260 m^2 (0.13 ha). The maximum access road length was 3040 m, whilst the average was 250 m.

3.2 Impact of well pads and setbacks on the land in the UK

For the UK, the direct footprint would mean a 33% probability of interacting with immovable infrastructure, rising to 73% with a 152 m setback and 91% with a 609 m setback (Table 3). The bootstrap analysis on the results from the 100 well sites showed that by a sample size of 80 wells, there was no change in the percentage of land impacted, thus the sample size of 100 well sites was appropriate.

3.3 Wells per license block

If each well pad had a subsurface footprint of 1 km^2 (100 ha) then one 100 km^2 (10000 ha) license block could potentially contain 100 well pads, as long as there were no restriction on the placement of the well pads at the surface. However due to streams, rivers and manmade infrastructure this will not be possible. Between 5 and 42 well pads were located in the 20 license blocks tested (Fig. 3) and the average license block could hold 26 well pads. These results highlight that a considerable amount of gas in-place cannot be extracted due to restrictions from infrastructure (Table 4). These results were subject to a bootstrap analysis, showing there was little movement in the average number of wells that could be allocated in each block after 10 blocks, thus our results indicated our sample size was sufficient.

Using footprint values determined from conventional well sites the likely direct physical footprint from 26 well pads would be 281000 m^2 (28.1 ha). However, the total footprint from the well site increases substantially to 2.4 km^2 (240 ha) when the recommended 152 m setback from the borehole is considered (Table 5); this would be 2.4% of the total area of the licensed block. The minimum number of well sites a licence block held was five, generating a direct physical footprint from the well pad of 54000 m^2 (5.4 ha) and a total footprint of 462000 m^2 (46.2 ha) (Table 5). The block that could accommodate 42 well sites would have a direct footprint of 454000 m^2 (45.4 ha), and a total footprint of 3.88 km^2 (388 ha) (Table 5).

Different shale gas development scenarios have been considered based on the physical number of well sites each block can develop, assuming all 127 licenced blocks that are currently leased are developed. The first scenario considers one well site being developed per block, 127 wells would generate a physical direct footprint of 1.37 km^2 (137 ha) and a total surface footprint of 11.7 km^2 (1170 ha) (Table 5). If five were developed in 127 blocks, 635 wells sites would be established generating a direct footprint of 6.86 km^2 (686 ha) and a total surface footprint of 58.7 km^2 (5870 ha) (Table 5). If the average 26 were developed in each block, a total of 3302 well sites would be developed. This would create a direct footprint of 35.7 km^2 (3570 ha) and a total surface footprint of 305 km^2 (30500 ha) (Table 5).

3.4 Conventional well setbacks

The mean setback for currently producing conventional wells in the UK was 329 m from a building. The minimum setback distance from a building, recorded for the Gainsborough 14 well, was 21 m. Of the 121 well sites examined, 33 had setbacks from buildings that were below the recommended 152 m set by Eshleman and Elmore (2013) (Fig. 4). Many of the producing well sites had a number of boreholes on the pad; the above mean values include all 680 wells located on the 121 well sites. If we give the mean value for just one well per well site, thus 121 well sites, the mean setback from a building is slightly lower at 303 m.

The mean setback from a house for all the wells was recorded at 447 m. The minimum setback from a house was 46 m, this was recorded for the Gainsborough 29 (A1) well. There were nine well sites with setbacks from houses that were less than recommended (Fig. 4). The mean setback from a house when one well per site was considered was 410 m.

There were 14 well sites within 650 m of a train line; four were within the recommended 152 m setback (Fig. 4). The mean and minimum setback distance from a train line for all wells was 238 m and 38 m. There were 51 well sites within 650 m of a pond, eight were below the recommended 152 m setback (Fig. 4). The mean and minimum distance from a pond was 371 m and 107 m. The mean distance from flowing water (dyke, stream, river, sea etc) was 219 m. The minimum distance from a dyke was 26 m. There were 58 well sites within 650 m of flowing water, 28 were below the recommended 152 m setback (Fig. 4).

3.5 Footprint of currently operating comparator industries in the UK

There were 8494 petrol stations in the UK in 2015 (UK Petroleum Industry Association, 2016). Based upon the random sample, the average area was 1360 m^2 (0.14 ha) with a range of 558 m^2 to 2600 m^2 (0.06 ha to 0.26 ha). The petrol station bootstrap analysis results indicate that our sample size was sufficient and that the variance was accounted for. Based on the number of petrol stations recorded in 2015 a rough approximation of the total footprint required by petrol stations was calculated at 11.6 km^2 (1160 ha). This is considerably less than the direct footprint of the available capacity for shale gas development in the current UK licensed blocks.

The 21 measured wastewater treatment works covered a range of PE from 1019 to 1.9 million, the physical footprint of the sites ranged from 2417 m^2 (0.24 ha, PE=1718) to 1.48 km^2 (148 ha, PE=1750000). The Department for Environment, Food and Rural Affairs (2002), recorded approximately 9000 wastewater treatment works across the UK; if we assume the range used in this study then the footprint of wastewater treatment works in the UK would be between 54 km^2 and 89 km^2 (5400 ha and 8900 ha) – less than the direct footprint of shale gas development within the current UK licensed blocks.

4.0 Discussion

The literature states that an average six well shale gas pad in the US is approximately 21000 m^2 (2.1 ha) (US Inner City Fund, 2009). This is slightly higher than UK estimates of 20000 m^2 (2 ha) for a well pad in the production phase (Taylor et al., 2013). These measurements and projections are higher than the average 10800 m^2 (1.08 ha) footprint measured for conventional onshore wells in the UK and the average 3000 m^2 (0.30 ha) site measured in Poland but they are considerably smaller than The Netherlands average of 44600 m^2 (4.46 ha). Area per well shows the UK's conventional oil and gas industry to be the most space efficient of the three European countries measured, with an average footprint that is lower than that reported for US shale gas well pads. These differences could be due to a number of factors. Historically, site regulations in the US have been much more relaxed. This is in part due to land ownership rights. Uniquely, out of the countries considered, in the US private individuals own the majority of the subsurface mineral rights. Many owners are willing to lease acreage for exploration and development as there is considerable financial gain (Jacquet, 2012). Equally, the UK is around seven and a half times (Taylor et al., 2013) and Poland three and a half times (The World Bank, 2016) more densely populated than the US, therefore the US is not under the same space restraints as many European countries. The US shale gas industry has developed substantially in areas such as the Eagle Ford, where population densities might be lower than average and have little existing infrastructure to disturb (Tunstall, 2015).

The UK and The Netherlands are both economically well developed and heavily populated, thus one would expect them to have similar laws and comparable well site sizes; however this appears not to be the case. It appears that each country must have slightly different framework objectives with varying planning laws. In addition, although not supported by the literature, it is possible some of the well site footprint in The Netherlands is inclusive of processing infrastructure, whereas the UK and Poland tend to have separate processing facilities offsite. For example, at the time of writing, Third Energy's four producing gas fields beneath the Vale of Pickering supply the offsite North Yorkshire's Knapton Generating Station. It is apparent when measuring sites in The Netherlands that extra attention has been made to protect surrounding areas against noise and visual pollution; this added mitigation technique also adds acreage to the well site footprint.

Access roads recorded within the US are between 40 m and 914 m long, occupying an additional 12000 m^2 (1.2 ha) of footprint (NYS DEC, 2015; Jantz et al., 2014). This study found access roads for conventional well pads in the UK averaged 230 m, whilst in Poland they averaged 250 m and in the The Netherland's 310 m. As in the UK, standard practise in the US involves connecting the well pads to the nearest existing public road, or if granted permission the nearest private road using the shortest possible distance (Racicot et al., 2014). US access roads are longer than in Europe, which is unsurprising given the lower population density of the US.

The British Geological Survey (BGS) in association with the UK Department of Energy and Climate Change (DECC, renamed 'BEIS' in 2016) estimated the resource (gas-in-place) for the Bowland Shale to be between approximately 2.33×10^{13} m^3 to 6.46×10^{13} m^3, and projected a central estimate of roughly 3.76×10^{13} m^3 (Andrews, 2013). More important is the highly variable technically recoverable reserve, a BGS report for DECC in 2010 estimated shale gas reserves of 1.33×10^{11} m^3 in the Upper Bowland Shale Basin (Andrews, 2013). The US Energy Information Administration (US EIA) at the Department of Energy estimated the total UK shale gas resource in place at 2.75×10^{12} m^3 and assumed a 21% recovery factor, resulting in recoverable reserves of 5.66×10^{11} m^3 (The Geological Society, 2012). Cuadrilla estimate at least 5.66×10^{12} m^3 shale gas resource is in place in the Bowland Basin, and they propose a conservative recovery factor of 15% would yield a reserve of around 1.27×10^{12} m^3. However, the BGS have since revised these calculations and noted that a recovery factor of 15% would in fact yield a technically recoverable reserve of 8.5×10^{11} m^3 (The Geological Society, 2012). The Geological Society (2012) summaries the three estimates of UK shale reserves at around 2.83×10^{11} m^3 (England only), 5.66×10^{11} m^3 (UK) and 8.5×10^{11} m^3 (Bowland Basin only).

Estimates of shale gas recoverable reserves have not considered the carrying capacity of the surface and have been governed by the volume of the organic-rich shales and the limitation of the technical recoverable fraction of the gas developed within that shale. However, the premise of this study has been that the recoverable reserve is limited by the carrying capacity of the surface. Taking into consideration Cuadrilla's technically recoverable reserve estimate of 8.5 x 10^{11} m^3, the actual accessibility due to infrastructure constraints and the fact that just 26% is likely to be recovered means that approximately 2.21 x 10^{11} m^3 could feasibly be extracted. To produce a more accurate extraction assessment a number of additional considerations need to be included. If setback restrictions were relaxed, additional well sites could be located per block: for example, if 42 wells were the average per block this would mean approximately 42% of the estimated shale gas could be extracted. In this instance, with Cuadrilla's corrected technically recoverable reserve estimate, approximately 3.57 x 10^{11} m^3 of gas could be extracted.

Setback restrictions within the US can vary considerably. This study used the setbacks recommended for the Marcellus Shale gas developments in Maryland. To determine if they were realistic we measured the setbacks of the currently producing wells in the UK. The study found the average has a setback from buildings of 329 m, with the minimum being 21 m. The Gainsborough 14 well has the shortest distance from a building; interestingly the building was built after the well was developed. The average setback from a house was recorded at 447 m. The Gainsborough 29 (A1) well has the shortest setback from a house (46 m); since the well was spudded in 1962 a housing estate has developed around the well. These results show the average is greater than those suggested by Eshleman and Elmore (2013) for developments in Maryland; however there are many cases where the setbacks for conventional wells are smaller than 152 m.

If we assume all 127 licenced blocks currently leased are developed with an average of 26 well pads per block, 3302 could be developed. This would generate a direct footprint of 35.7 km^2 (3570 ha), and a total surface footprint of 305 km^2 (30500 ha). The average area of a single petrol station was 1360 m^2 (0.14 ha), a rough approximation of the total footprint required for the 8494 across the UK was calculated at 11.6 km^2 (1160 ha), and for wastewater treatment works the total UK footprint was between 54 km^2 and 89 km^2 (5300 ha and 8900 ha). The footprint sizes calculated for these industries allow us to conclude that the footprint required for shale gas development is not unique when compared to other industries. However, the development in the UK of petrol stations, or of wastewater treatment works, does not have a regulated setback distance as has been considered here for shale gas development and when setbacks were considered the potential development of a shale gas industry has a far larger footprint. To minimise the footprint required for shale gas developments, sites should be multi-well and located as far apart as technically feasible. This will reduce the area required per well and ensure maximum use of horizontal drilling technology.

This study has largely focused on the shale gas industry within Europe but the methodologies applied are transferrable across other industries and different disciplines. The Buffon's needle analysis is a useful method to determine the spacing and the likely carrying capacity of future developments such as housing, retail centres and industrial sites (e.g. wastewater treatment works, recycling centres). With global population set to increase, these developments and additional infrastructure is inevitable, highlighting the need for a systematic approach to where these sites are located with minimum impact. Acknowledging the importance of site location and the need of setbacks in other industries, such as recycling centres, is also of vital importance when developing new sites. In a society that is continuously growing we need to protect specific infrastructure with appropriate setbacks. However, it should be remembered that the carrying capacity is always going to be defined by public consent and in this study we have assumed the importance of surface features and infrastructure, e.g. the immovability of rivers. In a different era such assumption of acceptability may be incorrect.

5.0 Conclusion

This study has developed a Buffon's needle analysis in order to understand the carrying capacity of new infrastructure developments and their impact on existing infrastructure and the environment. Using this analysis, we evaluated the potential impact of the development of a shale gas industry within the UK. We found that there is a 33% probability that a shale gas well pad would directly contact immovable infrastructure, but this increases to 91% when a setback of 609 m is used.

In the UK, the average actual setback from conventional onshore well pads is 329 m for any building or 447 m for a house, but can be as low as 21 m and 46 m, respectively. The carrying capacity of the surface is 26% on average but ranges between 5 and 42%. Thus, the likely maximum number of wells and associated setbacks that could be located within a block (typically 10 km by 10 km) would be 26. The carrying capacity of the land surface, as predicted by this approach, would limit the technically recoverable gas reserves for the Bowland Basin from the predicted 8.5 x 10^{11} m^3 to only 2.21 x 10^{11} m^3.

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Figures

Fig. 1 A section of the north of England showing blocks offered under the 14th Onshore Licensing round (Oil and Gas Authority (b), 2016). The cream coloured blocks indicate the 127 currently licensed onshore blocks over the Bowland Shale.

Fig. 1a Kirby Misperton 1, 3 and 7 wells, an example of wells with a 'strong indication' of where the well pad boundaries are located (image extracted from Google Earth Pro, 2016). There is little ambiguity as to boundaries location. Site location: latitude 54.2003 and longitude -0.81946.

Fig. 1b Castletown 1 well, an example of a well with a 'very poor indication' of where a well pad was once located (image extracted from Google Earth Pro, 2016). The field discoloration clearly indicates where a well site used to be present. Site location: latitude 53.054 and longitude -2.849.

Fig. 1c Northwood 1 well, an example of a well with a 'very poor indication' of where a well pad was once located (image extracted from Google Earth Pro, 2016). The pond in the woodland is the same size and shape as a well site indicating where a well site once was. Site location: latitude 52.974 and longitude -2.235.

Fig. 2 An example of a random drop site from the Buffon's needle analysis (map extracted from Digimap, 2016). At this locality, we can see that the well pad with a 609 m setback converges with fields, woodland, footpaths, houses, ponds and several major roads.

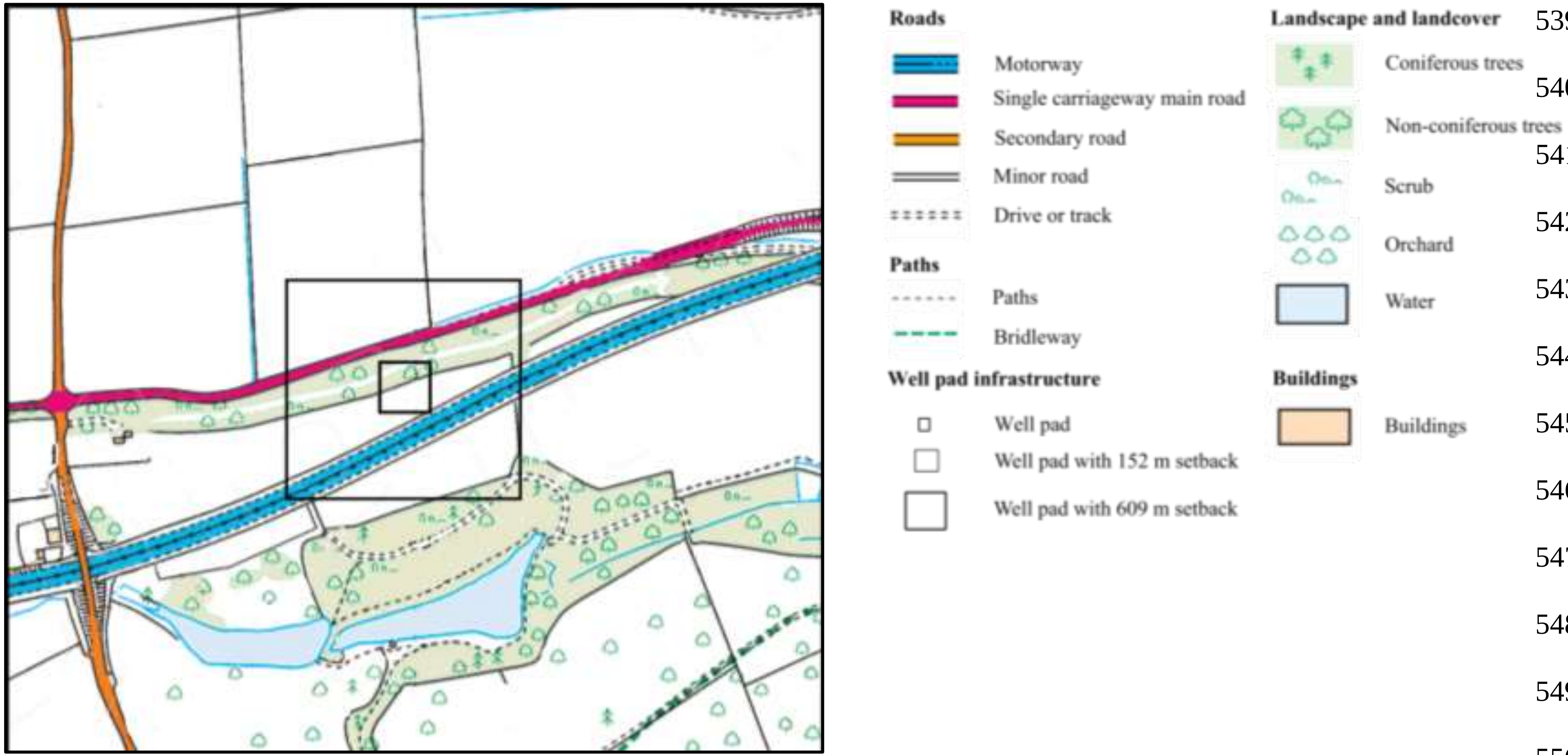
Fig. 3 A schematic example of how many well pads with the recommended 152 m setback and a 500 m lateral can be located within a currently licensed block (map extracted from Digimap, 2016). In this example, 31 well pads could be located within the 100 km^2 block without impinging on existing infrastructure.

Fig. 4 The distribution of the measured setbacks from the nearest building, house, train line, pond and flowing body of water (e.g. stream, dyke, river, sea) for the 121 sites.

Fig. 1

Fig. 1
Fig. 1a
Fig. 1b
Fig. 1c
N
NY
NZ
OV
SD
SE
SJ
SK
TF
CARLISLE
NEWCASTLE UPON TYNE
SUNDERLAND
MIDDLESBROUGH
SCARBOROUGH
MORECAMBE
YORK
BLACKPOOL
PRESTON
BURNLEY
LEEDS
BOLTON
BARNSLEY
DONCASTER
SCUNTHORPE
MANCHESTER
LIVERPOOL
SHEFFIELD
MACCLESFIELD
CHESTERFIELD
LINCOLN
CHESTER
MANSFIELD
SKEGNESS
NEWARK-ON-TRENT
WREXHAM
STOKE-ON-TRENT
NOTTINGHAM
DERBY
STAFFORD
TELFORD
LEICESTER
WOLVERHAMPTON
PETERBOROUGH
50 m
50 m
50 m

Fig. 2



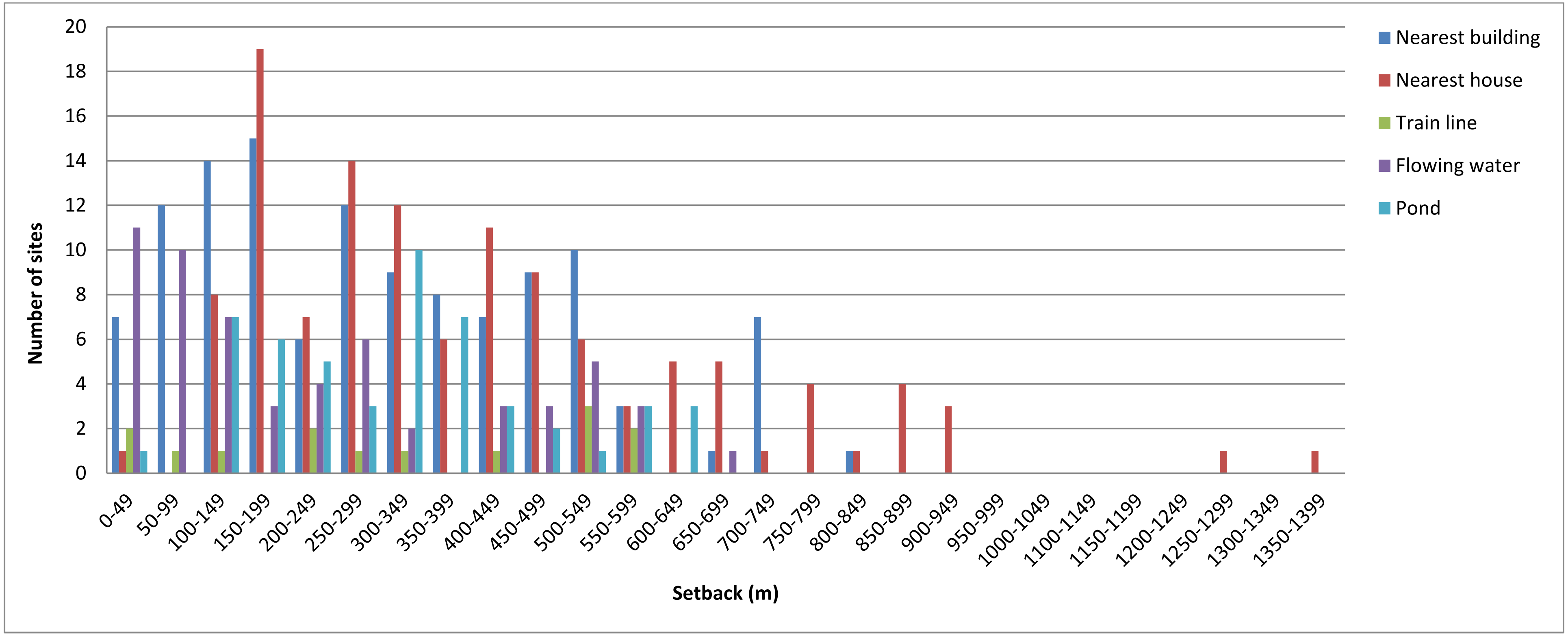
Roads
Motorway
Single carriageway main road
Secondary road
Minor road
Drive or track
Paths
Paths
Bridleway
Well pad infrastructure
Well pad
Well pad with 152 m setback
Well pad with 609 m setback
Landscape and landcover
Coniferous trees
Non-coniferous trees
Scrub
Orchard
Water
Buildings
Buildings

Fig. 3


Roads
Primary route dual carriageway
Primary route single carriageway
Multi level junction
A road single carriageway
B road single carriageway
Minor road over 4 m wide
Minor road under 4 m wide
Railway Features
Standard gauge railway
Water features
River
Cities towns and other settlements
City or large urban area
Small urban area
Land features
Woodland
Relief
Well pad infrastructure
Well pad with 152 m setback
500 m lateral from borehole

557 **Fig. 4**

558



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