Decommissioned wells: using factors associated with integrity to prioritise stewardship

Chief Scientist’s Group report

Date: December 2021

Version: SC190005/R1

Published by:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH

www.gov.uk/environment-agency

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Keywords:
Decommissioning, well integrity, oil and gas wells, fugitive gas, well leakage

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Project number:
SC190005/R1

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Professor Doug Wilson
Chief Scientist

Executive summary

Wellbore integrity failure at decommissioned petroleum wells is a historic and ongoing challenge for industry and regulators. Unfortunately, a small percentage of decommissioned wells develop integrity failure, resulting in releases of methane to the surrounding soils and atmosphere. Currently, the causes, risk factors, incidence rate and environmental risks associated with integrity failure are not well understood. As the number of decommissioned wells grows during the transition to net zero, it is essential that strategies for stewardship of these wells are developed if the legacy of environmental impacts from petroleum resource development is to be effectively and permanently managed.

This study reviews readily available data on all energy wells in England, in order to improve understanding of the potential integrity status of decommissioned onshore wells, and to develop a strategy for ongoing stewardship. The data cover the locations, types, intentions, and basic construction dates of wells. Five main factors, which are likely to influence the overall long-term integrity of decommissioned wells, and for which data are available are as follows:

1) Periods of extreme drilling activity, when the number of wells completed annually was significantly more than normal (defined as 2 standard deviations above the mean).
2) Construction before or after 1966, because this was when robust regulation and guidance on how wells should be constructed and abandoned were introduced (The Well Design and Construction Regulations and Borehole Site Operations Regulations and associated guidance).
3) Decommissioning before or after 1953, because this was when substantial standards for cementing oil and gas wells were first defined and applied (API Std. 10A).
4) Well orientation, and specifically whether or not a well is deviated from vertical.
5) The intent of the well, that is if it was designed for exploration, appraisal or production.

These factors are used to survey the potential long-term integrity of decommissioned wells in England, so that wells can be prioritised for stewardship. The survey results are used to segregate the stock of onshore decommissioned wells into ‘tiers’ corresponding to different levels of potential long-term integrity, based on the five main factors. Tier 1 contains wells with the greatest integrity, that is the lowest relative potential to release methane, and tier 6 contains wells with the lowest integrity, in other words, the greatest relative potential to release methane.

Out of a total of about 2,150 wells, about two-thirds were in the lowest 3 tiers, where potential integrity was greater. Specifically, there were 4%, 23% and 40% of wells in tiers 1, 2 and 3 respectively. The remaining third of wells were in tiers 4 and 5 where potential integrity was lower. Specifically, there were 23% and 9% of wells in tiers 4 and 5 respectively. There were no wells in tier 6, which corresponded to the least potential for long-term integrity.

The wells with the lowest potential long-term integrity were therefore those in tier 5, of which there were about 200. In general, these were production wells that were completed before 1953 and that deviated from vertical, or were completed during a year of extreme drilling activity. Of the 200 tier 5 wells in England, 134 are in the East Midlands, 19 in the south, 32 in the north-west, and 9 in Yorkshire and Humberside; the remainder are dispersed around the country.

Tier 4 and 5 wells have attributes that are known to reduce long-term well integrity, and so they have a greater relative potential to release methane. It is therefore recommended that they are prioritised for stewardship. It is also recommended that more information on decommissioned wells in England should be collated, for example, abandonment date, total depth, and details of construction and abandonment. This information can then be used to categorise wells more rigorously according to their potential long-term integrity, and to further develop the prioritisation scheme. Additionally, new field investigations are recommended for tier 4 and 5 wells, especially for those clustered in the East Midlands, the south, the north-west, and Yorkshire and Humberside. Such investigations would: (i) provide insight into the true status of wellbore integrity, (ii) characterise any potential environmental impacts, and (iii) allow validation and calibration of the prioritisation scheme. The findings of this study can guide future research and contribute to a risk-based approach for stewardship of decommissioned onshore petroleum wells in England and elsewhere.

Although this study provides information to guide a logical and prioritised approach to stewardship of decommissioned onshore wells, it is not a formal risk assessment and does not assess actual integrity status. Any conclusion that an individual well will, or will not, exhibit integrity failure now or in the future, is outside the scope of this study.

Introduction

Wellbore integrity failure is recognised as a critical environmental risk associated with petroleum resource development[1]. It has been suggested that it can occur in 0.1 to 75% of energy wells[2]. It results in petroleum fluid migrating within and/or outside a wellbore structure and into the environment[3]. Migrating petroleum fluids can impact groundwater[4-6], pose an explosion hazard[7] and contribute to greenhouse gas emissions upon reaching the atmosphere[8-10]. Once released, methane (CH_4) has a global warming potential 86 times greater than carbon dioxide (CO_2) over 20 years, and 25 times greater over 100 years[11,12]. Consequently, CH_4 emissions are a significant contributor to short-term global warming and their role in climate change is becoming increasingly recognised as scientists observe atmospheric concentrations continually rising[13,14].

Wellbore integrity failure is a complex and multifaceted phenomenon[15-17], in which it has been suggested that a combination of environmental factors (for example, geography, geology) and human factors (for example, engineering, regulation) play a role[3]. Integrity failure can occur in any ‘demographic’ of energy wells, for example, whether a well is shallow, deep, producing, abandoned, conventional, or unconventional. However, it is of particular concern with decommissioned wells (as opposed to active or suspended wells) where plug and abandonment have sought to seal and prevent fluids migrating within or outside them in perpetuity[18,19]. After decommissioning, there is clearly a benefit in monitoring, measuring and verifying abandonment conformance in order to ensure wells are sealed effectively and safely, and that there are no environmental impacts [20]. There are currently no such stewardship programmes for decommissioned wells in any regulatory regime, either in UK or overseas. Consequently, abandonment performance or the presence and nature of actual or potential environmental impacts remains uncertain and a point of debate.

While the UK does not have an extensive onshore oil and gas industry compared to some regions such as North America, it has approximately 2,150 onshore energy wells, most of which are decommissioned[2]. Recently, a field investigation was carried out as part of the Refine Project (http://www.refine.org.uk/) to assess the integrity of a subset of 100 of these decommissioned wells across England, and to identify if leaks of petroleum fluids might be occurring. It was reported that approximately 30 of the investigated well sites exhibited potentially elevated levels of methane at the soil surface around the abandoned well head location, compared to a paired control site. This was interpreted as indicating leakage due to well integrity failure[21]. However, the results and conclusions from this study should be viewed cautiously in light of more recent research, which has shown leakage from energy wellbores to be a highly complex phenomenon that varies in time and space[8,9,22,23]. The recent research and other studies show that surficial monitoring methods, like those used in the Refine Project, have limited potential to conclusively detect or quantify leaks associated with well integrity failure.

Since the initial work by the Refine Project, no other research has sought to further understand the status of decommissioned onshore wells in the UK, or to assess factors that may determine wellbore integrity. For example, it is not clear which regulatory standards were in place during the construction or abandonment of the UK's onshore wells or how these standards have changed, despite the strong influence that standards have on the likely integrity of wells. Similarly, it is unclear if it is possible to obtain, collate or review data held on decommissioned wells (for example, regarding construction or abandonment configuration) despite the importance of that data for assessing potential long-term well integrity. Finally, there has been no exercise to develop a method for prioritising stewardship of the UK's onshore wells, so that the supervision and/or further investigation of well integrity can be optimised, targeted and managed in future as part of a risk-based approach.

Consequently, a collaborative project was initiated by Heriot-Watt University and the Environment Agency, in order to build on previous work and to advance understanding of the integrity status of decommissioned onshore wells in England. The project comprises 3 related tasks:

1) A literature review of decommissioning guidance and regulations in England over the past 100 years, and of other factors that may potentially influence long-term well integrity.
2) An assessment of the potential long-term integrity of decommissioned onshore wells in England, based on the influential factors identified in task 1.
3) Field investigations to further assess the integrity of selected wells where the fieldwork of the Refine Project suggested there was evidence of integrity failure.

This technical report summarises the findings of tasks 1 and 2. Here, readily available data on onshore decommissioned wells in England is assessed, and factors are identified from that data which are likely to influence long-term integrity. Subsequently, these factors are integrated into a method for prioritising stewardship of decommissioned wells in England. Here, all decommissioned wells are segregated into 6 tiers, corresponding to different levels of potential long-term integrity. Finally, recommendations are made for potential next steps to increase understanding of well integrity at onshore wells and for their ongoing, optimal management and stewardship.

Method and scope

The work described in this report comprises tasks 1 and 2, as described above. It was conducted as a desk study based on extensive literature searches, and on detailed reviews of wellbore construction and abandonment regulations and guidance for the UK. The study also involved liaising with leading subject matter experts at the UK Oil and Gas Authority (OGA), the UK Health and Safety Executive (HSE) and the Environment Agency. Additionally, publicly-available data from the OGA online repository was used to attain basic information on the UK onshore well stock. This included data on well type, intent, orientation, location and age (dates of spud, completion and rig release), from which potential long-term integrity could be inferred.

The scope of this study is to assess the evolution of regulatory, guidance and technological frameworks for the construction and abandonment of wells in England, in order to identify critical factors that are likely to influence long-term wellbore integrity. From these factors, the potential long-term integrity status of onshore decommissioned wells in England is inferred. The study aims to provide information to steer and guide a logical approach to stewardship and management of decommissioned onshore wells in the UK. It does not assess actual integrity status and is not a risk assessment, and it should not be used to conclude that any wells have exhibited integrity failure, or will exhibit it in the future.

Availability of data on onshore wells

Basic data on onshore wells in the UK is available from the UK OGA online data centre. These data were downloaded for this investigation on 4 January 2020, and they include important basic attributes associated with each well (Table 1).

During the project the OGA, HSE and the Environment Agency were engaged to assess the accessibility and availability of additional, more detailed data relevant to the construction and abandonment of onshore wells in the UK. Important information was sought, such as well construction details (cement tops, casing depths), abandonment dates, abandonment configurations (number and nature of plugs), and cement types used. Unfortunately, this data is not readily available in a condensed or collated form for all onshore wells. However, uncollated well data for select (typically more modern), individual onshore energy wells in England is potentially available from either the OGA or HSE on request.

Table 1. Readily-available data on basic energy-well attributes for UK onshore wells from the Oil and Gas Authority online data centre.

Attribute	Definition	Example
Name	Well site name identifier	GAINSBOROUGH 67
Operator	Company that designed, installed and operated the well.	BP
Type	Fluid target and/or produced: conventional oil and gas (COG), coal bed methane (CBM), shale gas (SG), mine gas (MG) or gas storage (GS).	COG
Released	Date that well information and results were released.	14/08/1990
East	Easting coordinate.	480451
North	Northing coordinate.	390478
Dev	If well was deviated from vertical (yes or vertical).	V
County	County of location within UK.	Lincolnshire
Spud	Date the well was spudded/drilling began.	28/07/1985
Completed	Date well was completed.	14/08/1985
Intent	Intended purpose of the well (Exploration, appraisal or development).	D

It should be noted that extensive data for UK onshore wells drilled and operated by BP (including its predecessors, such as D’Arcy) are available as archives. These data were donated to the UK Onshore Geophysical Library (www.ukogl.org.uk) and made publicly available in 2016. The relevant files contain significant information on specific wells, including drilling reports and well construction details, as well as information on geology, geophysics, and, in some cases, abandonment. However, this data is not collated or, in some cases, is not fully digitised, for example, it is in large reports that are only available as low-quality scans. It is therefore difficult to use the data at a country-wide scale. Consequently, only the data collated by the OGA data centre for the UK's population of wells (Table 1) was readily available, and was used for this investigation.

General overview of onshore wells In England

Data from the OGA onshore repository shows that there are 2,149 wells in the UK spread across all regions in various basins (Figure 1). The oldest well was completed in 1902 (119 years old) and the most recent in 2013; the average well completion age is approximately 50 years old. Data shows that the onshore well stock comprises 834 exploration wells, 249 appraisal wells and 1,066 production wells. The vast majority of wells are associated with conventional oil and gas (a total of 1,994), with much lower numbers of wells associated with coal bed methane, mine gas, shale gas and gas storage (99, 48, 5 and 3 wells respectively). In terms of well orientation, 1,434 are specified as vertical, while some 715 are identified as deviated. There are more than 100 operators listed for all onshore wells in the UK, with BP and its subsidiaries accounting for more than half of all wells (1,309 for BP, D'Arcy and Candecca). Other companies typically operate a total of less than 50 wells in the UK, with an average of 5 wells per operator. More than 50 companies operated only one well, so they appear to be very small, and it is likely that they no longer exist.

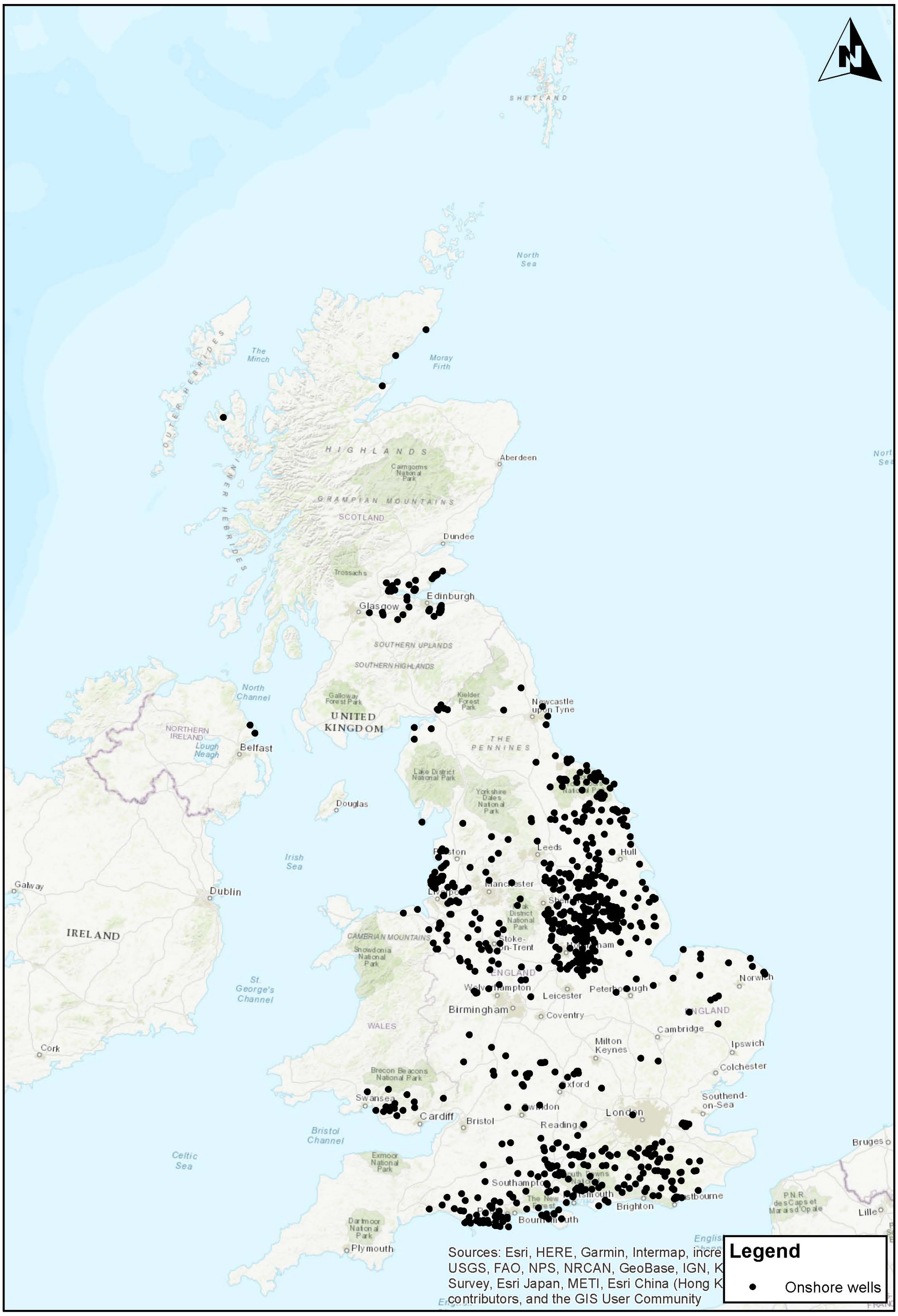


Figure 1: Map showing location of 2,149 UK onshore energy wells. The average UK well is 50 years old, and is typically a vertical well for conventional oil and gas production.

Factors likely to influence long-term well integrity in England

Drilling activity

The development of onshore petroleum resources in the UK began with the discovery of oil in Scotland in 1851, and then gas in England in 1896. After this, a slow but consistent advancement of onshore drilling activity proceeded, with 3 noticeable upturns (Figure 2). These upturns are attributable to geopolitical or economic events which necessitated or increased the desirability for domestic petroleum production. Specifically, the upturns coincided with World War 2, a period following the Suez Crisis, and a period covering the 1979 Iranian Oil Crisis and the Gulf War. Upturns in drilling were interspersed with steady, sustained and ongoing low levels of development that continue to the present day. Overall, an average of approximately 23 energy wells were completed each year from 1902 to 2013, with a maximum of 141 wells completed in 1943.

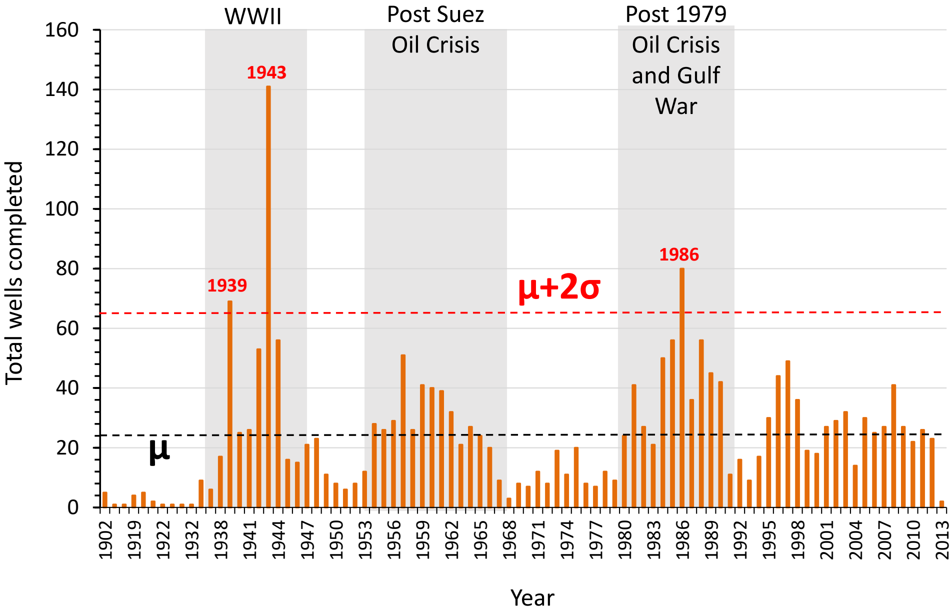


Figure 2. Timeline of onshore wells completed annually in the UK, showing how upturns in activity were initiated by various geopolitical events. The black line indicates the mean (μ) number of wells drilled each year since 1902, and the red dashed line indicates outlier years of extreme drilling (defined as μ+2σ).

Increases in integrity failure at energy wells have previously been linked to regional upturns in drilling activity induced by economic factors, for example, higher oil or gas prices driving increases in drilling activity, and/or geopolitical factors, such as instability in global petroleum resource supply. For example, Watson and Bachu[24] showed a direct positive correlation between oil price and the incidence of failure (manifesting as surface casing vent flow or gas migration) in Alberta, Canada between 1973 and 1999. Ingraffea and others[25] also identified a link between sudden and rapid upturns in drilling activity (related to the unconventional shale revolution in Pennsylvania from 2006 to 2012) and an increase in the likelihood of integrity failure. These relationships are likely to arise from trying to satisfy high demand in 'boom times' using limited equipment or resources or from a general decrease in the quality of well construction or abandonment due to rushed development and consequently increased rates of structural integrity loss. The incidence of integrity failure may be related to economic factors (based on oil prices, as previously described), or to an urgent need for petroleum to maintain supplies during wartime. Consequently, we identify upturns in drilling activity in England as a potential crucial risk factor in the development of integrity failure at onshore wells. We propose here that the years when the number of wells completed were more than 2 standard deviations ($\sigma = 21$) greater than the mean ($\mu=24$) were years when wells were likely to have been constructed under duress, so that long-term integrity may be reduced (years where 66 or more wells were completed). Figure 2 shows the number of wells completed annually since 1902, and that 1939, 1943 and 1986 were years when more than 66 wells were completed.

Well age

Data on the ages of onshore wells in the UK are readily available. While no direct, simple correlation with age and wellbore integrity has previously been proven[21], the year in which a well was constructed and abandoned will undoubtedly have influenced its long-term integrity. It is logical to assume that the regulatory framework and technology available when a well is completed or abandoned will have a strong influence on its long-term integrity. Consequently, here we review the evolution of regulatory and technological frameworks for well construction and abandonment in the UK, and we identify critical dates before and after which wells will potentially have more or less long-term integrity.

UK regulatory framework for construction and abandonment

With a global history exceeding 150 years, the regulation of petroleum resource development has evolved significantly with time and by region. Some of the first regulations relating to well construction and particularly abandonment appeared in the Pennsylvania mining statutes (Act May 16t, 1878; P.L. 56 para1). These stated "All owners and operators of oil lands within this commonwealth shall in all practical manner plug their oil wells at proper depth with wood sediment, in a manner sufficient to exclude all fresh water from oil bearing rock and to prevent the flow of oil and gas into fresh water". Such rudimentary practices for abandoning a well in the early periods of development are commonly reported, including the use of trees, hay and other material, inserted into an energy wellbore in the hope that it would seal it appropriately[18].

In the UK, general legislation concerning petroleum resource development was introduced in 1918 with the Petroleum Production Act, which sought to encourage (as well as to control) exploration and production. This was replaced by a new Act in 1934, after which various pieces of general legislation were combined to form the 1998 Petroleum Act, which encompasses rules relating to decommissioning energy wells, both onshore and offshore.

The administration of this legislation has also evolved significantly during the last 100 years, with responsibility for its application passing between government departments as they have been formed, disbanded, replaced or combined. For example, the merger of the Board of Trade and the Ministry of Technology led to the Department of Trade and Industry in 1970. This encompassed petroleum resource development until 1974, after which the Department of Energy took control from 1974 to 1992.

Currently, all petroleum resource development in the UK is overseen by the Oil and Gas Authority which was founded in 2015 and is:

“responsible for maximising field life and economic revenues as well as ensuring that decommissioning is executed in a safe, environmentally sound and cost effective manner. The Department for Business, Energy and Industrial Strategy (BEIS) is the competent authority for decommissioning and regulates offshore oil and gas decommissioning under the Petroleum Act 1998. The OGA works with BEIS and is specifically required to assess decommissioning programmes on the basis of cost, future alternative use and collaboration”.

Specific regulations concerning well construction, abandonment and decommissioning appear to have evolved in several phases. The first reference to construction and abandonment of wells appears in the Offshore Installations (Operational Safety, Health and Welfare) Regulations of 1976 (SI 1976/1019). This was followed by the Offshore Installations (Well Control) Regulations of 1980 (SI 1980/1759), which was superseded by the Offshore Installations (Well Control) (Amendment) Regulations of 1991 (SI 1991/308). However, these regulations are mostly high-level, and do not provide specific details on how wells should be constructed, abandoned or managed; instead they just say that they should be adequately constructed and sealed. Consequently, no firm conclusions can be drawn on the construction, abandonment or long-term integrity of wells from the development of regulations up to and including 1991, except that standards are likely to have improved continually and gradually with time.

Modern regulations were achieved through the Wells Design and Construction Regulations (1996), commonly referred to as the DCR. These regulations were, in part, developed as a result of the Piper Alpha Disaster[26]. Following this incident, it was recognised that a more robust construction and abandonment process was needed, and that in the coming decades many more energy wells would reach the end of their economic life and would need to be abandoned safely and effectively. It should be noted that the DCR were primarily developed for the offshore industry, however, they are stated as being applicable to onshore wells too.

Important regulations relevant to well construction and abandonment in the DCR are 13, 15 and 16 which cover aspects of well integrity, decommissioning design, and materials used for decommissioning. Leading statements (as highlighted in the Oil and Gas UK guidance) are:

Regulation 13

“The well operator shall ensure that a well is so designed, modified, commissioned, constructed, equipped, operated, maintained, suspended and abandoned that:

a. so far as is reasonably practicable, there can be no unplanned escape of fluids from the well
b. risks to the health and safety of persons from it or anything in it, or in the strata to which it is connected, are as low as is reasonably practicable

Regulation 15

Ensure that a well is so designed and constructed that, so far as is reasonably practicable:

c. it can be suspended or abandoned in a safe manner
d. after its suspension or abandonment there can be no unplanned escape of fluids from it or from the reservoir to which it led

Regulation 16

The well operator shall ensure that every part of the well is composed of material which is suitable for achieving the purposes described in Regulation 13.”

The DCR also introduced additional safeguards to ensure greater integrity at abandoned wells in the form of an independent well examiner. The independent examiner would review information on the design and construction of a well and on the sub-surface environment, including any hazards which the geological strata and formations may contain.

Aside from the DCR, another important piece of regulation relating to the integrity of onshore oil and gas wells is the Borehole Sites and Operations Regulations introduced in 1995 (BSOR). BSOR primarily concerns the management of the borehole site and the operational aspects of well decommissioning, whereas the DCR outlines the actual downhole requirements for the decommissioning of wells.

The implementation of the DCR and BSOR regulations coincided with the development of practical guidance documents on how to meet required specifications produced by OGUK (an industry body representing the UK offshore oil and gas industry). Released in 1995, these guidelines were subsequently revised 5 times: in 2001, 2005, 2009, 2015 and to the current version in 2018. In summary, this guidance states explicitly, for the first time, that operators should identify and isolate all potential zones of flow along a wellbore. It also explicitly states how this should be achieved (for example, number of barriers, lengths of cement and use of bridge plugs).

Together the DCR, BSOR and related OGUK guidance led to a much more robust framework for how onshore wells should be constructed and abandoned. This undoubtedly led to a significant increase in general well integrity. For full details on how construction and abandonments should be completed according to the DCR and BSOR regulations and guidelines, the reader is referred to the OGUK guidance.

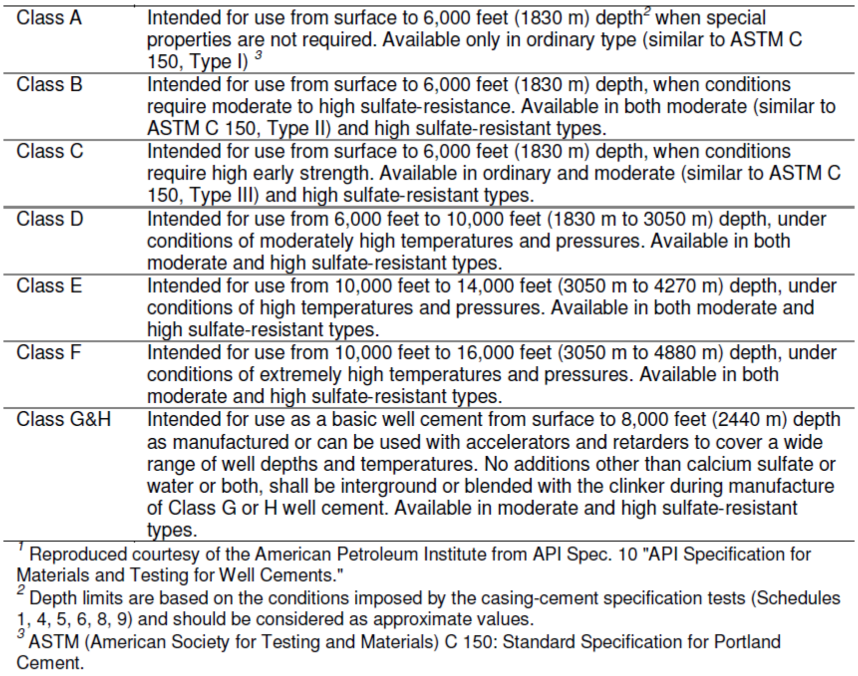
From this review of the regulatory and guidance framework it is clear that, after the DCR and BSOR regulations and associated guidance were introduced in 1996, there can be more certainty about how robustly wells have been constructed and abandoned. For the purposes of this project, we conclude that 1996 is an important date in terms of UK energy well construction and abandonment integrity. It follows that an energy well that has been constructed and/or abandoned post-1996 can be assumed to be ‘modern’ and is likely to be of superior integrity. Conversely, wells constructed or abandoned before 1996 are likely to have relatively lower overall long-term integrity, although this does not imply that pre-1996 wells are, or will be, subject to integrity failure.

Development of cementing technologies

Although legislative and regulatory frameworks set standards for well construction and abandonment, the availability of technology, and especially of materials, ultimately determines how effective a well’s construction and abandonment will be for long-term integrity. Cement is the major component in well construction and abandonment, so it is necessary to consider how cementing technologies have evolved historically in order to assess how effective construction and abandonment might be for long-term integrity. The following is a summary of important historic developments in oil field cementing practices, based on an extensive literature review carried out as part of the project.

Various leading developments in cementing procedures have occurred over the past century, driven mostly by the US petroleum industry[1,17,27]. Beginning early in the 20th century (1903), Portland cement was first used as a robust seal for energy well casings and abandonments. By 1917, more oil field cements were being developed and used. By 1919, the American Petroleum Institute (API) was established and began a more systematic and rigorous approach to the development of well cementing techniques for completing and abandoning wells. By 1928, more new cement types and additives for different subsurface conditions had been developed, and centralisers had been introduced to ensure correct placement of cement within a well. In 1937, the API formed a subcommittee on cementing and cement quality, which through to 1947 developed various cement testing procedures, types and standards. Overall, this led to the release of API Code 32 in 1948 and API Std 10A in 1953, which sought to standardise cementing types and methods. Development of plugging materials continued after 1953 to the present day, with other important updates including API Spec 10A in 1972 followed by ISO 10426 in 2000. A summary of cement types developed as part of API Std 10A is shown in Table 1.

Table 1: Overview of cement types and use after API Std 10A (taken from the IEA GHG report on well integrity for CO_2 storage [17]).



Class A	Intended for use from surface to 6,000 feet (1830 m) depth[2] when special properties are not required. Available only in ordinary type (similar to ASTM C 150, Type I) [3]
Class B	Intended for use from surface to 6,000 feet (1830 m) depth, when conditions require moderate to high sulfate-resistance. Available in both moderate (similar to ASTM C 150, Type II) and high sulfate-resistant types.
Class C	Intended for use from surface to 6,000 feet (1830 m) depth, when conditions require high early strength. Available in ordinary and moderate (similar to ASTM C 150, Type III) and high sulfate-resistant types.
Class D	Intended for use from 6,000 feet to 10,000 feet (1830 m to 3050 m) depth, under conditions of moderately high temperatures and pressures. Available in both moderate and high sulfate-resistant types.
Class E	Intended for use from 10,000 feet to 14,000 feet (3050 m to 4270 m) depth, under conditions of high temperatures and pressures. Available in both moderate and high sulfate-resistant types.
Class F	Intended for use from 10,000 feet to 16,000 feet (3050 m to 4880 m) depth, under conditions of extremely high temperatures and pressures. Available in both moderate and high sulfate-resistant types.
Class G&H	Intended for use as a basic well cement from surface to 8,000 feet (2440 m) depth as manufactured or can be used with accelerators and retarders to cover a wide range of well depths and temperatures. No additions other than calcium sulfate or water or both, shall be interground or blended with the clinker during manufacture of Class G or H well cement. Available in moderate and high sulfate-resistant types.

[1] Reproduced courtesy of the American Petroleum Institute from API Spec. 10 "API Specification for Materials and Testing for Well Cements."

[2] Depth limits are based on the conditions imposed by the casing-cement specification tests (Schedules 1, 4, 5, 6, 8, 9) and should be considered as approximate values.

[3] ASTM (American Society for Testing and Materials) C 150: Standard Specification for Portland Cement.

The history of well completion and cement engineering is long and complex. While a more comprehensive review of the topic is desirable, it is beyond the scope of this report. Over time, cementing techniques have undoubtedly improved continually, and many factors contribute to the overall integrity of a specific cementing job. Nonetheless, this study concludes that 1953 was an important event after which API Std 10A was available. Subsequently, a range of cement types was available as well as guidance on how/where to use them, which will have significantly increased general energy wellbore and abandonment integrity. This view is also held in the industry and is referred to in several journal articles[16,17]. Consequently, we propose using this timed event as a factor for assessing likely long-term well integrity; specifically, we infer that wells completed after 1953 are likely to have greater long-term integrity, and that integrity was relatively lower before this date.

It should be noted that in many parts of the world API well cement was, or still is, difficult or impossible to obtain. Consequently, other, less effective cements may have been used after 1953, and even up to the present day in certain regions[28]. Therefore, while completion pre- and post-1953 serves as a potentially crucial factor in indicating potential long-term well integrity, it is not certain that any given well will have used these cements when constructed or abandoned after 1953. For the purpose of this report, we will assume API cement standards were used when considering energy wells drilled in England after 1953.

Figure 3 shows the cumulative number of onshore wells completed in the UK since 1900, in the context of the age factors that influence long-term integrity. 568 wells were drilled before the introduction of the API cementing standards (delineated by the sub-period labelled A), 1,706 before the modern regulatory framework was introduced (delineated by the sub-period labelled B) and 442 after (delineated by the sub-period labelled C). Age with respect to periods A, B and C is used here as an indicator for long-term well integrity, because these periods cover different, and improving, standards of cementing practice.

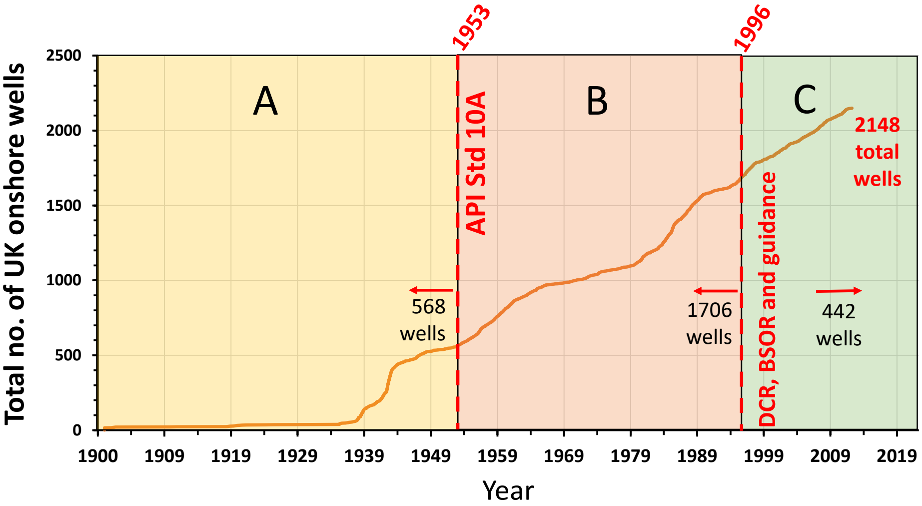


Figure 3: Timeline showing cumulative number of wells completed onshore in the UK since 1900, and age-related factors and periods that influence long-term well integrity. These include the introduction of the DCR and BSOR regulations and associated guidance in 1996, and advances in cementing practices due to the introduction of API Std 10A in 1953.

Well orientation

Energy wells are deviated from vertical for various reasons, for example, most recently horizontal drilling of thin layered, low-permeability shale reservoirs was done to make production more economically viable. Although deviation can increase productivity, it can also make well completion more challenging, and this can influence general long-term well integrity[24,29,30]. For example, during analysis of information held by the Alberta energy regulator on 315,000 energy wells in the province of Alberta, it was observed that deviated wells were 4 to 5 times more likely to exhibit integrity failure than vertical wells (15% vertical well integrity failure rate compared to 65% for deviated wells)[24]. Similarly, others have shown that deviated wells are more likely to exhibit integrity failure than their vertical counterparts in the Wattenberg Field, Colorado[29]. The cause of decreased overall well integrity is likely to be associated with poor cementing due to mechanical/physical factors, such as poorly centralised casing or poor mud removal (both a direct result of a deviated orientation). These deficiencies, in turn, result in cement slumping, bridging, shrinkage and deboning, which are all known to lead to reduced integrity[31]. Although these issues are ubiquitous challenges for cementing in energy wells, they are seemingly exacerbated in deviated wells where they lead to the development of more leakage pathways (for example, voids, fractures or micro-annuli) that allow migration of fluids along or outside the wellbore (well integrity failure).

Consequently we propose using available data on deviation for onshore wells in England as another indicator for inferring potential long-term well integrity. Where a well is identified as vertical (not deviated), it is deemed to have greatest integrity, but where a well is identified as deviated, it is assumed to have relatively less long-term integrity.

Well intent

Well intent has previously been shown as a leading factor that may strongly influence the long-term integrity of energy wells[24]. In particular, cased or completed wells appear to have a much greater chance of suffering integrity failure with time, compared to wells which are drilled and immediately abandoned (in other words, with no casing or tubing installed). The reasons for this may include the presence of perforations in a cased well, and/or the intricacies of cementing wells that contain casings and tubing. These intricacies include the typical risks associated with cementing, as previously described, including poor mud removal, cement shrinkage, and debonding. In contrast, wells drilled and then abandoned immediately, without casings or other paraphernalia in the well, will not present the same challenges. Therefore, it is likely that these wells are generally more stable after abandonment and have greater integrity in the long term.

In the context of English onshore wells, information is available on intent, that is, exploration, appraisal or production. We assume here that appraisal and development wells may, or will, have casing or tubing installed. By contrast, we assume that exploration wells would not have casings or other paraphernalia, because these wells would typically be drilled and immediately abandoned. Intent is therefore used here as another indicator for long-term well integrity for onshore decommissioned wells in England. In particular, exploration wells are assumed to be more likely to have greater long-term well integrity, and appraisal and production wells relatively less.

Summary

The following 5 main factors (for which data is readily available for onshore wells in England) have been identified as likely to control overall long-term decommissioned well integrity:

Extreme drilling activity: Our review shows that periods of extreme drilling activity (due to geopolitical or economic instability) have an influence on general wellbore integrity, as suggested elsewhere[24,25]. Here, we conclude that wells completed in years when the number of completed wells exceeded the annual mean number by more than 2 standard deviations (that is, more than 66 wells completed for an English onshore annual mean of 24) are likely to have lower long-term integrity.

Regulatory framework: Our review indicates that the introduction of the DCR and BSOR regulations and their associated guidance in 1996 is an important watershed for long-term well integrity. After 1996, this combination of regulation and guidance, including the introduction of independent well examiners, made the construction and abandonment of energy wells much more robust. Consequently, we identify this as a critical factor that will influence long-term well integrity. Wells drilled post-1996 are assumed to have the greatest possible integrity, while there is less certainty about the robustness of wells drilled before this date and they are likely to have relatively lower long-term integrity.

Technological framework: Our review suggests that cementing practices are crucial in determining well construction and abandonment integrity. Cementing has evolved continuously since its introduction in 1903 to the present day. However, an important step was the development of API Std 10A in 1953, which significantly increased general wellbore and abandonment integrity. Consequently, we identify this development as a critical factor that is likely to influence long-term well integrity. Wells drilled post-1953 are assumed to have greater long-term integrity, while wells drilled before this date are assumed likely to have relatively lower long-term integrity.

Well orientation: Our review suggests that well orientation (specifically deviation from vertical) is a crucial factor that is likely to influence long-term well integrity. Consequently, wells identified as deviating from vertical are assumed likely to have relatively lower long-term integrity than vertical wells.

Well intent: Our review suggests that the intent of a well, and more specifically whether or not casing and/or tubing were installed, will affect cementing and completion effectiveness. This will directly influence long-term well integrity. Consequently, wells whose intent was appraisal or production, which were likely to have had casing and tubing installed, are assumed to have relatively lower long-term integrity, compared to exploration wells which were unlikely to have had them installed.

Method for prioritising stewardship

Based on the 5 main factors identified, for which data is readily available, a method for prioritising stewardship of onshore decommissioned wells in England is proposed. The method identifies energy wells that potentially have the lowest overall long-term integrity of all onshore wells, and therefore should be prioritised for monitoring and stewardship. The proposed method uses the 5 main factors to segregate wells into tiers, according to their potential long-term integrity. The method considers whether each well was/is:

1) completed in a year of extreme drilling activity, when the number of wells drilled was significantly more than normal (defined as 2 standard deviations more than the overall mean number each year);
2) completed before or after the introduction of a robust regulatory and guidance framework for how wells should be constructed and abandoned in 1996 - the Well Design and Construction Regulations and Borehole Site Operations Regulations and associated guidance;
3) completed before or after the evolution of cementing standards for oil and gas wells post-1953 (API Std. 10A);

4) deviated from vertical;
5) intended for exploration, appraisal or production.

All wells are initially classed as tier 1, which corresponds to a score of 1 and to the greatest relative long-term integrity. This initial tier and score can then be increased, depending on factors related to the year of well completion (which affects 3 factors), orientation (which affects one factor) and intent (which affects one factor). The potential maximum level is therefore tier 6, which corresponds to a score of 6 and to the lowest relative long-term integrity, as shown in Table 2. A tier assignment decision tree is shown in Figure 4.

Table 2: Criteria for tier assignment based on temporal evolution of the geopolitical, regulatory and technological framework in which wells were constructed and or abandoned. All wells start as tier 1, corresponding to maximum potential integrity, and tier factors are then added depending on identified attributes for which data is readily available.

Attribute	Tier factor	Rationale
Drilled post-1996	No change (remains tier 1)	Modern regulatory framework with highly prescriptive guidance on abandonments.
Drilled pre-1996, post-1953	+1	Weaker regulatory framework and little guidance, however, cementing practices were developed.
Drilled pre-1953	+1	Cementing practices poorly developed, making effective construction and abandonments less likely,
Drilled during extreme drilling activity	+1	Pressure on supply chains and urgency leading to chance of lower quality cementing job.
Wellbore deviated from vertical	+1	Other studies have shown that there is a statistically significant association between deviated wells and integrity failure.
Well intent	+1	Production and appraisal wells have been shown to suffer poorer integrity in the long term due to the presence of casing/tubing, leading to complexities with construction and abandonment compared to exploration wells.

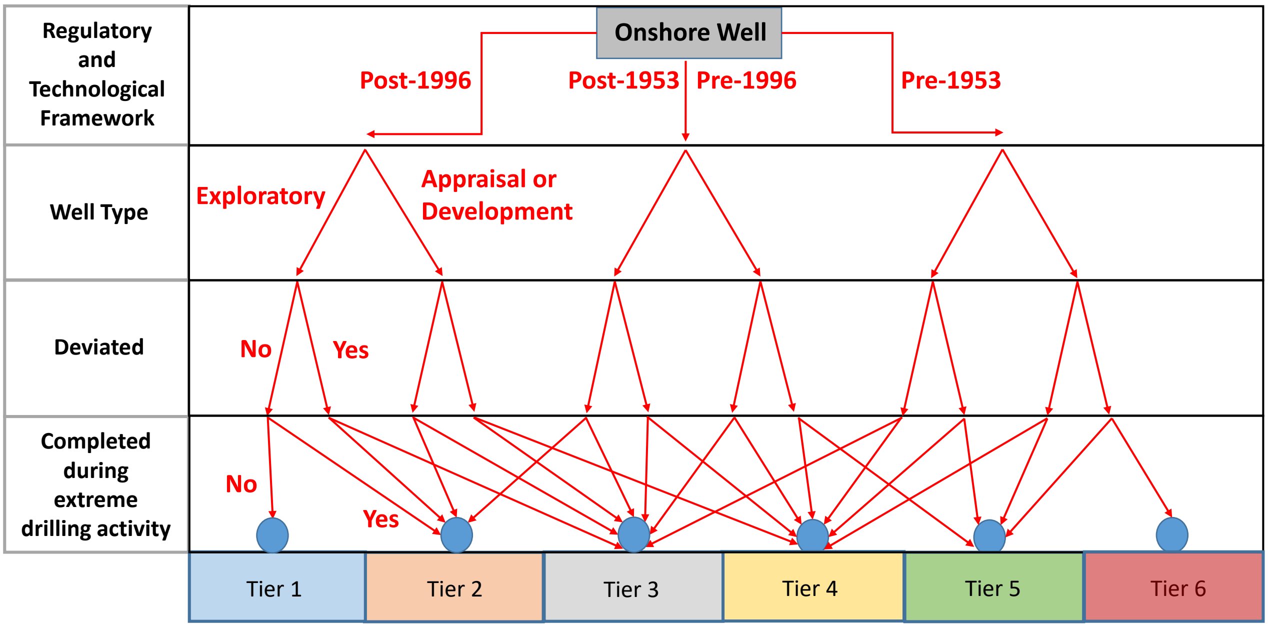


Figure 4: Tier assignment decision tree showing how identified factors are used to assign wells to increasing tiers, based on factors known to induce potentially lower overall long-term well integrity.

Results

Following the method described above, all 2,149 onshore wells were assigned a tier from 1 to 6. Table 3 shows examples of each tier assignment. Figure 5 is a pie chart showing the percentage of onshore wells in each tier. Table 4 shows the number of tier 4 and tier 5 wells in those English counties that have more than 5 wells in both tiers combined. The spatial distribution across England of wells in different tiers is shown in Figures 6, 7 and 8. There were 6 areas with significant clusters of 5 or more wells belonging to tier 5; Table 5 lists these areas and includes the rationale for assigning the wells to tier 5.

Table 3: Example of prioritisation assignment for identified criteria showing range and inferred potential long-term integrity.

UK well county location (completion date)	Tier factors summary	Tier	Potential long-term well integrity
South Yorkshire **(October 2004)**	Vertical exploration well completed post-1996	1	Greatest
Cheshire **(January 1994)**	Vertical exploration well completed pre-1996, post-1953	2	Relatively very good
Lincolnshire	Deviated development well, completed post-1996	3	Relatively good

(January 2011)			
Leicestershire **(December 1943)**	Vertical exploration well completed pre-1996, pre-1953 in year of extreme drilling activity	4	Relatively moderate
Nottinghamshire **(November 1986)**	Deviated development well completed pre-1996, post-1953 in year of extreme drilling activity	5	Relatively low
No wells In England met these conditions	Deviated development well completed pre-1996, pre-1953 in year of extreme drilling activity	6	Relatively lowest

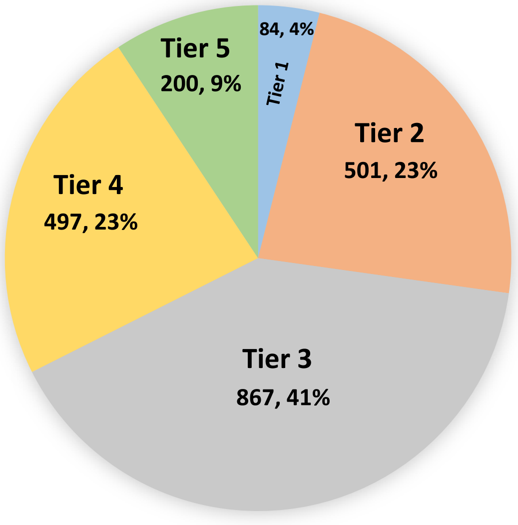


Figure 5: Segregation of onshore English well population into tiers according to factors identified as influencing potential long-term integrity. The highest possible tier assignment was 6, but no wells were assigned this tier.

Table 4: Tier 4 and 5 wells by county (for counties with more than 5 wells in both tiers combined). Nottinghamshire, Lincolnshire and Dorset have the greatest number of tier 4 and 5 wells combined.

County	Tier 4 wells	Tier 5 wells	Total
Notts	192	126	318
Lincs	82	6	88
Dorset	85	3	88

Lancs	23	32	55
Hants	22	14	36
N Yorks	13	9	22
Leics	16	2	18
Lothian	12	3	15
W Sussex	14		14
Surrey	11	2	13
Humbs	5	1	6
Total	475	198	673

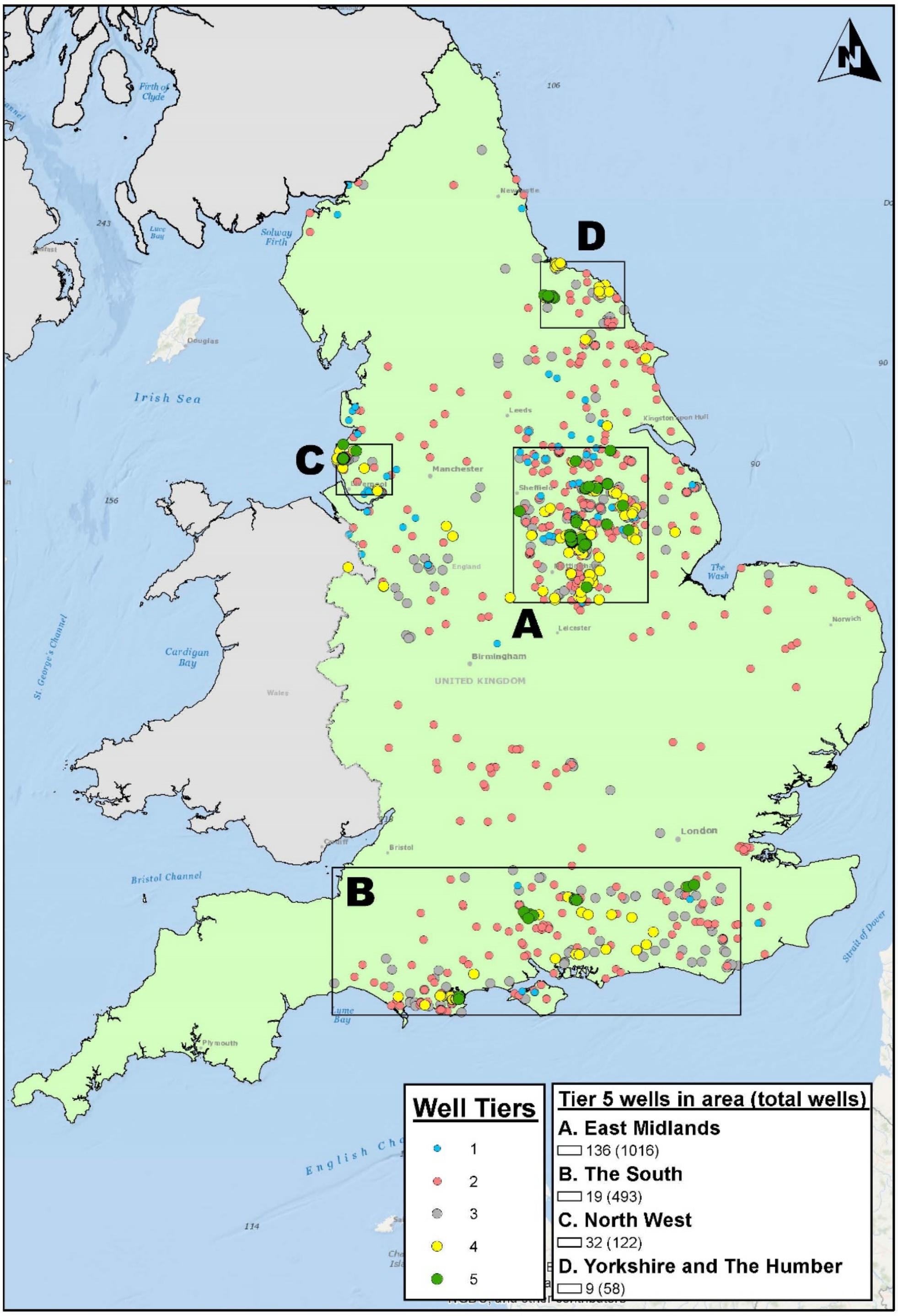


Figure 6: Map showing distribution of onshore wells for different tiers of potential integrity (based on identified factors). The map shows that tier 5 wells are clustered in 5 regions: A) the East Midlands (136 wells), B) the south (19 wells), C) the north-west (32 wells) and D) Yorkshire and Humberside (9 wells).

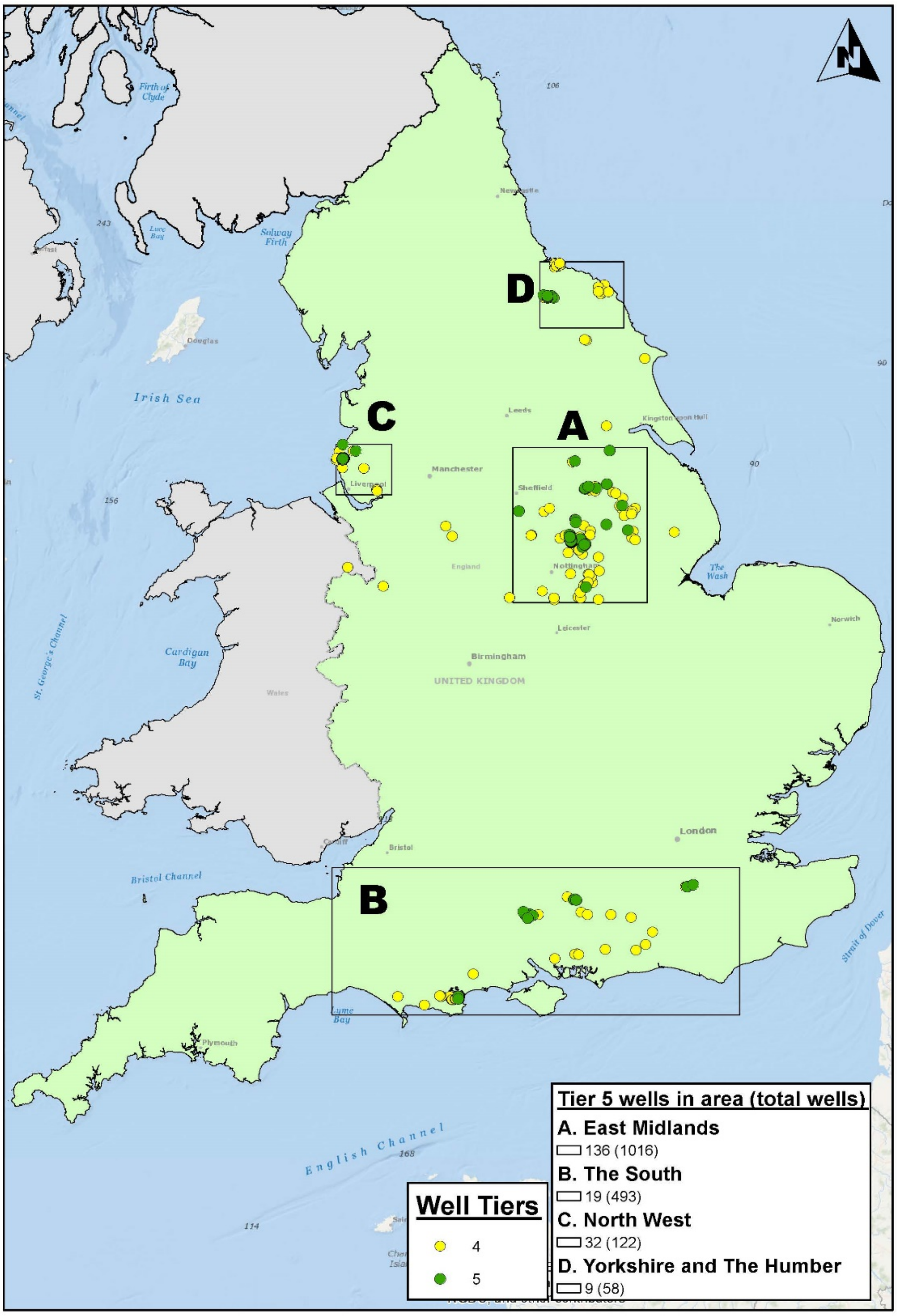


Figure 7: Simplified map showing only tier 4 and 5 wells clustered in main regions, with the total number of tier 5 wells stated and the total number of wells in the region in brackets: A) the East Midlands (136 tier 5 wells out of a total of 1,016), B) the south (19 tier 5 wells out of a total of 493), C) the north-west (32 tier 5 wells out of a total of 122) and D) Yorkshire and the Humber region (9 tier 5 wells out of a total of 58).

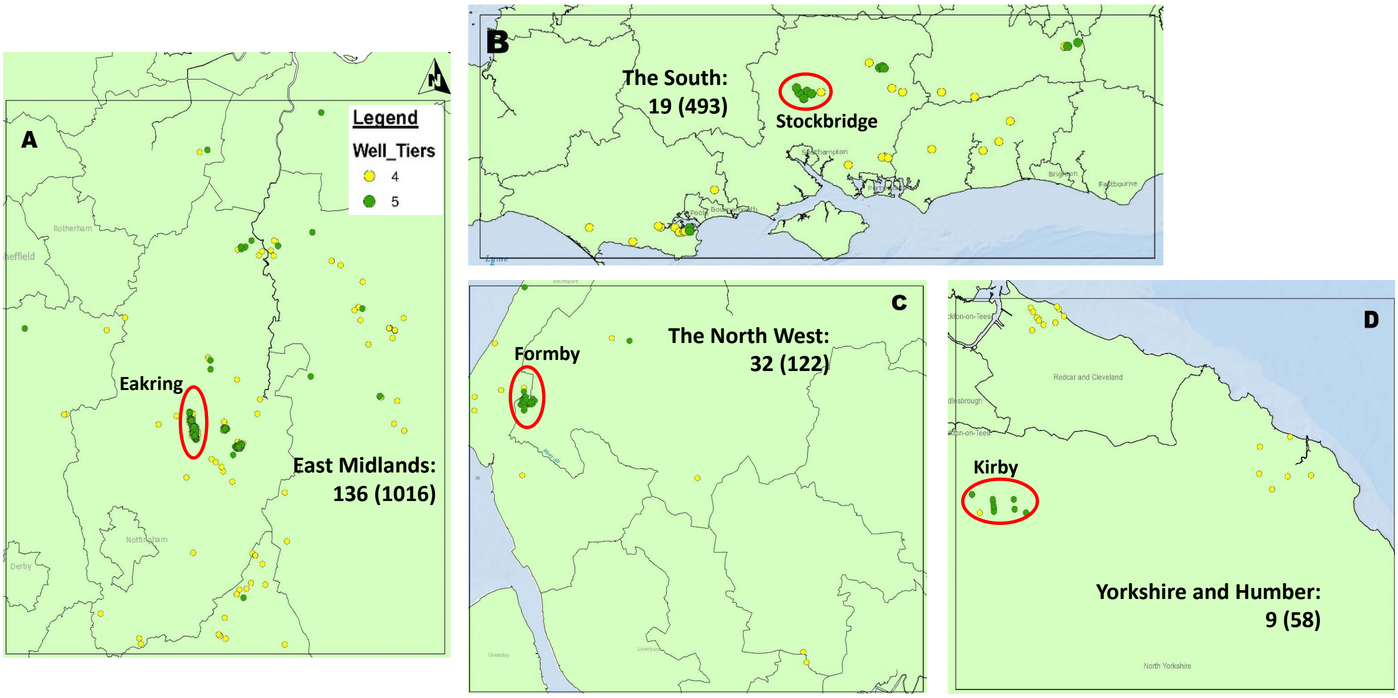


Figure 8: Distribution of tier 4 and 5 wells by main regions of England. Each map states the total number of tier 5 wells, with the total number of energy wells in the region in brackets. Wells are clustered in several locations, with particularly high density near Eakring (79 tier 5 wells), Stockbridge (8 tier 5 wells), Formby (31 tier 5 wells) and Kirby (9 tier 5 wells) in the East Midlands, the south, the north-west and Yorkshire and Humber respectively.

Table 5: Main clusters of tier 5 wells including rationale for tier 5 status.

Tier 5 well cluster area	Number of tier 5 wells in cluster	County	Completion date	Tier 5 rationale
Eakring	79	Nottinghamshire	1943	Pre-1953, pre-1996 production well completed in year of extreme drilling activity
Formby	31	Lancashire	1943	
Kelham	31	Nottinghamshire	1943	
Caunton	10	Nottinghamshire	1943	
Kirby	9	N. Yorkshire	1939	
Stockbridge	8	Hampshire	1986	Pre-1996, deviated production well completed in year of extreme drilling activity
Humbly	6	Hampshire	1986	

The results show tier 4 and 5 wells are mainly found in 4 regions: the East Midlands, the south, the north-west, and Yorkshire and Humberside. Tier 5 wells tend to be in clusters that are associated with petroleum development in response to a specific geopolitical event. For example, the East Midlands, which has by far the largest number of tier 4 and 5 wells, has a cluster of 79 decommissioned tier 5 wells near Eakring which were drilled in World War 2 to secure petroleum fuels. These wells are assigned tier 5 because they are production wells that were drilled before 1953, in a year of extreme drilling activity. There are similar clusters of tier 5 wells in the north-west near Formby, and in Yorkshire and Humberside near Great Broughton (totaling 31 and 9 wells respectively); these wells also relate to increased drilling activity during World War 2. Again, these clusters are assigned tier 5 because they are production wells drilled before 1953, in a year of extreme drilling activity. There are 2 smaller clusters of tier 5 wells in the south; near Stockbridge and Humbly (totalling 8 and 6 wells respectively). The tier 5 wells in the south differ from those in other regions because they are newer and comprise deviated production wells that were completed before 1996 and during a year of extreme drilling activity.

Discussion and conclusions

Well integrity is a complex issue associated with all petroleum wells. It is of particular concern in relation to abandoned and decommissioned wells, which are required and assumed to be sealed in perpetuity. A complex combination of environmental, engineering, regulatory and geopolitical factors can interact and compound to determine if a well suffers integrity failure in the long term. The UK, and particularly England, has a modest, but still significant, onshore population of decommissioned energy wells. The current status of these wells and their potential long-term integrity is poorly constrained. Large numbers of decommissioned energy wells, such as those onshore in England, will need to be managed and monitored into the future. This will be necessary in order to ensure that they are effectively sealed, are not causing undesired environmental impacts, and are not releasing greenhouse gases into the atmosphere that would hamper decarbonisation efforts towards net zero. Here, we reviewed basic, readily available data on the onshore well population and identified factors that are likely to influence their long-term integrity. These factors are associated with geopolitical, regulatory and technological considerations that affect how wells were constructed and/or abandoned. These factors comprised:

1) periods of extreme drilling activity in which the number of wells completed was significantly more than normal (defined as 2 standard deviations more than the mean);
2) the introduction in 1996 of a robust regulatory and guidance framework for how wells should be constructed and abandoned (The Well Design and Construction Regulations and Borehole Site Operations Regulations and associated guidance);
3) the evolution of cementing standards for oil and gas wells post-1953 (API Std 10A);
4) if a well is deviated from vertical;
5) the underlying intent of a well, in others words, whether it was for exploration, appraisal or production’

The identified factors were used to develop a method for prioritising the stewardship of decommissioned onshore wells in England, according to their potential long-term integrity. The prioritisation method provides various permutations for assigning a tier to a given well, based on leading data attributes relating to the 5 identified factors (Figure 4). The method was used to segregate the stock of onshore decommissioned wells into tiers 1 to 6, with tier 1 having the greatest potential integrity, and tier 6 the least. The percentages of wells that were identified as tiers 1, 2 and 3 were 4% (84 wells), 23% (501 wells) and 41% (867 wells) respectively. Wells identified as tiers 1, 2 and 3 are likely to have relatively greater potential for long-term integrity, and are dispersed relatively evenly across the resource development basins of England. The percentages of wells that were identified as tiers 4 and 5 were 23% (497 wells) and 9% (200 wells) respectively. Tier 4 and 5 wells are inferred to have lower potential for long-term integrity. Tier 4 and 5 wells are generally characterised as production wells which were completed before 1953, and which may have been deviated from vertical and/or completed during a year of extreme drilling activity. Tier 5 wells are clustered in several regions in England, including the East Midlands (136), the south (19), the north-west (32), and Yorkshire and Humberside (9). No wells in England were assigned to tier 6 which corresponds to the lowest potential for relative long-term integrity.

Tier 4 and 5 wells have potentially lower relative long-term integrity, and generally occur in 4 regions: the East Midlands, the south, the north-west, and Yorkshire and Humberside. Tier 5 wells have the lowest potential for overall long-term integrity; they tend to have similar attributes and to occur in clusters in discrete areas such as Eakring, Kelham or Formby. These clusters typically comprise production wells that were completed before 1953, and in years of extreme drilling activity associated with World War 2 when petroleum fuels were urgently needed. The clusters of tier 5 wells are likely to have relatively low long-term integrity because they were constructed under duress (during extreme drilling activity), when cementing practices were in their infancy, and when regulations and guidance on construction and abandonment were less detailed or rigorous. Moreover, as production wells, they would have contained various casing and tubing paraphernalia, which would have made it more challenging to accurately and effectively cement them. This combination of factors has been shown elsewhere to directly influence long-term well integrity, and it implies that the clusters of tier 5 wells should be prioritised for stewardship.

There are 2 small clusters of wells in the south of England that are ranked as tier 5. The attributes that led to this assignment are distinct from those in the northern regions, because these southern wells are much younger (completed in 1986), and are deviated production wells. They were completed before the introduction of the Wells Design and Construction Regulations in 1996, or the Borehole Sites and Operations Regulations in 1995. Consequently, there is less certainty about the robustness of their construction or abandonment.

As tier 5 wells are almost exclusively located in high density clusters in small, discrete areas, they will potentially be easier to manage, monitor and assess in any ongoing stewardship programme. For example, the largest clusters of tier 5 wells are located in the East Midlands, (Eakring, Kelham and Caunton), which contain 120 out of the 200 tier 5 wells in England. The Eakring cluster in particular contains 79 tier 5 wells all within a 2km^2 area. Consequently, many tier 4 and 5 wells could be monitored or assessed in a short period at modest cost during multi-well field investigations, and perhaps by deploying longer-term remote monitoring stations at main sites (for example, Eakring). Furthermore, airborne measurements might be effective in monitoring the integrity of many tier 5 wells in a short time at modest cost. In order to monitor and ensure maintenance of ongoing well integrity, it is recommended that the clusters of tier 5 wells identified in Table 5 are targeted for ongoing periodic assessment and monitoring of surficial and shallow subsurface conditions (for example, every 5 years or so).

It should be noted that the assignment of wells to tiers and the inference of different potential long-term integrities in this report do not imply that identified wells will lack or have lost integrity. The tier assignment suggests only that these wells should be prioritised in any ongoing or future stewardship scheme. The inference of potential long-term well integrity as stated is reasonable, based on evidence and findings from elsewhere. Current understanding suggests that the identified tier 5 wells, in particular, have attributes which will potentially lead to a higher risk of developing long-term integrity failure, compared to other wells in England.

The main conclusions of this report are:

- Well integrity failure is a complex and multifaceted phenomenon where various risk factors must interact and compound in order for failure to occur. The majority of energy wells do not exhibit integrity failure.
- A recent field study concluded that ~30 out of a subset of ~100 wells investigated in England showed signs of integrity failure; this conclusion was inferred from elevated methane concentrations at the soil surface around the well head.
- There are many uncertainties about the status of onshore wells in the UK, and it is currently not possible to draw firm conclusions on their general integrity status or on how this will develop in future.
- Basic data relevant to the integrity of onshore wells in England is available from the OGA data centre. Other more detailed data (for example, abandonment date, configuration and construction details) is not readily available in a collated form, but is potentially available for individual sites.
- Five factors were identified, based on available data, which are likely to influence the overall long-term well integrity of onshore wells in England. These factors cover geopolitical, regulatory and technological aspects of construction and abandonment.
- The identified well integrity factors were used in a method that assigned onshore wells in England to 6 tiers (1 to 6 with decreasing potential long-term integrity). These assignments showed that 200 wells (9%) may be considered to be in tier 5, and so to have the lowest potential long-term well integrity. No wells in England were assigned to tier 6, which corresponds to the lowest relative potential long-term integrity.
- Tier 5 wells exist in discrete, high density clusters in the East Midlands (136 tier 5 wells), the south (19 tier 5 wells), the north-west (32 tier 5 wells) and Yorkshire and the Humberside (9 tier 5 wells).

The tier 5 clusters, like those identified, should be prioritised for monitoring, assessment and ongoing stewardship because their attributes suggest that they have relatively lower long-term integrity than other wells in England.

Recommendations

The following recommendations are made based on the findings of this investigation:

- Detailed data on the construction and abandonment of onshore wells in the UK should be collated and centralised for use when assessing well integrity (for example, development of a more detailed database system for onshore wells).
- The prioritisation method developed here should be refined and expanded to include other factors known to influence wellbore integrity failure such as local geology, construction details, including casing and abandonment configurations, and more detail on abandonment practices and their evolution.
- The method for making factor-based assessments of wellbore integrity should be validated by comparison with field data and investigations. This will ensure a more accurate and robust assignment of prioritisation, so that future stewardship can be optimised.
- Wells identified as tier 4 and 5 should be further investigated by desk and field studies, including collation of cluster-specific data. New field studies should be progressed in all the regions in England that have been shown to contain tier 4 and tier 5 wells, in order to assess and verify the integrity status of these wells, and to better assess the validity of the proposed prioritisation framework.

It is recommended that the relevant regulatory bodies formulate and progress a strategy for the ongoing management and stewardship of onshore decommissioned wells in England, which should include field monitoring. Such a strategy will ensure that well integrity is maintained, and, where necessary, it will allow effective identification and mitigation of any risks to the environment posed by leaking wells, especially risks to groundwater and from greenhouse gas emissions.

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Acknowledgements

Input and advice from Sian Loveless (Environment Agency), Doug Boddy (Environment Agency), Toni Harvey (OGA), Alan Poole (OGA) and Trevor Sexty (HSE) is recognised and appreciated. This work was led by Dr. Aaron Cahill in a jointly funded Environment Agency and Heriot-Watt University project.

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