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Water Impact Statement

If poorly managed, wastewater generated during hydraulic fracturing for shale gas can pose a significant environmental threat. This research assesses the viability and cost of wastewater management options for the UK shale gas industry. Using data from the UK and the US, volumes and chemistries of wastewater to be managed are predicted, and assessed against current UK capacity.





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ARTICLE

Assessing the Viability and Cost of Managing Wastewater from Hydraulic Fracturing in the UK

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The safe and effective management of wastewaters from unconventional hydrocarbon production using the hydraulic fracturing (fracking) process poses a major challenge¹⁻⁵. Exploitation of unconventional hydrocarbons, such as shale gas, remains controversial in the UK primarily due to concerns surrounding the hydraulic fracturing process required to extract the resource. The key issue of how waste fluids produced by hydraulic fracturing in the UK will be safely managed has yet to be adequately addressed, and the capacity for the specialist treatment required is currently uncertain. To address this critical knowledge gap we review, for the first time, the available management options for these waste fluids in the UK. We find that these are limited in comparison to the options available in the U.S., due to uncertainty surrounding whether wastewater injection wells will be permitted in the UK. Consequently, it is highly probable that these fluids will need to be treated and safely disposed of at the surface. In order to constrain the composition of wastewater which will require treatment in the UK, we analyse the only existing data set of returned waters from hydraulic fracturing (n=31). We supplement this with measurements of wastewater from UK conventional onshore hydrocarbon (n=3), and offshore hydrocarbon (n=14), operations which produce water from similar formations as those currently targeted for shale gas exploration. Comparison of this limited UK data to the more extensive unconventional production dataset from the United States (n=3092) provides confidence in our projected UK wastewater compositions. We find that the high level of salinity and concentration of naturally occurring radioactive material (NORM) in UK wastewaters will be problematic to treat for disposal into a freshwater environment. We use our data compilation to estimate costs of treating such wastewaters in a number of relevant scenarios. We find that the projected salinity in FP waters from UK hydraulic fracturing operations can be treated at a cost of between \$2,701 (~£2,000) and \$1,376,093 (~£1,047,000) per well, requiring between 2 and 26 % of expected revenue. Additional costs, specific to the UK of up to £163,450 per well, will be incurred due to the legislative requirement for disposal of NORM concentrated sludge in permitted landfill sites. We find that existing capacity to receive NORM waste at currently permitted UK treatment facilities is limited, and that this will pose management problems if wastewaters are generated from multiple unconventional wells simultaneously.

Introduction

Hydrocarbon production from shale formations has become an increasingly prominent source of energy over the last decade, yet exploitation of the resource remains controversial. The majority of this controversy is due to concerns surrounding the hydraulic fracturing (fracking) process which is required to extract the hydrocarbons, and the management of resulting wastewater¹⁻⁵. During the process, injected fluids (typically consisting of 99.5% fresh water and proppant to maintain fracture connectivity, and 0.5% chemical additives such as biocides, surfactants, viscosity adjusters, cross-linkers, breakers, corrosion inhibitors, bactericide, and friction

reducers⁶ react with the freshly fractured and exposed minerals and mix with the formation fluids within the shale rocks being targeted. On de-pressurisation of the well following the fracturing process, these fluids are returned to the surface having inherited heavy metals, naturally occurring radioactive material (NORM), salts and hydrocarbons from interaction with the rocks and fluids at depth. The chemistry of fluids returned is determined by the base chemistry of fracturing fluid, geochemistry of the rock, and the fluid chemistry of any formation waters residing in the pore space⁷, with potential influence from the chemistry of residual drilling fluid. Volumes of fluid returned vary depending on (1) the volume of fluid injected, (2) local geological characteristics that control water retention in the subsurface such as imbibition and extent of fracture network⁸ and (3) well length⁹. We collectively define and refer to these fluids as flowback and produced water (FP water), after Nicot et al. 2014¹⁰.

FP waters generated by unconventional hydrocarbon operations - such as hydraulic fracturing or coal bed methane

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extraction - require appropriate management to ensure that they are stored, transported, treated and disposed of in a way that minimises the operational need for fresh water, maximises the efficiency and cost of the processes and reduces risks posed to the environment. The expected volumes and chemistries of FP water, or the capacity for their treatment¹¹ or disposal in the UK is poorly understood, as outlined in a recent joint report from the Natural Environment Research Council (NERC), National Science Foundation (NSF), and Royal Society of Chemistry (RSC)¹². This is the only literature published in the public domain that covers the management of FP waters from shale gas extraction in the UK to date, and concludes that the potential cost of treatment of FP waters could render extraction of shale gas reserves in the UK uneconomic¹². However, this conclusion was based on a limited review of available data that made no comprehensive assessment of UK FP water management options. To address this critical knowledge gap we review the available options for management of these wastes in the UK.

Options for FP Water Management in the UK

FP water can be disposed of through injection into geological formations, such as depleted oil and gas reservoirs, or saline aquifer bodies^{6,13,14}. This relies on the geological suitability and capacity for subsurface storage and cannot be uniformly depended upon^{15,16}. Currently, concerns exist over the suitability of underground disposal for the UK, due to observed increases in induced and triggered seismicity across the U.S. where injected fluids lubricate critically stressed fault systems or high injection rates are used¹⁷⁻¹⁹, and the evidence of surface water degradation within the vicinity of injection sites²⁰. Through examination of publically available data, we have established that 99.9% of the produced water generated by conventional onshore oil and gas operations in the UK is reinjected back into the formation from which it was recovered²¹. This practice requires no interim treatment as the FP water composition is similar to that of the formation water. Hence, there is currently no precedent for the treatment of large volumes of FP water that will result from extensive shale gas exploitation in the UK.

Reinjection of wastewater is frequent practice for enhancing hydrocarbon recovery and provide pressure support for depleted conventional reservoirs¹³. Between 20 and 25% of water produced from conventional operations in the UK sector of the North Sea is reinjected for this purpose²². However, in the case of unconventional operations, the storage space required does not exist within the low porosity, and relatively impermeable, shale rocks to allow the reinjection of FP waters. Disposal of these waters by injection into the subsurface would require the existence of additional geological storage space with specific characteristics, such as sealing cap rocks and lithological heterogeneity. However, no comprehensive assessment of such sites in the UK has yet been undertaken, and combined with public concerns around such disposal, the viability of injection of FP water into the subsurface for disposal is uncertain.

Without prior treatment or separation, FP water disposal through underground injection also confines large volume of fresh water used in the fracturing process to waste, which will significantly increase the amount required for UK shale gas operations. Further, the disposal of liquid wastes into landfill sites is currently prohibited in England and Wales by The Landfill (England and Wales) Regulations 2002, as result of the EU Directive 99/31/EC on the landfill of waste (Landfill Directive) which also applies to Scotland and Northern Ireland. Whilst the Environment Agency (England and Wales) and Scottish Environmental Protection Agency (SEPA) will classify the FP water produced by the hydraulic fracturing process as mining waste¹¹, the legality of permitting this to be disposed of through deep injection via disposal wells has yet to be established^{23,24}.

Reuse of FP waters in subsequent hydraulic fracturing operations (internal reuse) is frequent practice in the in the Marcellus Shale region of the U.S., where up to 90% of produced waters were reused in 2012, however reuse values vary significantly by region with only 5 – 10% reuse in the Barnett Shale region²⁵⁻²⁷. Reuse can reduce fresh water consumption, but can lead to concentration of contaminants by repetitive exposure of the waters to fresh rock surfaces and multiple stages of mixing with fracturing additives²⁸. Operators opting for internal reuse in the U.S. have observed reduced well clean out times as untreated FP waters can reach chemical equilibrium with the rock formation considerably faster than fresh waters²⁹. Although internal reuse can eradicate the need for treatment to discharge standards in the interim, most operators opt for some degree of water treatment to reduce risk of reduced hydrocarbon production⁹ and scaling of infrastructure³⁰. These factors, combined with the financial incentive proven in the U.S.³¹ strongly imply that even with internal reuse in place, a degree of FP treatment will be required in the UK.

FP waters can be thoroughly treated to discharge standards and be directly discharged to a surface water body such as river, estuary or canal. Discharge of FP waters to surface water requires the waters to be treated to an environmentally acceptable level, guided by the Water Framework Directive (2000/60/EC) before they can be released to the environment, (S.I. 1). This will require specialist treatment focusing on removal of the most concentrated, and highest risk contaminants. Treatment can be performed on-site, using mobile treatment technology, or off-site via transport to a specialist treatment works.

Treatment of Salinity

FP waters typically contain levels of total dissolved solids (TDS) ranging from 50,000 – 250,000 mg/L³², meaning that 5 – 25 % of the mass of every litre of FP water is comprised of contaminants in solution. These dissolved solids are predominantly sodium and chloride salts and hence TDS is commonly referred to as *salinity*³³. Current UK regulations for disposal to freshwater water courses require the salinity of FP waters to be reduced to a maximum concentration of 200



mg/L Na, and 250 mg/L Cl (S.I. 1), equating to a 99.5 – 99.9% reduction in concentration.

Treatments to reduce or remove TDS from FP waters include distillation, and reverse osmosis¹³. Distillation, evaporation, or compression use heat to evaporate the contaminated water in an enclosed environment whereby the potable water re-condenses, leaving the contaminants concentrated within the residue. Reverse osmosis utilises fluid pressure differences to pass FP water through a membrane filter removing some contaminants. Reverse osmosis is more cost effective and less energy intensive than distillation, however its application is limited to waters with TDS below 50,000 mg/L, restricting its suitability to treat most FP waters, including the ones considered in this study. Additionally, osmotic membranes can require frequent maintenance and replacement due to fouling and permeability reduction³.

The unrecoverable waste, or sludge, becomes concentrated with contaminants not targeted by this treatment such as heavy metals or naturally occurring radioactive materials and will require additional focused treatment or permanent disposal in permitted landfill.

Treatment of Naturally Occurring Radioactive Materials (NORM)

Rocks rich in organic matter, such as gas-bearing shales or other hydrocarbon source rocks, contain naturally occurring radionuclides, including uranium (²³⁸U) and thorium (²³²Th). These radionuclides decay to form a number of daughter particles, notably radium (Ra²²⁶), which is particularly soluble³⁴ and therefore partial to leaching by formation or injected waters. During hydraulic fracturing the injected fluids mix with the radium enriched formation waters within the rock, and subsequently contaminate the FP water with naturally occurring radioactive material (NORM). The decay of radionuclides causes radiation to be emitted prompting negative health impacts at critical doses²⁸, so monitoring and appropriate control of NORM in waste streams is extremely important.

NORM contaminated waste streams generated by the conventional hydrocarbon industry can be re-injected into the source formation onshore or offshore to provide pressure support to enhance reservoir recovery, or can be diluted and dispersed offshore into the marine environment within set limits^{35,36}. As previously mentioned, the capacity or legality of re-injection of FP waters in the UK is uncertain. Additionally, the dilution and dispersion of pre-treated FP waters high in NORMs directly to the offshore environment will not be feasible due to limitations on marine contamination enforced by The OSPAR Treaty (2007) as outlined in Section B.44, UK NORM Waste Management Strategy³⁷.

Concentrations of radionuclides in unconventional waste streams are expected to be 1.5 times higher than in conventional hydrocarbon waste streams as a result of the direct contact of the waters with the radionuclide-rich hydrocarbon bearing shale rocks³⁸. NORM levels will become concentrated within precipitates that form during evaporation treatment and in the sludge collected by filtration,

sedimentation, or separation. The disposal of this precipitate is subject to the Radioactive Substances Regulations (2011) conditions of low-level radioactive waste only within an appropriately permitted landfill. The UK Department for Energy and Climate Change (DECC) highlighted a lack of capacity to treat NORM-contaminated FP water in their Strategic Environmental Assessment for Further Onshore Oil and Gas Licensing (2013).

Treatment of Heavy Metals

Human exposure to heavy metals in water can cause serious negative health effects, and therefore regulations exist to minimise exposure from treated and discharged wastewaters³⁹. A review of research on wastewater treatment for heavy metals by Fu & Wang (2011) identifies seven key treatment methods; (1) chemical precipitation, (2) ion-exchange, (3) adsorption, (4) filtration, (5) coagulation & flocculation, (6) flotation, and (7) electrochemical treatment. Chemical precipitation (1) utilises chemicals to cause metal ions to precipitate out of solution which can then be removed by filtration or sedimentation⁴⁰. Ion-exchange (2), specifically targets the metals required for removal with exchangeable cations⁴¹. Adsorption (3) removes contaminants of concern by collecting them on an adsorbent surface creating adsorbate film⁴⁰. Filtration (4) utilises a barrier screen designed to trap or block any particulate material from passing through with the treated effluent. Coagulation and flocculation (5) occurs by a flaking agent causing particles to coagulate that can then be sifted or filtered out. Flotation (6) brings the contaminants to the surface of the fluid by attachment to air bubbles. Electrochemical treatment (EC) (7), alters the surface charge on contaminant particles held in the water causing them to separate and accumulate in an easily removable mass.

A comprehensive study of the performance of UK wastewater treatment plants⁴² highlighted a wide variation in removal rates of between 25 – 79 % for heavy metals. This variation was attributed to variations in composition of wastewater being treated and the operation parameters at individual treatment works⁴². Removal of trace metals dissolved in solution currently pose the most significant challenge to the industry in comparison to other trace contaminants, so it will be pertinent to consider the contribution shale gas operations may make to the waste load requiring treatment in future work. However, in this work, due the limited dataset available from UK operations at present, we focus on assessing options for treatment of the two major problem contaminants in UK FP waters; salinity and NORM.

Methods

Our review of the options for FP water management in the UK highlights that some degree of water treatment will be required following hydraulic fracturing. Hence, we consider the costs associated with this treatment, and estimate the capacity within existing UK facilities to receive and treat such wastes.



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Constraining expected volumes of UK FP water

The volume of fluid injected to undertake the hydraulic fracturing process depends on; the depth and length of well to be fractured, the number and length of stages to be perforated, the properties of the fracturing fluid, and the geological characteristics of the formation^{43,44}. Concurrently, volumes of FP water produced vary according to the volume of fluid injected, local geological characteristics that control water retention in the subsurface such as imbibition and extent of fracture network⁸, and the well length⁹. To date, only one well, targeting the Carboniferous Bowland Shale Formation, located at Preese Hall in Lancashire, England, has been subjected to high volume hydraulic fracturing in the UK. In 2011, Cuadrilla Resources injected 8,399 m³ of fluids, and perforated six fracturing stages in this well, before operations ceased and approximately 8,000 m³ of FP water was produced at the surface.

As this operation provides the only FP water volume datum for the UK at present, additional estimates of the likely volume of FP water returned to the surface can be made using injection volume estimates from the British Geological Survey and published ranges of percentages of injected fluid returned by the in the following equation (1) (S.I.4 & 5).

$$\text{Volume } (V_{\text{returned}}) = \text{Volume } (V_{\text{injected}}) \cdot \text{Percentage } (P_{\text{returned}}) \quad (1)$$

Calculating costs of FP water treatment

The cost of FP water treatment can be determined by the following equation (adapted from Webb & Woodfield, 1981):

$$C = R + VP + \left(\frac{St}{Ss} * S\right) \quad (2)$$

Where;

C is the total cost to the operator,

R is the cost of receiving the waste at the facility in question including storage and transport costs,

V is the volumetric cost of waste treatment imposed by the plant,

P is the cost per volume of the primary treatment applied to the waste,

St is the Total Suspended Solid (TSS) concentration of the waste,

Ss is the Total Dissolved Solid (TDS) concentration of the waste,

and S is the cost of the treatment of solids.

To forecast the cost of treatment of wastewater (C), the volume of waste to be treated (V) and the chemistry, or solid salinity, (St, Ss) must be determined and combined with the cost of auxiliary treatment (R, P, S).

We apply the results of the volume calculation (S.I.2) to a simplified cost projection equation (3) to identify the expected range in cost of treatment for our simulated range of FP water volumes. To provide a contextual and holistic estimate of the likely cost of treatment, published costs (C_{treatment}) for reverse osmosis (RO) and distillation by mechanical vapour

compression (MVC), were used⁴⁵ (S.I.3). These costs were supplemented with a cost range provided by a specialist treatment plant in Pennsylvania, U.S. which uses a combination of chemical adjustment, filtration, settling, and distillation to produce dischargeable and re-usable effluent⁴⁶. A Monte Carlo simulation (n=10,000) was performed to estimate the range in total cost likely to arise from changes in expected injected and returned volumes of fluid, and to estimate the sensitivity of each parameter within the calculation to the total cost of treatment. The input parameters for all Monte Carlo calculations are provided in Table S.I.2.

$$\text{Cost } (C_{\text{total}}) = \text{Volume } (V_{\text{injected}}) \cdot \text{Percentage } (P_{\text{returned}}) \cdot \text{Cost } (C_{\text{treatment}}) \quad (3)$$

Assessing the capacity for FP water treatment in the UK

Non-specialist public treatment works in the UK are unable to treat highly saline and NORM contaminated waters^{16,47}. Hence, the removal of salinity (TDS) and NORM can only be undertaken at specially permitted treatment facilities³⁷. There are currently four treatment facilities in the UK that are appropriately permitted to handle liquid waste containing NORM⁴⁸⁻⁵¹. Publically available permitting documents for these four sites provide information on the environmentally agreed limits for accumulation and disposal of aqueous radioactive waste on a daily, monthly and annual basis. Amalgamating these provides the total daily accumulation and disposal limits for the UK (correct as of November 2017). Using the measured radioactivity in FP waters from the 2011 hydraulic fracturing at Preese Hall and the projected volumes of FP water, we estimate the range in radioactivity expected to be received and disposed of by the sites listed (Equation 4).

$$\text{Radioactivity } (A_{\text{projected}}) = \text{Radioactivity } (A_{\text{measured}}) \cdot \text{Volume } (V_{\text{projected}}) \quad (4)$$

Figure 1 – Table of end-member variables used for Monte Carlo Simulations, see Supplementary Information for more detail.

		Minimum	Maximum	Source
V_{injected}		7,000m ³	18,000m ³	See S.I.4
P_{returned}		10%	70%	See S.I.5
$C_{\text{treatment}}$	RO	\$0.50/m ³	\$12.33/m ³	See S.I.3.1
	MVC	\$0.47/m ³	\$25.16/m ³	See S.I.3.1
	CBD	\$50.30/m ³	\$164.50/m ³	Eureka Resources ⁴⁶

Results**Volumes of FP Water**

The British Geological Survey estimate between 7,000 m³ and 18,000 m³ of injection fluid will be required for each UK hydraulic fracturing operation⁵² (S.I.4). The American Petroleum Institute cite that between 10 % and 70 % of this fluid typically returns to the surface⁵³ (S.I.5). Using Equation 1



with the bounding values listed allows calculation of expected return water volumes of between 700 m³ and 4,900 m³, if 7,000 m³ is injected. If the volume injected is nearer to the upper bound of 18,000 m³, then the range of returned waters increases to 1,800 m³ – 12,600 m³. These do not represent exhaustive volume limits, as corroborated by the wider range of volumes recorded in the U.S.⁴³, but provide reasonable estimates within the confines of existing data for the UK.

To improve upon this volume estimate, a Monte Carlo analysis (n=10,000) was performed on this volume projection to determine the 95% confidence intervals, given a uniform probability distribution assumed between the BGS end-member values. These simulations determine that in 95% of cases the FP water volume is likely to be between 1,253 m³ and 10,544 m³, and only in 1 % of cases will the FP water volume exceed 12,224 m³. The volume of water retained by the formation could vary from 2,227 m³ to 12,754 m³ under these injection volume scenarios.

In comparison, the return of 8,000 m³ fluids from the 8,399 m³ injected by Cuadrilla Resources in the only hydraulic fracturing of a shale formation in the UK to date highlights that 95 % of the injected fluids returned to the surface. However, this well was not completed and produced in the planned fashion, with no shut-in period due to the triggered seismic events, and hence these ratios are not representative and are not used in the modelled volumes of FP water. The fluid volume injected at Preese Hall is well within the 5th and 95th percentile volumes of fluids injected for hydraulic fracturing in 38,530 wells in the U.S. between 1st January 2011 and 28th February 2013 which range from 135 m³ to 32,700 m³ respectively, with a median volume of 6,800 m³⁴³. However, these data include volumes for fractured vertical wells and coal bed methane operations, which typically use significantly less fluids. A higher and more concise volume range would be expected should the hydraulic fracturing of only high volume, horizontally drilled wells be considered, but unfortunately, the U.S. data sampled is not reported by well type.

Cost of FP Water Treatment

The expense and energy intensity of FP water treatment is dependent on the composition of the water to be treated as defined by Equation 2. The minimum, mean, and maximum, levels of dissolved solids measured in the FP waters collected by Cuadrilla for treatment, at Preese Hall were; 94,000 mg/L, 128,750 mg/L and ; 210,000 mg/L⁵⁴, respectively. Whilst these data are limited by being from a single well, this provides the best estimates of future compositions of UK FP waters currently available. Confidence in this salinity range is provided from examination of data from offshore operations that produce waters from wells drilled to the Bowland Shale or underlying Viséan limestone formations. The salinities of these waters range from 164,460 mg/L to 398,240 mg/L⁵⁵, indicating that higher salinities may be possible from fracturing of other areas of the Bowland Shale. These offshore produced waters are typically discharged directly to the sea, and are only

treated to separate co-produced hydrocarbons to the limit of 30 mg/L⁵⁶.

Additionally, produced waters from conventional onshore production at Kirby Misperton in Yorkshire, England from the Permian Kirkham Abbey and Permo-Triassic Sherwood Sandstone Formations overlying the Carboniferous Bowland Shale exhibit a range of salinities from 180,000 mg/L to 349,000 mg/L⁵⁷. These comparisons provide confidence that the salinity levels measured at Preese Hall are comparable, on average lower, than salinities measured from fluid produced during offshore Carboniferous production and onshore Permo-Triassic production as outlined in Figure 2. .

Figure 2 – Stratigraphic chart annotated with mean salinities (mg/L) of FP and produced water data by source formation for the UK.

Period	Epoch	Age	Mean Salinity				Age (Ma)
			Sherwood Sandstone	Kirkham Abbey Formation	Bowland Shale (offshore)	Bowland Shale (onshore)	
Triassic	Late	Rhaetian	185,000 mg/L	349,000 mg/L	282,427 mg/L	168,750 mg/L	250,193 mg/L
		Norian					201
		Carnian					209
	Middle	Ladinian					228
		Anisian					237
		Olenekian					241
	Early	Induan					247
							250
		Lopingian					252
							254
Permian	Guadalupian	Capitanian	260				
		Wordian	265				
		Roadian	269				
	Cisuralian	Kungurian	272				
		Artinskian	279				
		Sakmarian	290				
		Asselian	296				
Carboniferous	Pennsylvanian	Gzhelian	299				
		Kasimovian	304				
		Moscovian	307				
		Bashkirian	315				
	Mississippian	Serpukhovian	323				



Figure 3. Waste treatment facilities in the UK, and their permitted radioactivity accumulation and disposal limits as outlined in their environmental permits by the Environment Agency.

Facility Name	Operator	Location	Permit No	Radionuclide or Group of Radionuclides	Accumulation Limit (Bq/day)	Disposal Limit (Bq/day)
FCC Knostrop	FCC Environment (FCC Recycling UK Ltd)	Leeds	BB3538DH	²³⁸ U	1.54E+07	5.33E+06
				²³² Th	1.79E+07	4.73E+06
Bran Sands	Northumbrian Water Ltd.	Middlesbrough	PB3438DJ	²³⁸ U	1.50E+08	3.33E+06
				²³² Th	1.50E+07	3.33E+07
Castle Environmental	Castle Oils Ltd.	Stoke-on-Trent	QB3339DQ	²²⁶ Ra	2.44E+07	8.22E+04
				²²⁸ Ra	3.33E+06	6.03E+05
FCC Ecclesfield	FCC Environment (FCC Recycling UK Ltd)	Sheffield	ZB3395DX	²³⁸ U	2.57E+06	2.74E+06
				²³² Th	2.00E+06	2.19E+06
TOTAL				²³⁸ U	1.92E+08	1.15E+07
				²³² Th	3.82E+07	4.09E+07

The Environment Agency enforce volumetric as well as activity limits on the volume of aqueous waste containing NORM that can be received at available treatment sites, currently amounting to 825 m³ per day across the UK. If the volume of FP water produced during fracturing exceeds this the capacity of the available treatment facilities could become critically stressed. Hence, without alternate storage options or emergency treatment capacity, operations would be forced to cease until the fluids can be appropriately handled.

Implications for FP treatment in the UK

Cost of Salinity Treatment

The values of salinity measured in FP waters from the hydraulic fracturing of the Bowland Shale in the UK range from 98,000 to 210,000 mg/L. Salinity of FP water can vary geographically within a single shale basin due to lithological heterogeneity and distribution of relatively saline horizons^{34,63}. However, these values lie well within the reported salinity ranges observed in FP waters from unconventional production in the Haynesville, Marcellus and Barnett shale plays of the U.S. (35 – 358,000 mg/L). Additionally, they are lower than measured salinities of produced water from conventional hydrocarbon extraction onshore (180,000 – 349,000 mg/L) and offshore (164,000 – 398,240 mg/L) in similar formations in the UK (Figure 4).

It is clear that FP water with higher levels of contaminants, including TDS, will be more costly and energy intensive to treat. Waters with TDS levels above 50,000 mg/L can only be treated by distillation (MVC), as filtration and osmosis has been proven to be ineffective at high salinities⁶⁴.

The 95% confidence range of estimated costs of desalination, per well, for FP waters from fracturing of the Bowland Shale in the UK by MVC range from \$3,952 to \$196,484. Disposal of

desalination by-products such as sludge contaminated with NORM will significantly increase the cost projections. The U.S. Energy Information Administration calculate that the mean estimated ultimate recovery (EUR) from shale gas wells is 1.8 x 10⁶ MMBtu⁶⁵. With the current price for natural gas at \$2.94/MMBtu (correct as of November 2017), each well can be estimated to generate on average \$5,292,000 in revenue. Therefore, up to 3.7 % of the total revenue from a single shale gas well could be absorbed by desalinating treatment costs alone. Variations in the price of natural gas can cause the percentage of expected revenue required for FP water treatment by MVC to vary from 2 % up to 5 %.

Additionally, if multiple treatment processes are required to target multiple contaminants within the waste, the cost can increase significantly. Eureka Resources, a specialised FP water treatment company based in Williamsport (PA), typically charge \$50.30 – 164.50/m³ to treat FP water at their designated facility⁴⁶. If these prices are to reflect the total combined treatment cost in the future for the UK, between \$107,683 to \$1,376,093 (95 %CL), or up to 26% of the estimated revenue per well would be required. The U.S. has also benefitted from the use of portable treatment facilities that reduce salinity and remediate against some contaminants on-site before re-use. These reduce the transport requirements associated with off-site waste treatment, but increase the likelihood of onsite spills as a result of increased on site waste handling.

Cost of Naturally Occurring Radioactive Material Treatment

Aqueous NORM waste in the UK is treated by following the principal of 'dilute and disperse' within the sewerage and water treatment system³⁷. Given that underground disposal of FP waters has been discounted as an option for the UK to date, treatment for re-use or effluent discharge will be required.



Figure 4. Table of summary statistics for comparable data sets of salinity measured in onshore and offshore operations in the UK and USA.

Total Dissolved Solids (mg/L)	UK			USA	
	Offshore Conventional	Onshore Conventional	Onshore Unconventional	Onshore Conventional	Onshore Unconventional
Sample size	n=14	n=3	n=24	n=88,261	n=174
Minimum	164,460	180,000	94,000	0.1	35
Maximum	398,240	349,000	210,000	528,700	358,000
Mean	273,217	239,666	168,750	83,490	65,120
Median	280,430	190,000	180,000	51,220	24,700
	99% confidence interval in min-max to correct for outliers			156 – 392,963	37 – 355,751

It is also pertinent to consider the volume of solid or sludge NORM waste generated as a by-product. Radium, the most common NORM in FP water, is chemically similar to other alkaline earth elements such as magnesium (Mg), barium (Ba), strontium (Sr), and calcium (Ca) and so readily co-precipitates generating NORM concentrations in scale and sludge produced during MVC treatment. This sludge by-product will require disposal to landfill with the appropriate radioactivity permits unless exempt due to low activity by the Radioactive Substances Regulations (2011).

Within the context of Equation (2), the S value for FP water containing NORM will be inflated by the cost of obtaining and maintaining a RSR permit, with application fees for 2017 ranging from £980 – £2640, and subsistence costs ranging from £154 to £3940 per year depending on the conditions and nature of the mining waste activity proposed⁶¹. Additionally, disposal of these sludge wastes at landfill will incur a 'gate fee' and landfill tax, between £89 - £135 per tonne in 2014/15⁶⁰. Utilising the known salinity of waters returned at Preese Hall, the total mass of solids available for removal from waters returned during fracturing of a single well can be projected to be between 10 and 3269 kg (53 – 2053 kg, 95% CL). Between 1 and 99% of the volume of sludge is comprised of residual wastewater⁶⁶ and therefore the total volume to be disposed of varies in proportion to the percentage water content. Dewatering processes significantly reduce the volume of waste to be disposed⁶⁶, but if 100% recovery of solids is assumed and no dewatering performed the volume of sludge to be disposed varies from 10 kg – 329,600 kg (0.01 – 326.9t). This equates to an additional cost of £1.00 – 326.90 in regular landfill gate fees per well, or up to £163,450 (£500 per m³ of sludge) at the LLW Repository exclusive of permitting levies for the cost incurred in obtaining an RSR permit, transportation costs, and radioactivity charges such as those imposed at the LLW Repository⁶². The maximum projected disposal cost of NORM waste of £163,450 equates to an additional 3 % of the estimated overall revenue generated from a single well. Therefore under these scenarios is unlikely that the additional costs of disposing this low level radioactive sludge will render

unconventional extraction uneconomic, however the issue of available capacity remains pertinent.

Lessons for the UK on FP water management from the U.S.

A number of the FP water management options practised in the U.S. have caused surface contamination, which has impacted the ecology and environment. It is crucial that the UK learns from the mistakes and subsequent regulatory improvements made in the U.S. to prevent similar problems occurring in the UK.

Treating waters returned by hydraulic fracturing operations at centralised or municipal treatment works in the U.S. has led to increased concentrations of contaminants such as TDS, bromide, and chloride in the receiving waters due to the incompatibility of the treatment facilities with the waters concerned^{4,67,68}. Inadequate treatment of these waters has also been shown to reduce water quality downstream from treatment works^{16,68-71}. Consequently, treatment of water in public or municipal works has since been banned by the U.S. Environmental Protection Agency, and treatment may now only be performed by specialist or designated treatment works⁷².

Leaks and spills associated with transport and storage of these waters can also cause detriment to water quality, as well as due to casing failure or poor well integrity at deep injection sites⁷³. Containment of waters within unlined surface ponds or impounds can allow leaching into the water table and contamination of nearby ground and surface waters⁷⁴. However, this practice will not be permitted in the UK⁷⁵, and regulatory changes in some states in the U.S. mean that full lining of any hydraulic fracturing site is now required, which combined with a means of secondary containment of FP water has significantly reduced contamination risks⁷⁶.

Conclusions & Recommendations

We find that disposal options in the UK are limited by current restrictions on the underground injection of waste. Hence it is



certain that some form of treatment will be required before waters will be re-usable, either for hydraulic fracturing operations or externally, or for safe to discharge to the environment. We find that whilst the salinity and NORM levels in future FP waters from UK hydraulic fracturing operations can be treated, this will cost between \$2,701 and \$1,376,093 per well for salinity. This will require up to 26 % of the revenue generated by a typical shale gas well, and up to £163,450 (3% of revenue) for NORM management.

We have found that there is currently limited treatment capability for receiving returned waters from unconventional gas operations in the UK that are contaminated with NORM, and no uniquely dedicated treatment plants currently exist. As the UK shale gas industry is in its infancy, the limited treatment capacity for returned waters should not pose a problem in the short term, unless especially high volumes of FP water are experienced that cannot be received at the currently permitted facilities.

However, significant expansion of the shale gas industry resulting in simultaneous FP water production from multiple wells would critically stress the current capacity to receive, treat and dispose of NORM contaminated, highly-saline wastewaters. We strongly recommend that this area receives further attention from the emergent unconventional gas industry, the established waste water management industry and regulatory bodies in the UK, in order to produce a coherent strategy for the for the future management of FP waters. Our work has found that no such co-ordinated strategy currently exists, and limited FP management capacity in the UK will present a significant hurdle to future expansion of the industry unless it is urgently addressed.

We advise that future shale gas activities in the UK make their returned water composition data publically available so as to improve upon the estimates presented in this study. We further recommend that future treatment options are reviewed in light of new data once it becomes available.

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