Energy production and well site disturbance from conventional and unconventional natural gas development in West Virginia

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Abstract Natural gas production from the Appalachian region has reached record levels, primarily due to the rapid increase in development of unconventional oil and gas (UOG) resources. In 2020, over 65,000 conventional wells reported natural gas production; however, this only represented 5% of the total natural gas produced. The remaining 95% of natural gas production can be attributed to 3,901 UOG wells. There has been a wide body of research on disturbance trends related to unconventional development in the region; however, there is limited characterization of disturbance related to production of conventional oil and gas (COG) or research that details energy production in relation to land disturbance. This study compares land disturbance from COG and UOG development as well as energy production. Land disturbance related to COG and UOG development was assessed for wells drilled during 2009–2012. Production data were summarized for the same wells during the period of 2009–2020. The average area disturbed for COG pads was 0.82 ha while UOG pads disturbed 4.02 ha. Results from this study showed that COG wells disturbed significantly less land area during construction; however, UOG wells produced almost 28 times more energy per hectare of land disturbed. This energy production imbalance as well as the over 65,000 COG wells reporting production in 2020, indicates that the retirement and restoration of COG infrastructure could be done without significantly impacting total energy production. Continued research that includes ecosystem services and carbon sequestration opportunities in relation to production losses from retiring existing infrastructure should be considered.

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1 Introduction

Worldwide natural gas production declined by 2.5% in 2020, which was the first decline in total gas production seen since 2009 (IEA 2021b). Wang and Bentley (2020) forecasted natural gas production could reach a peak between 2019–2060; however, the recent decline in natural gas production were largely due to the COVID-19 pandemic and lower energy prices that resulted. Consumption of natural gas declined 1.2% in 2020 (IEA 2021b) after almost 2% year-over-year growth each year during 2010–2017. Growth in global natural gas markets over the past decade have been attributed to reductions in coal use (IEA 2020). Recent projections indicate global electricity demand is increasing at a rate that is faster than the adoption of renewable fuels, which is expected to continue to drive demand for natural gas in the future (IEA 2021a).

Natural gas production from the Appalachian Basin, which includes Pennsylvania, West Virginia, and Ohio has reached record levels in 2021 (USEIA 2021a). These three states represent more than 33% of the USA total onshore natural gas production (USEIA 2021b) and are a significant contributor to global development. Proven resources from this region include both the Marcellus and Utica/Point Pleasant shale plays as well as several conventional hydrocarbon reservoirs. The Utica shale and Point Pleasant formations cover a prospective area of 220,000 km², while the prospective area of the Marcellus is estimated at over 186,000 km² (Popova 2017a, 2017b).

The Appalachian Basin has a long history of oil and gas production, with both Pennsylvania and West Virginia having claimed the first oil and gas wells in United States history in the late 1800s. Early production was based entirely on conventional oil and gas (COG) formations and techniques, while production over the last 15 years has increasingly shifted towards unconventional oil and gas (UOG) wells. Pennsylvania is credited with the first UOG well completed in the Marcellus shale in 2004 (Carter et al. 2011), and by 2006, over 25 UC wells were completed in West Virginia. Most production in the basin has trended towards UOG resources since this time. In 2020, there were over 65,000 wells producing in West Virginia, of which approximately 4013 are UOG.

Typically, COG wells are drilled vertically into shallow formations or geologic traps to produce hydrocarbons. The United States Energy Information Administration (EIA) classifies conventional oil and gas production as that occurring where a well is drilled into a geologic formation that permits free flow to the wellbore. Conversely, UOG production is typically associated with those that have horizontal laterals and require hydraulic fracturing (Scanlon et al. 2017) of unconventional reservoirs such as coalbed methane, tight gas and shales (Fangzheng 2019). Song (2015) identified unconventional resources as those in which the source and the reservoir coexist, with very low permeability and without buoyancy-driven migration. Drilling, completion, and infrastructure needs also vary between COG and UOG production. Because they are vertical wells drilled into shallower formations, drilling and fracture stimulation completion equipment is smaller and less complex in COG wells. Conversely, UOG wells with horizontal well bores rely on much larger drilling rigs as well as the tremendous resources necessary for fracture
stimulation and completion of these wells. For example, Scanlon et al. 2017 found that UOG wells required 5 × the amount of water for stimulation than COG wells located in the Permian basin. This difference is used to specify well permitting under the WV Department of Environmental Protection. In West Virginia, UOG wells are regulated under the 2012 Horizontal Well Act. This act applies to all wells that use a horizontal drilling method and disturb more than 3-acres of land or use more than 210,000 gallons of water in a thirty-day period (WVDEP 2016).

For both COG and UOG wells, most of the land disturbance can be attributed to well locations and access roads, midstream infrastructure, and associated pits and impoundments. Disturbance related to UOG production has been well documented. Disturbance due to UOG pad development has been found to range from 2.5 to 5.6 hectares per well pad (Harris 2020; Jantz et. al. 2014; Johnson et al. 2010, Slonecker et al. 2012a, b). When midstream infrastructure, such as gathering lines, compressor stations and transmission pipelines is included, disturbance has found to increase for UOG wells between 64% (Jantz et al. 2014) and 250% (Langlois et al. 2017).

There is little empirical data on disturbance associated with COG wells in the eastern United States. Johnson et al. (2010) stated that the footprint for COG wells is bigger than UOG but did not present data to support this statement. In British Colombia, Appiah et al. (2019) found more forest change associated with UOG production than COG; however, UOG represented a significantly greater proportion of the wells drilled. Slonecker and Milheim (2015) found that the total land area occupied by COG wells was greater than UOG wells. In China, Wang et al. (2021) showed that shale gas wells had more environmental impacts than conventional wells; however, due to the significant reserves UOG wells were deemed more environmentally friendly.

As the number of UOG wells drilled in West Virginia increased over the last decade, so has land area impacted by this development. Characterizing the differences in land impacts and energy production between historical COG and current UOG techniques provides data on both the environmental and societal impacts of these changes. Future hydrocarbon development will be dominated by UOG production and providing metrics that relate environmental impacts to energy production provides important baseline information. This is the first research project to compare surface disturbance characteristics of COG and UOG development at the well level in the USA while at the same time relating this disturbance to energy production. This was done by developing a rate-ratio of energy production to land disturbance for UOG and COG wells. This metric can help understand potential impacts of future energy development as well as drive targeted restoration of past energy production systems.

2 Methods

2.1 Site selection

In WV, permitting of natural gas and oil wells is overseen by the West Virginia Department of Environmental Protection (WVDEP), which requires all well locations to be recorded and submitted under the 2011 WV Horizontal Well Control Act. This act sets in place permits and regulations that must be completed before a UOG well can be drilled. Part of this process includes a fee that is based on the number of planned wells. In addition to the fee, an application is submitted to the state, which includes 19 individual sections applicants must complete. These sections include lease summaries, plat surveys, well restrictions, required notifications and other permits forms necessary before a well application can be received (WVDEP 2016). UOG permit records are hosted by the WVDEP in a web-based database and were used as the original source of data for this project. Data from the West Virginia Geologic and Economic Survey (WVGES) were also used to verify permit dates, spud dates, and well types. The WVGES catalogues the WVDEP well data, which provides an added form of error control. For this study, data were summarized for a total of 3907 UOG and 61,642 COG wells producing energy during the 2007–2020 period (Fig. 1).

To understand the relationship between disturbance and energy production, we subset only those wells drilled from 2009–2012, which would provide up to 12-years of production data. This period was in the early stages of UOG development; however, it represented the first years with significant increases in drilling. Likewise, it was still early enough in the unconventional shale development cycle that conventional wells were still being drilled and produced.

COG wells included all those wells determined by the WVGES to be traditional vertical wells into shallow formations and UC were only those wells with a horizontal bore into a shale formation. Wells were individually identified by their American Petroleum Index (API) number, which was used as a primary key for the combination of the multiple permitting, drilling, and production datasets.

A total of 1555 COG and 1167 UOG wells were identified as drilled in the 2009–2012 data subset. These wells were randomized and a 20% subsample was selected from each type (COG and UOG). Individual well locations were then imported into a GIS and site conditions were examined based on 2007 United States Department of Agriculture National Agriculture Imagery Program (NAIP) imagery (USDA NAIP 2007), which represented the pre-exploration and production time-period for each of the
wells. If well site related disturbance was apparent from the 2007 imagery on the randomly selected well, it was not used in subsequent analyses. A total of 206 UOG wells and 296 COG wells were identified as having been on a location that had been disturbed during the study period.

Once all locations meeting the developed criteria were located and referenced in a GIS, a 20-ha circular buffer was created around each well bore. This buffer size was selected because it was large enough to include the majority of all surface disturbances, i.e., roads, ponds, pipelines, and pads, involved with the development, but yet not so large that it covered multiple wells in the same area or connecting midstream infrastructure. The 20-ha buffer is slightly larger than that used in comparable studies (Drohan and Brittingham 2012) (Entrekin et al. 2011); however, we found that a 15-ha buffer was too small and did not always encompass development associated with unconventional wells (Zinkhan 2016).

### 2.2 Site characteristics

To identify land use changes due to well pads, the disturbance associated with well locations was visually determined using NAIP imagery (Table 1). NAIP imagery has been used in several similar studies to assess land cover characteristics in areas of unconventional development (Drohan et al. 2012; Jantz et al. 2014; Slonecker et al. 2012a; Pierre et al. 2018; Liu 2021). A temporal range of orthophotos was used in this study to determine the baseline surface conditions for a well prior to natural gas development, and those occurring after natural gas development had taken place. For example, a well initiated in 2010 used the 2007 imagery files to determine the surface conditions pre-development and the 2011 and 2014 imagery files to determine the surface conditions post-development. By using multiple sources of aerial imagery, the periods of maximum disturbance during development could be identified. Once the most appropriate pre- and post-imagery had been selected for each well through visual inspection, the extent of disturbance was digitized within each 20-ha buffer by overlaying the well locations and post-drilling imagery. All disturbance was digitized at a scale of 1:10,000 (Fig. 2).

Cover type and slope within the conventional and unconventional well buffers before development were evaluated using National Land Cover Dataset (NLCD), Ecological Land Units (ELU) (McNab 1993) and digital elevation models (DEM) (Table 1). NLCD from 2006 was resampled to a 1-m resolution and cover types were assessed for the pre-construction period (Donnelly et al.

### Table 1 Spatial data type, source, and description for the assessment of land disturbance related to unconventional (UOG) and conventional (COG) natural gas wells drilled in West Virginia

| Spatial Data | Description | Source |
|--------------|-------------|--------|
| 2007 NAIP (1 m) | National Agriculture Imagery Program Color aerial orthophotos | USDA-NAIP (2007) |
| 2009 NAIP (1 m) | National Agriculture Imagery Program Color aerial orthophotos | USDA-NAIP (2009) |
| 2011 NAIP (1 m) | National Agriculture Imagery Program Color aerial orthophotos | USDA-NAIP (2011) |
| 2014 NAIP (1 m) | National Agriculture Imagery Program Color aerial orthophotos | USDA-NAIP (2014) |
| 2006 NLCD | National land-cover dataset | Fry et al. (2011) |
| 2003 DEM | West Virginia Statewide Digital Elevation Models | USGS (2005) |
| 2003 ELU | WV Ecological Land Units | NRAC (2012) |
NLCD data were reclassified into 1 of 7 categories including percent-developed, barren, forest, grassland, crops, and wetland cover types. Slope characteristics were determined by resampling 2003 and 2009 DEM data at a 3-m cell size within the digitized disturbed areas. Temporal data chosen for these analyses were based on availability and relation to pre- and post-development.

2.3 Natural gas production

A key component of UOG that differs from COG development is that operators often drill multiple wells on a single pad. Co-location of wells on a pad provides for shared infrastructure and can help minimize development costs, while more effectively producing UOG resources. Once individual well pads were identified for the 206 UOG and 296 COG wells, all wells permitted and producing on that pad from 2009–2020 were identified. This included wells beyond the original sample from 2009–2012 and represented all development on the pad. This was done by creating a 100-m buffer centered on the identified COG and UOG wells within the digitized disturbed areas (well pads) and assigning all buffered wells to those pads. These data were checked against WVDEP records to ensure the location of multiple wells on a pad. Once wells were assigned to the pads, production information for every well in WV was acquired for the period of 2009–2020 and included over 800,000 data records. Operators are required by state law to report their production information, these data were supplied by the WVDEP and the WVGES on an individual well basis. Production data included natural gas (reported in thousand cubic feet), natural gas liquids (reported in barrels), and oil (reported in barrels). Data were converted to therms (100,000 BTU) using BTU equivalencies for each energy source (USEIA 2021c) and summarized at the well level for each reported month of production.

2.4 Statistical analyses

Normality assumptions for total disturbed area were tested using the Shapiro–Wilk test statistic for individual well types as well as aggregated data. Data collected for the total disturbed area were normal for COG wells but were...
positively skewed for UOG wells. This was due to a limited number of samples that had extremely large impacts on surface parcels. Since the aggregated data did not meet normality assumptions \( (p < 0.0001) \), and the extreme observations were not considered outliers, nonparametric statistical methods were used. The Wilcoxon rank-sum method was used to test for differences in the total disturbed area between COG and UOG wells. These nonparametric tests were also used for the NLCD, ELU, and terrain metrics developed in this study. Spearman’s rank correlation was used to measure the statistical dependence between the total disturbed area and the year the well was originally spudded.

3 Results

A total of 1167 UOG wells were identified as being spudded, or having drilling commence, during the period of 2009—2012. The number of UOG wells increased rapidly between 2009 and 2011, then declined in 2012 (Fig. 3). The majority these wells were drilled with the purpose of producing natural gas (66%) or natural gas and oil and natural gas liquids (25%). During the same period, a total of 1555 COG wells were spudded. The number of COG wells decreased sharply between 2009 and 2012, as more operators increased their use of unconventional drilling techniques. Again, most of the COG wells were drilled with the purpose of producing natural gas (75%) or oil and natural gas (12%).

The 296 COG wells selected from 2009–2012 were located on 296 distinct well pads, an average of 1.08 wells per pad. However, an average of 3.8 UOG wells were drilled and producing on the pads selected in this study when reporting aggregate data through 2020. The average area disturbed for the development of COG pads was 0.82 ha. UOG well pads disturbed an average of 4.02 ha, which was significantly greater than the disturbance associated with COG wells \( (Z = 18.08, p < 0.0001) \) with a mean rank of 388.1 for UOG wells and 151.0 for COG wells. Disturbance related to well pad construction remained constant from 2009–2012 for COG wells \( (r = 0.06, p = 0.3125) \) and had a minimum of 3.4 ha in 2009 to a maximum of 4.3 ha in 2011 for UOG wells. There was a significant positive trend in disturbance size for UOG wells during the study period \( (r = 0.18, p = 0.0142) \). UOG wells drilled in 2009 averaged 3.4 ha which increased to 4.1 ha for those wells drilled in 2012.

Well site selection for COG versus UOG wells were similar in relation to slope and topography; however, UOG wells tended to be sited more frequently on flatter terrain (Fig. 4). COG wells were sited on side slopes, upper slopes, and slope crests whereas UOG wells were sited on upper slopes, side slopes, and slope crests. Almost 15% of UOG wells were sited on flat summits. The ELU characteristics found for these wells corresponded with the slopes determined for the areas selected for drilling. Areas disturbed for COG wells during 2009–2012 had an average slope of 15.0% versus UOG wells with an average slope of 10.8%. This difference was significantly different \( (Z = −9.26, p < 0.0001) \) with a mean rank of 169.9 for UOG wells and 290.8 for COG wells.

Due to their prevalence and data resolution, NLCD comparisons of UOG versus COG were only completed for
the forested and grassland cover types. The combination of forested and grassland cover types represented 95.3% of the pre-disturbance well pad area for COG and 92.5% of the area for UOG wells. Those sites chosen for UOG wells were on average 55% forested and 37% grassland. This compares to COG well sites that were on average 86% forested and 9% grassland. These results indicate that COG well sites were selected in areas with significantly greater forest cover than UOG wells \((Z = -10.43, p < 0.0001)\), with a mean rank sum score of 295.4 for C wells and 162.7 for UC wells. Likewise, UOG well sites were selected in areas that had significantly greater grassland cover than COG wells \((Z = 10.15, p < 0.0001)\), with a mean rank sum score of 317.9 for UOG and 195.7 for COG wells.

From 2007–2020, the number of UOG gas wells reporting production in WV increased from 84 to a total of 3,907. During this same period, COG wells reporting production ranged from a low of 52,949 in 2009 to a high of 61,642 in 2020. In 2008, UOG wells represented only 3% of the total gas produced and less than 1% of the total well sites. Conversely, in 2020, UOG wells represented 6% of the total wells drilled and 95% of the total statewide production (Fig. 5).

All COG wells chosen for this study reported production during the study period. For UOG well sites included in this project, a total of 716 wells reported production from the 206 well pads between 2009 and 2020. This represents an average of 3.5 wells per unconventional pad that reported production. An average of 104 months of
production was recorded for COG wells and 77 months for UOG wells. Initial monthly production averaged 15,763 therms for COG wells versus 359,691 therms for UOG wells in this study. On average, individual COG wells produced 675,193 therms versus an average of 3,114,560 therms produced per UOG well through 2020. Total production was 199,857,282 therms for COG wells from the 296 well pads and 22,297,357,484 therms for UOG wells from 206 well pads, a 111-fold difference in total production per pad.

The relationship between energy production and well pad development impact was evaluated by calculating the rate-ratio of total production to overall disturbance at the pad level for COG and UOG wells. An average of 1,129,579 therms were produced per ha disturbed from COG wells which is significantly less ($Z = 17.01, p < 0.0001$) than the 31,298,989 therms per ha disturbed for UOG wells during the study period (mean rank sum score of 156.8 for C wells and 379.1 for UC wells). This represents over a 2600% increase in hydrocarbon production from UOG wells per ha disturbed.

4 Discussion

Oil and gas development in the Appalachian Basin has evolved rapidly over the last 15 years. Before 2006, drilling and production were done by COG methods. Permitting data from WV show that since 2010, UOG overtook COG well permitting, with UOG being the dominant well type and producer of natural gas from 2010 onward. In 2020, 61,642 oil and gas wells reported production in West Virginia, the majority (94%) of which were COG wells. Despite the dominance of COG wells, this research found that they only account for approximately 5% of the total energy production and produced significantly less energy per area of land disturbed.

The development of COG and UOG has documented impacts on land resources in the Appalachian Basin. These include increasing forest fragmentation (Drohan et al. 2012, Donnelly et al. 2017, Langlois et al. 2017, Liu 2021), accelerated forest canopy loss (Young et al. 2018), disturbance to avian communities (Farwell et al. 2020; Johnson et al. 2010), and impairment of water quality caused by increased sedimentation in local stream systems (Olmstead et al. 2013). In the current study, environmental monitoring was focused on land area disturbance and terrain features associated with well pads. This study found that well pad disturbance related to UOG well pads and other infrastructure was similar to that reported by other researchers (Harris et al. 2020; Jantz et al. 2014; Johnson et al. 2010; Slonecker et al., 2012a, b). However, this research is the first to compare UOG disturbance to COG disturbance in the same geographic location during the same time. Results indicate that UOG wells disturb almost 5 times more land area at the well site than COG wells drilled during the same time frame. This study did not quantify midstream or related impacts beyond a 20-ha buffer of the well pad, which can be significant contributor to land use change (Donneley et al. 2017; Langlois et al. 2017). It could be hypothesized that due to the excessive volumes of natural gas produced from UOG wells and thus the larger pipelines and compressor stations needed to transport this volume of gas, disturbance related to midstream infrastructure could be greater for UOG wells. However, it is also possible that COG midstream infrastructure could have a greater impact due to the larger number of locations throughout the state and the disjointed nature of the drilling. Data from the current study confirm that only 1 well is typically drilled on these COG pads, and they are distributed over a larger geographic area. The diffuse locations of COG wells reduce the efficiency of transportation networks, leading to more land disturbance needed per well than with UOG wells. Research is needed to understand midstream impacts related to UOG versus COG development.

This study found that UOG and COG well pad location terrain features were generally very similar; however, in West Virginia UOG wells were in areas with less slope. Construction in areas with less relief would incur less costs by limiting cut and fill activity. This would also reduce environmental impacts from construction activities. No other research has reported on terrain position or average pre-slope conditions of COG wells; however, our results are somewhat greater than those found by Drohan et al. (2012) who found that the majority of UOG wells in Pennsylvania were located on areas with slopes less than 8%.

Recent research has shown shale development can have land impacts concentrated in grass and agricultural cover types. For example, in the Permian basin, UOG development has significant impacts on shrublands and grasslands/pasture and were strongly dependent on production volumes (Wang 2021). Likewise, Allred et al. (2015) found that drilling on croplands and rangelands in central North America had significant impacts on net primary productivity. However, impacts to agricultural sites may be overestimated when cover changes during both the pre- and post-drilling periods are not analyzed (Fitzgerald et al. 2020). In the parts of Ohio and Pennsylvania in the Appalachian basin, Donnelly et al. (2017) found that most of the land changes occurred in hay and pasture cover types than in forest during UOG development. While this study found that both UOG and COG wells were primarily located in forest cover types, it is more a function of the prevalence of this ecosystem in West Virginia. A more
important observation is the fact that UOG wells were drilled in grassland areas significantly more often than COG wells. While research in the Appalachian basin has shown that UOG can have significant impacts on core forest (Drohan et al. 2012, Donnelly et al. 2017, Langlois et al. 2017, Liu 2021), it is important to note that from a forest fragmentation standpoint, COG wells would have greater cumulative impacts based on development patterns and density (Appiah et al. 2020; Scanlon et al. 2017) than UOG wells in WV.

A key finding from this study was that UOG wells produced 28 times (2600%) more energy than COG wells, per hectare of land disturbed. Over the period of this study, the total energy produced was much greater for UOG versus COG wells, mainly due to the high production rates recorded per well, and the number of wells drilled on each pad. Over the past 14 years, production from UOG wells has grown from 0 to 95% of West Virginia’s total natural gas produced, while representing only 6% of the total number of wells. Much of the increase is due to the efficiency of UOG development, especially in terms of well density per individual pad. In the initial years of shale development, pads contained at most 2 wells (Drohan and Brittingham 2012); however, recent estimates have shown that well densities average upwards of 5.6 wells per pad in the Marcellus region (Harris 2020). Some companies have expanded even more and are targeting up to 40 UOG wells per pad (Litvak 2018). This is also supported by the increase in UOG well pad disturbance found in this study from 2009 through 2012. As more wells are drilled on these pads, well pads are getting larger; however, energy produced per pad is outpacing this increase. Currently, the trends in production efficiency and scale have placed more emphasis on UOG development rather than COG in the Appalachian basin. This is especially true if historical COG well development is included in estimates. Datasets used in this study document over 60,000 COG wells producing in 2020 in WV; however, this does not all represent all the potential wells that exists. Riddick et al. (2018) estimated the lower bounds of all COG wells in the state was much greater. They estimated that for every well drilled and accounted for in WV DEP records, that between 58,000 additional have been drilled and plugged and 63,080 wells have been abandoned. Based on these estimates of well site locations, total impacts on the landscape due to COG well pads would be more than 148,000 ha at this time.

As COG wells currently represent a small portion of WV’s total production, but account for 94% of the total drilling locations, strategies should be initiated that would accelerate the retirement and restoration of these sites. Reclamation of COG infrastructure could have significant benefits to regional ecosystem services including agricultural, timber and carbon benefits (Allred et al. 2015; Nallur et al. 2020). Reductions in greenhouse gas emissions could also be achieved through reclamation strategies that target COG infrastructure. Omara et al. (2016) found that individually, unconventional wells can release more CH4 than conventional wells, which is mainly attributed to the higher production of these wells. However, when normalized on production, COG well pads in PA and WV produced approximately 41% greater CH4 emissions in the region. In OH, marginal natural gas wells were found to emit a significant portion of the natural gas produced, whereas oil wells vent upwards of 100% (Deighton et al. 2020). For both studies (Omara et al. 2016; Deighton et al. 2020) most of the methane emissions came from a small number of wells; however, they are still a nationally significant source of CH4 emissions (Deighton et al. 2020). Overall, the energy sector is the second largest emitter of methane (Karakurt et al. 2012) and thus provides significant opportunities for emission reduction. Based on results of this study, policy that contributes to COG site reclamation would not impact total natural gas production from the region. When CH4 emissions are coupled with site impacts and the low production rates, COG wells represent a strong opportunity for the restoration of ecosystem services and sequestration activities in WV. Although restoration activities may be impeded by current regulations (Mitchell and Casman 2011), they should become a focus through ecosystem service incentive programs.

5 Conclusions

Globally, natural gas use has increased over the past decade and will continue to be an important component of the world energy supply in the future. This study found that infrastructure related to UOG well pads on average, disturbed 5 times more land area than did COG wells constructed during the same period. However, UOG wells produced 28 times more energy per land area disturbed. While UOG gas wells represent a small portion of the total land impacts, they contributed 95% of West Virginia’s current natural gas production. Globally, the use of renewable energy is increasing; however, current rates of renewable deployment are not keeping pace with energy demand. Therefore, new policy should focus on reducing the impacts associated with UOG development, since UOG well permitting is trending upward in WV and the entire Appalachian basin. Research has shown that a 38% reduction in environmental impacts can be achieved with a 20% increase in well construction cost (Milt et al. 2016). Results from the current study suggest that even more benefits could potentially be realized from restoration activities associated with COG wells and infrastructure without impacting energy production. Policy focused on
COG restoration must include the cost and benefits of restoration while considering energy output. These costs can be significant, Nelson and Fisk (2021) found that in WV, well plugging and abandonment costs averaged $12,617 from 1992–2006. These costs are much higher today and not always covered by bonding costs. Current legislation in the USA is incentivizing the plugging of COG wells which will provide better data on these costs. More research is needed that categorizes these costs in relation to the potential environmental benefits restoration creates. Further research that explores the relationship between potential ecosystem services and carbon sequestration benefits in relation to production tradeoffs from existing COG infrastructure should be considered.

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