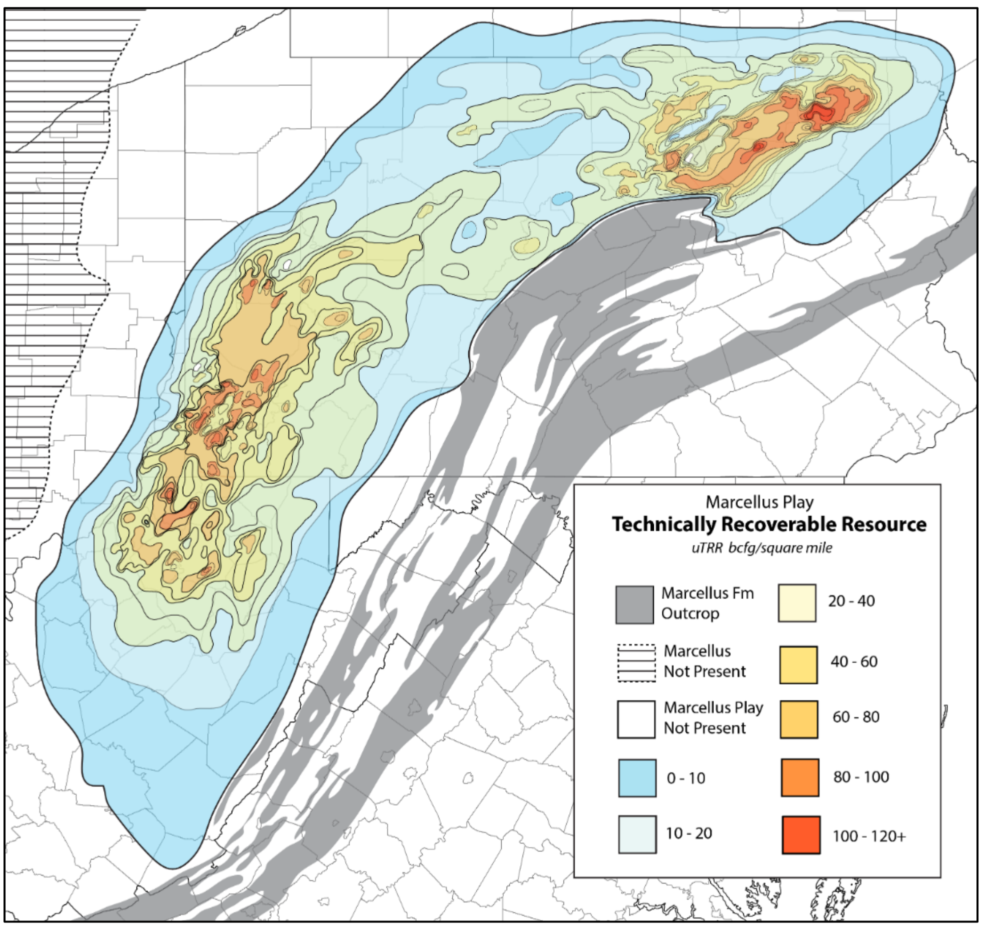
EVALUATION OF TECHNICALLY-RECOVERABLE RESOURCES IN THE MARCELLUS AND UTICA SHALE GAS PLAYS OF THE APPALACHIAN BASIN

RAY BOSWELL



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Disclaimer

Author

Ray Boswell[1]

[1]National Energy Technology Laboratory (NETL)
*Corresponding contact: ray.boswell@netl.doe.gov

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ACRONYMS AND ABBREVIATIONS

AEO	Annual Energy Outlook
ARI	Advanced Resources International
AU	Assessment unit
bcf	Billion cubic feet
bcfg	Billion cubic feet of gas
bcfge	Billion cubic feet of gas equivalent
Co.	County
cum.	Cumulative
DI	DrillingInfo
DOE	Department of Energy
dTRR	Developed technically recoverable resources
EIA	Energy Information Administration
EUR	Estimated ultimate recovery
Fm	Formation
fsTRR	Future supply technically recoverable resources
ft	Feet
Hrz	horizontal
mi^2, sq. mi.	Square mile
NETL	National Energy Technology Laboratory
NY	New York
OH	Ohio
PA	Pennsylvania
PGC	Potential Gas Committee
psi	Pounds per square inch
PUD	Proven, undeveloped (reserves)
rTRR	Remaining technically recoverable resources
ruTRR	Remaining unproven technically recoverable resources
SSAE	Strategic Systems Analysis and Engineering
tcf	Trillion cubic feet
tcfg, Tcfg	Trillion cubic feet of gas
tcfge	Trillion cubic feet of gas equivalent
TRR	Technically recoverable resources
U.S.	United States
USGS	United States Geological Survey
UT-BEG	University of Texas-Austin, Bureau of Economic Geology
uTRR	Ultimate technically recoverable resources
WV	West Virginia
WVGES	West Virginia Geological and Economic Survey
yr	Year

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EXECUTIVE SUMMARY

Domestic gas resources are critical contributors to the United States (U.S.) economy and will be key to enabling the sustainable and carbon-neutral fuel systems of the future. Recent assessments by the Energy Information Administration (EIA) continue to identify resources of the Appalachian region as critical to meeting energy demand, with the Marcellus and Utica-Point Pleasant ("Utica") shale plays combining for more than 30 percent of projected U.S. domestic natural gas production through 2050. [1] Several federal agencies periodically assess the gas volumes expected to be available from these plays (remaining technically recoverable resources [TRR] or "rTRR"). However, production from both plays has consistently outpaced projections, casting doubt on the reliability of prevailing resource estimates. Despite growing databases for both plays, the disparity among resource assessments and, therefore, the uncertainty in likely resource availability continues to increase. For the Marcellus play, recent estimates of rTRR range 98–560 trillion cubic feet of gas (tcfg). For the Utica gas play, the estimates range 103–782 tcfg rTRR.

The National Energy Technology Laboratory's Strategic Systems Analysis and Engineering (SSAE) approach is to utilize existing well production data for those multi-well developments that are most reflective of expected future productivity to ground truth resource estimates. To aid comparison, all estimates are converted into TRR/square mile (mi^2) by rigorous measurement of variable well length and spacing. SSAE's review of data for 3,706 Marcellus wells (as reported in the Enverus DrillingInfo™ database) shows that wells within the primary play fairway have already produced at an average rate of ~25 billion cubic feet gas (bcfg)/mi^2 over an average production history of only 5 years. This extraction is roughly double that predicted for remaining undrilled play core locations in the most conservative estimates. Analyses of Enverus' projected well-level estimated ultimate recovery (EUR) translates to an average of 60 bcfg/mi^2 in the play core and 30 bcfg/mi^2 on the play margins. For the Utica play, 1,991 well histories indicates that the average productivity to date is ~17 bcfg/mi^2 and that ultimate productivity could exceed 35 bcfg/mi^2 over the full area of the play (and higher in the play core). SSAE surmises that the primary reason for the persistent and growing discrepancy in resource assessment is in the handling of the input well productivity data. To obtain the revised TRR/mi^2 estimates, SSAE reviewed the database of historical wells and excluded those wells unlikely to be representative of future well productivity. This includes all vertical wells as well as all horizontal wells drilled before 2013 (when stimulation advances resulted in a step change in well productivity). SSAE also generally excludes wells with less than 24 months of production history as potentially unreliable. Further, SSAE selects groups of wells that reflect coordinated developments to allow incorporation of variable well spacing with time and location.

It is recognized that these evaluations are dependent on the accuracy of the Enverus EUR estimates, and it is noted that alternative approaches can produce EURs up to 30 percent less or 15 percent more. Further, SSAE considers the potential for future drilling to be limited to accessing only 85 percent of remaining acreage. However, even at those lower levels, future productivity from these plays can be expected to be approximately five times more than the most conservative prevailing federal estimates.

1 Introduction

Domestic natural gas resources are critical contributors to the United States (U.S.) economy and will be central to enabling a seamless transition to the sustainable and carbon-neutral fuel systems of the future. Recent assessments by the Energy Information Administration (EIA) continue to identify resources of the Appalachian region as critical to meeting energy demands, with the Marcellus and Utica-Point Pleasant ("Utica") shale plays combining for more than 30 percent of total projected U.S. domestic natural gas production through 2050. [1]

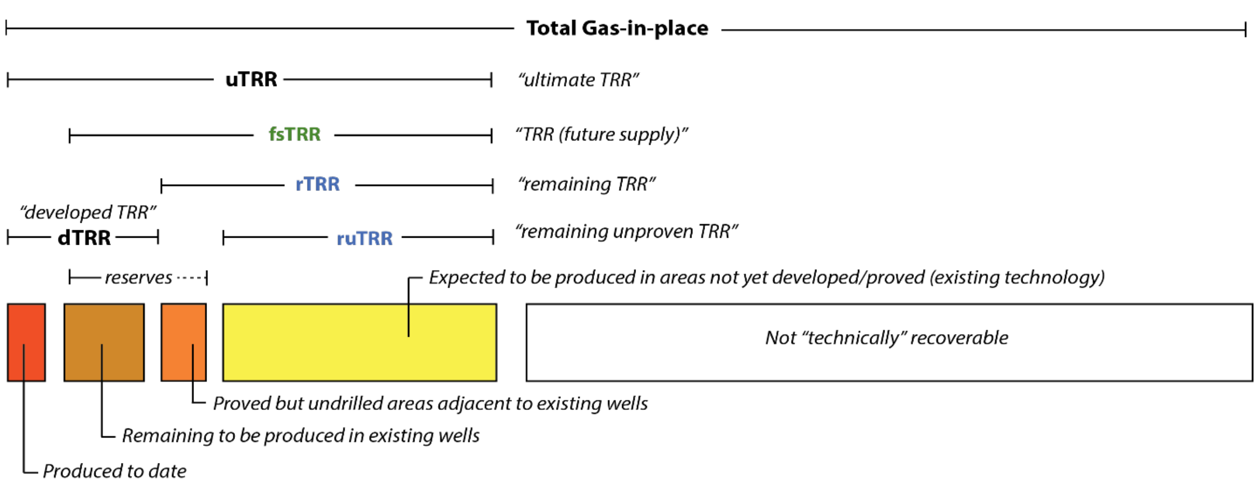
Several agencies periodically assess the gas volumes expected to be available from these plays. The quantity assessed is typically referred to as "technically recoverable resources" (TRR), which is generally considered to be the volume of gas available to contribute to future production. Since the inception of shale gas development in the Appalachian basin circa 2005, productivity has consistently outpaced projections. Further, despite growing databases of well productivity histories for both plays, the disparity among various resource assessments and, therefore, the uncertainty in expected resource availability continues to increase.

This analysis expands on methods outlined in previous reports on Marcellus recoverability in West Virginia (WV) to provide estimates of TRR for the Marcellus and Utica gas plays throughout the Appalachian basin. [2, 3] Evaluation of production histories from more than 6,000 wells indicates that recent federal assessments substantially understate available resources.

1.1 Definitions

TRR is a term well engrained in the literature but with uncertain definition (Exhibit 1-1). In this analysis, the National Energy Technology Laboratory's Strategic Systems Analysis and Engineering (SSAE) differentiates various TRR quantities as follows: "ultimate" TRR (uTRR) is the total volume of gas available to be produced during the life of the play; "developed" TRR (dTRR)

Exhibit 1-1. Terminology used in the assessment of technically recoverable resources



includes recoverable gas associated with drilled acreage. dTRR includes gas already produced and gas yet to be produced in existing wells (proved developed reserves). "Remaining" TRR includes all recoverable gas on undrilled acreage. A complication arises due to reserves assigned to "proved undeveloped" reserves (PUDs), which includes resources associated with planned, but undrilled wells within established developments. Excluding those PUD volumes from "remaining" TRR (rTRR) yields remaining undeveloped TRR ("ruTRR"). "Future supply" TRR (fsTRR) includes rTRR and all reserves.

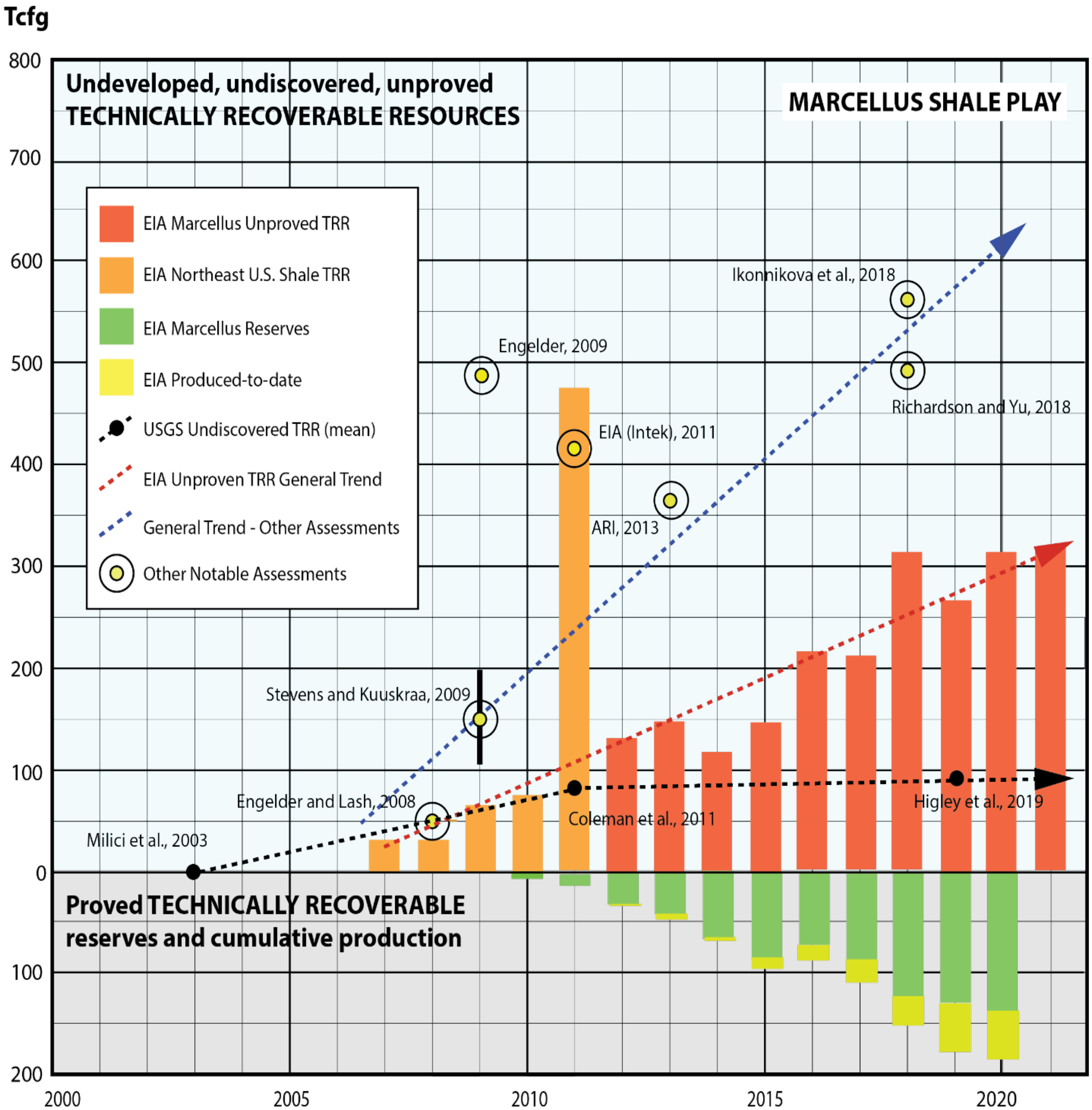
SSAE believes that rTRR closely equates to the quantities assessed by both EIA (as part of Annual Energy Outlook [AEO] modeling) and the United States Geological Survey (USGS). Assuming the geologic characterization for a play does not change, rTRR would decrease each year as ongoing development shifts resources into the dTRR category. However, it is quite common for all varieties of TRR to grow with each re-assessment, particularly within the early stages of play development. A primary reason for this growth is that the share of the in-place gas resource that is technically recoverable increases as experience is gained and technology advances. In this sense, early assessments that now seem very low were not necessarily in error. A second reason for TRR growth with time is that resource assessments tend to be conservative, particularly when data are limited. As data become more abundant and more reliable, assessors are less likely to temper assessments with cautious assumptions.

The common method of estimating rTRR is to determine a total area (play or sub-play), subtract that area already developed/proved by drilling, assign a representative cell size (or drainage area, commonly set to equal expected well spacing), assess the potential for stacked laterals, and assign a representative per cell recovery. rTRR then equals the number of undeveloped cells multiplied by recovery per cell. Additional factors may be included to accommodate geologic risk. Care should be taken with such factors, however, to not conflate geologic risk with operational difficulties or economic factors, both of which can result in unproductive wells despite the occurrence of TRRs. TRR is commonly reported as trillions of cubic feet of gas (tcfg) converted to surface pressure-temperature conditions. A probabilistic estimate uses distributions for each parameter; a deterministic estimate uses best estimates for each parameter.

1.2 Existing TRR Assessments

USGS periodically reports probabilistic assessments of rTRR for major plays. Their terminology is "undiscovered TRR." For the Marcellus play, the initial assessment provided an appropriately low value of 1.9 tcfg given that the recent advances in horizontal drilling and high-volume slickwater hydraulic fracturing developed in the Barnett Shale of Texas would not be tested in the Appalachian basin until the following year. [4] USGS has subsequently re-assessed the Marcellus play on two occasions: Coleman et al. raised the assessment to 84.2 tcfg; [5] Higley et al. again raised the estimate to 96.5 tcfg (Exhibit 1-2). [6]

Exhibit 1-2. Trends in prior assessment of TRR in Marcellus shale gas play resources



The EIA annually assigns an rTRR value for select major oil and gas plays to support energy supply modeling conducted for the AEO. Their terminology is "unproved TRR." Appalachian basin shale first appeared as the "Northeast U.S. Shale" play in AEO-2007 and was assigned 28.2 tcf (Exhibit 1-2). This value grew to 73.2 tcfg for AEO-2010. For AEO-2011, the assessment grew to 472.7 tcfg; incorporating work by Intek assigned 410.3 tcfg rTRR to the Marcellus. [7] Shortly thereafter, USGS released its 2011 assessment (~84 tcfg). The disparity between EIA and USGS assessments was widely noted, and partly in response, EIA began to assess the Marcellus as a standalone play. The Marcellus was assigned 140.6 tcfg for AEO-2012. Subsequently, the EIA

Marcellus assessment again began to rise, eclipsing 300 tcfg for AEO-2018. The latest EIA estimate sets the Marcellus at ~319g tcfg. [1]

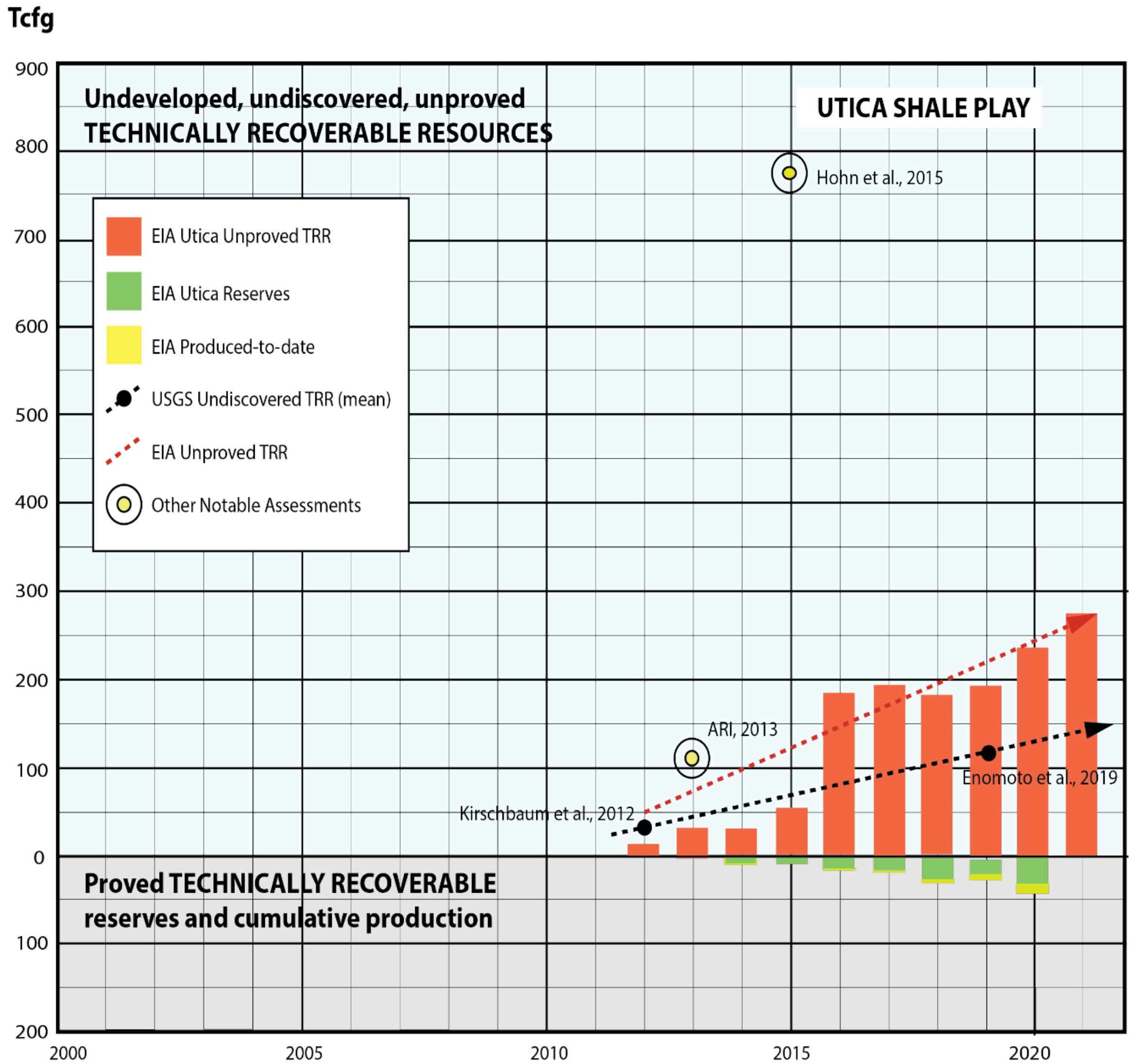
Various independent research groups have periodically assessed recoverable resources in the Marcellus shale play. Perhaps the most impactful assessment was a simple volumetric calculation initially suggested by Engelder and Lash [8] and then revisited by Engelder [9] that noted the sheer size of the basin and the productivity of analog wells to indicate that rTRR in the Marcellus should be on the order of 490 tcfg. Stevens and Kuuskraa [10] initially assigned ~150 tcfg rTRR to the Marcellus and shortly thereafter increased the value to 369 tcfg. [11] Subsequently, the Engelder assessment has been widely accepted as most consistent with continuing drilling results. [12] Recent engineering and geological analyses tend to support the original Engelder TRR estimates as well, including Richardson and Yu [13] at 492 tcfg and Ikonnikova et al. [14] at 560 tcfg rTRR.

Assessments for the gas-prone portions of the Utica play (Exhibit 1-3) show a similar trend to those for the Marcellus. In 2011, the USGS conducted its first assessment of the play indicating mean undiscovered TRR of 37.3 tcfg. [15] EIA first recognized the Utica as a distinct play in AEO-2012, and through 2015, gradually increased its assessment from ~16 tcfg to 53 tcfg rTRR. A consortium of Appalachian basin geological surveys integrated very early drilling results in the highly over-pressured Utica “deep” gas trend along the eastern margin of the play to set rTRR at 774 tcfg. [16] For AEO-2016, the EIA assessment increased to 184.5 tcfg and gradually climbed to 200 tcfg by AEO-2018. In 2019, USGS released a second assessment for the gas-prone portion of the Utica of 102.7 tcfg. [17] The most recent EIA estimate for AEO-2021 for the Utica is 266.2 tcfg rTRR.

The Potential Gas Committee (PGC) assesses U.S. natural gas resources biennially but does not report numbers at the play level. The group reported 700 tcfg total as most likely technically recoverable resource (ruTRR) for the Appalachian basin for its 2014 report. [18] This number increased to 1,037.4 tcfg ruTRR for the 2018 report primarily due to ongoing revisions related to both the Marcellus and Utica shales. [19]

When USGS, EIA, and various “independent” assessments are compared through time (Exhibit 1-2 and Exhibit 1-3), it is clear that while all show growth in TRR, the disparity between the various assessments is broad. For the Marcellus, the latest assessments of rTRR range ~97–560 tcfg—a spread of ~500 percent. For the Utica, the range is ~750 percent. As this spread widens, the true potential of these resources becomes increasingly uncertain.

Exhibit 1-3. Trends in prior assessment of Utica shale gas play resources



1.3 EXISTING ASSESSMENTS, TRR DENSITY

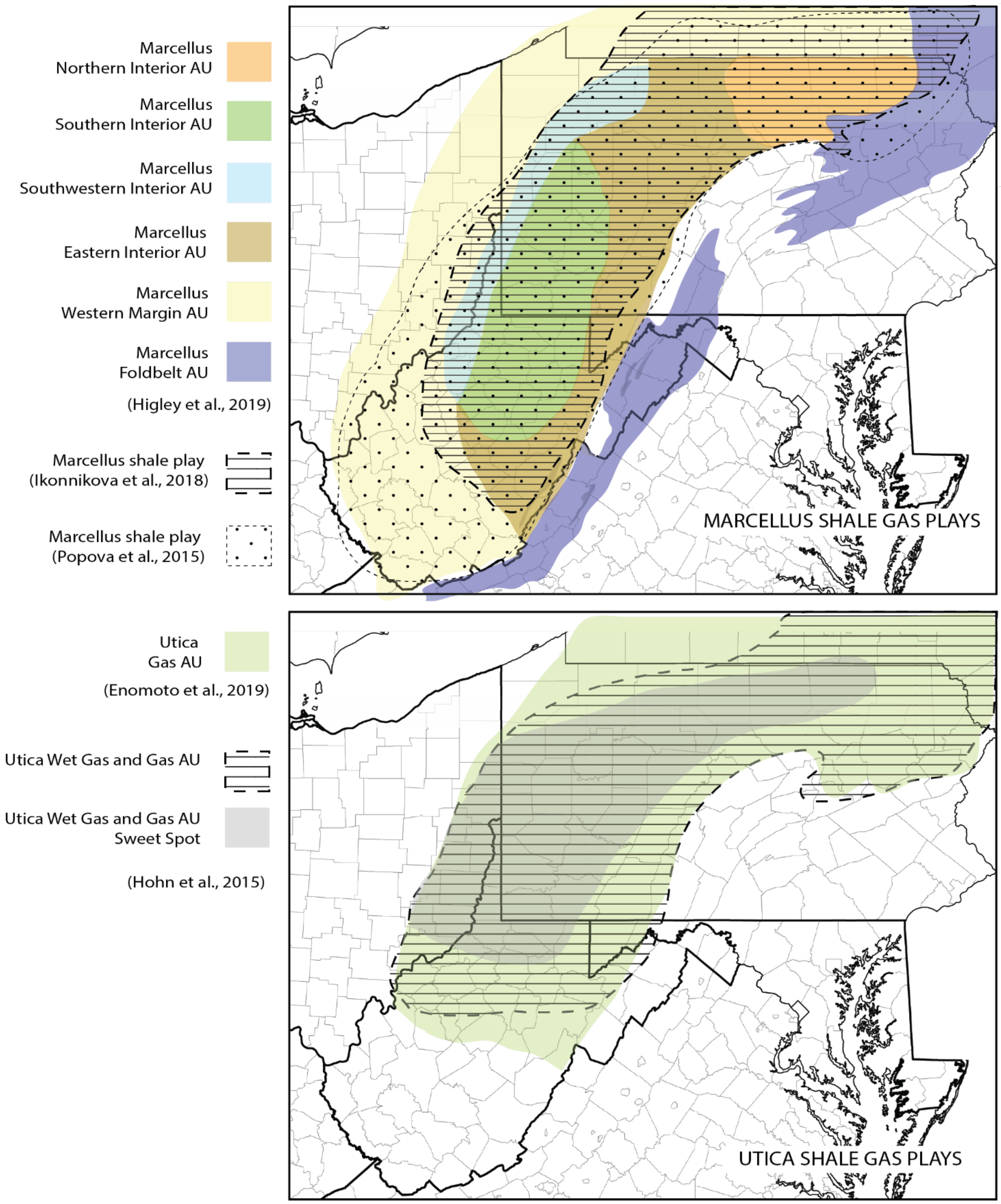
Total volume estimates for plays of the sheer size of the Marcellus and Utica can be misleading. Different assessments can use different play boundaries with different total play areas (see Exhibit 1-4 and Exhibit 1-5); for example, the remaining Marcellus play as defined by USGS is 14,000+ square mile (mi^2) larger than the play area as defined by EIA. Within a play, regional averages tend to grossly understate potential in the core areas and similarly overstate potential on the commonly much larger margins. To address this issue, USGS uses six primary sub-plays to capture some share of this heterogeneity. EIA uses 3 sub-plays, although one of those ("Marcellus Interior") accounts for 87 percent of EIA's total Marcellus acreage. Due to the variability in play size and use of different TRR definitions, TRR density (TRR/mi^2) is useful to compare productivity assumptions between assessments (Exhibit 1-4). For any undrilled location (or single cell), the rTRR as applied at that location should be equivalent (it is only in drilled cells where these values differ). For example, the USGS 2019 assessment for the Marcellus indicated total net productivity on remaining undrilled acreage at 10.5 billion cubic feet (bcf)/mi^2 for the "Marcellus Northern Interior Assessment Unit," representing the northeastern Pennsylvania (PA) Marcellus core area. TRR density is less in other sub-plays. In comparison, the EIA AEO-2021 assessment equates to 14.1 bcf/mi^2 for the "Marcellus Interior" sub-play. Ikonnikova et al. similarly determine average TRR density for the Marcellus (across the full play) at 14.2 bcf/mi^2. [14] In contrast, a study of the Marcellus in WV, Boswell et al. indicate common TRR density in excess of 50 bcf/mi^2 within the play core. [2] Similar and larger values (~80 bcf/mi^2) have been indicated by industry. [20, 21] The reported variation in TRR density is more pronounced for the Utica play: USGS indicates average recovery of 5 bcf/mi^2, [6, 17] EIA indicates 23.7 bcf/mi^2 in the play core, [22] and West Virginia Geological and Economic Survey (WVGES) assess 52.2 bcf/mi^2 within the dry gas sweet spots. [16]

Exhibit 1-4. Comparison of recent Marcellus and Utica shale play assessments

Source	Sub-play Play - TOTAL	Assessed Area (mi^2)	Cell Size (acres/mi^2)	Net per cell recovery* (bcf)	Total Mean TRR (tcf)	TRR Density (bcf/mi^2)
EIA	Marcellus Interior	22,475	148.8 / 0.23	3.27	315.8	14.1
	Marcellus Foldbelt	867	148.8 / 0.23	0.06	0.2	0.2
	Marcellus Western	2,477	116.4 / 0.18	0.21	2.9	1.2
	Marcellus - TOTAL	**25,819**			**318.9**	**12.35**
USGS	Marcellus Northern Interior	2,461	146.7 / 0.23	2.40	25.8	10.5
	Marcellus Southern Interior	4,206	146.7 / 0.23	1.50	27.6	6.6
	Marcellus Southwestern Interior	2,333	146.7 / 0.23	1.72	17.5	7.5
	Marcellus Eastern Interior	5,816	146.7 / 0.23	0.82	20.9	3.6
	Marcellus Western Margin	16,603	83.3 / 0.13	0.03	4.0	0.2
	Marcellus Foldbelt	8,791	83.3 / 0.13	0.01	0.7	0.1
	Marcellus - TOTAL	**40,209**			**96.5**	**2.4**
UT-BEG	**Marcellus - TOTAL**	**39,400**	**143.7 / 0.22**	**3.2**	**560**	**14.2**
EIA	Utica Gas Zone - Core	8,794	128 / 0.20	4.73	208.1	23.7
	Utica Gas Zone - Extension	14,623	213 / 0.33	1.32	58.1	4.0
	Utica Gas - TOTAL	**23,417**			**266.2**	**11.4**
USGS	**Pt Pl.- Utica - TOTAL**	**20,586**	**126.7 / 0.20**	**0.99**	**102.7**	**5.0**
WVGES	Utica Wet Gas Sweet	1,391	100 / 0.16	6.29	56.0	40.2
	Utica Wet Gas Non-Sweet	557	100 / 0.16	0.13	0.5	0.8
	Utica Gas Sweet	13,616	100 / 0.16	8.15	710.3	52.2
	Utica Gas Non-Sweet	30,735	100 / 0.16	0.037	7.2	0.2
	Utica Gas - TOTAL	**46,299**			**774.0**	**16.7**

*Includes assigned geologic risk

Exhibit 1-5. Comparison of mapped extents of Marcellus and Utica gas plays and sub-plays as reported by the USGS [6, 17], UT-BEG [14], WVGES [16], and EIA [22]



2 METHODS

The primary input data for this study are well-level estimated ultimate recovery (EUR) "best estimate" predictions as obtained through the Enverus DrillingInfo (DI) "Best Effort-Segmented" calculations using an industry-standard assumption of 50-year well life. [23] As the Marcellus and Utica have only been active plays for ~15 years, there is no direct evidence of appropriate well life. However, for an assessment of TRRs, there is unclear justification to limit well life to capture economically driven well abandonment decisions. Also, long well lives (50 years or more) have been noted for the Appalachian Huron shale play, which was first developed in the 1930s (although until recently, only developed with vertical wells). [24]

The method by which well-level EURs are converted to estimates of uTRR/mi^2 at high spatial resolution in this analysis is detailed in Boswell et al. with reference to a study of Marcellus wells in WV. [2] Here, SSAE applied that method to the full extent of the Marcellus and Utica plays throughout the Appalachian basin. This approach does not rely on determining future per-well productivity by setting a cell size that equates to well spacing. Instead, SSAE's focus is on potential technical recoverability per mi^2 of land area. The primary features of the approach are discussed further below and include 1) careful screening of wells for which EUR estimates will be gathered to include only those likely to be representative of future well results; 2) determining and mapping average recovery density (billion cubic feet of gas [bcfg]/mi^2) not at the well level, but for a really-distributed, individual multi-well developments; and 3) normalization of well production data by consideration of both well length and well spacing. Later, SSAE estimates dTRR to estimate rTRR at the county/sub-county level.

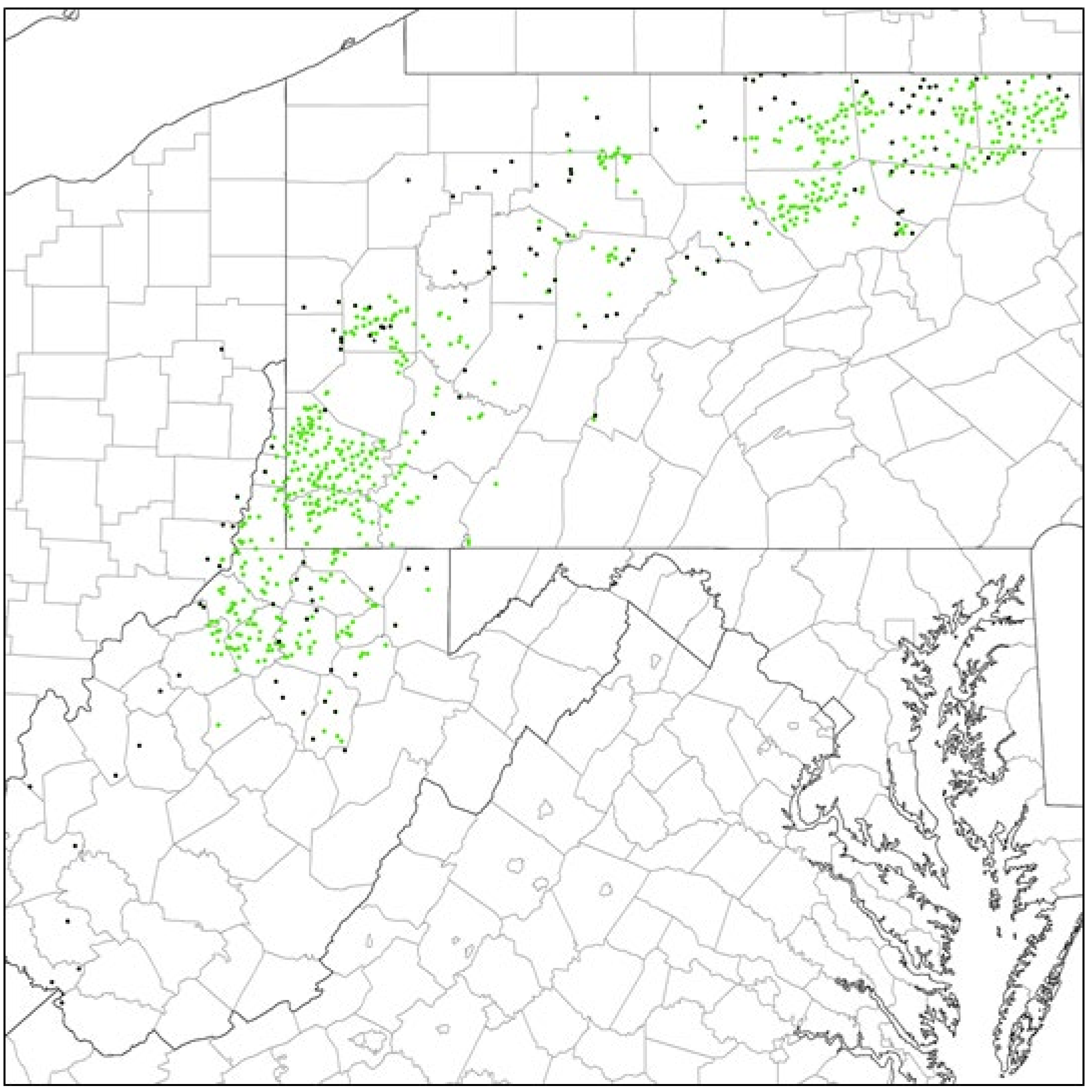
2.1 DATA SCREENING

All existing wells within the two plays in the basin were reviewed. An initial screening was conducted to exclude those wells for which performance data are thought to be either unreliable or unrepresentative of wells to be drilled in the future. Unreliable data are those from wells drilled too recently to allow confident extrapolation of EURs (nominally set as 24 months—see discussion). Unrepresentative wells are those drilled prior to 2013, where a step change in well performance across the play was achieved via reduced fracture cluster spacing and increased proppant concentrations. [25] SSAE also excludes all non-horizontal wells regardless of vintage as fully unrepresentative of future well productivity. With these filters, it is expected that future wells will perform in a manner similar to the wells included in the database, which is a key goal of assessments focused on remaining (future) potential. While most research and development effort continues to focus on operational efficiencies and cost reduction, any future step changes in productivity enabled by additional technology improvement may render these predictions somewhat conservative.

2.2 ASSIGN uTRR AT THE LEVEL OF MULTI-WELL DEVELOPMENTS

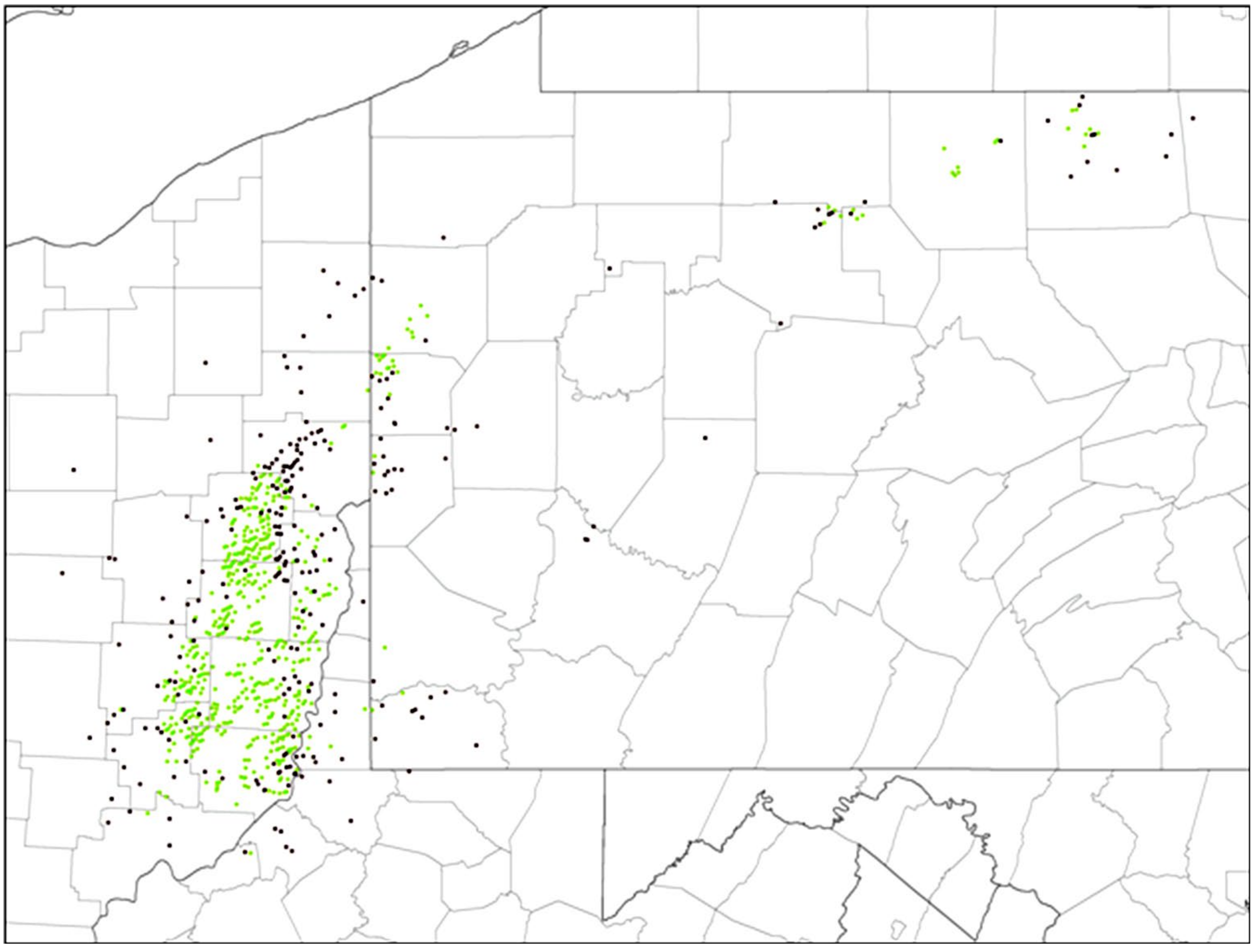
Even where wells are intended to be drilled in a consistent manner, per-well productivity data may be locally erratic due to site specific factors related to drilling and completion operations or geologic heterogeneity. To account for this, SSAE does not map individual well productivity, but instead the cumulative productivity represented by multiple wells within a larger, coordinated, well development. For each multi-well development "site," a single point estimate of uTRR/mi^2 is generated that corresponds to the sum of the individual well EURs divided by the area intended to be drained by that development. SSAE defines a "site" as one where multiple wells were drilled within a short period and at a common well spacing by a single operator with clear intent to drain a contiguous area. Exhibit 2-1 and Exhibit 2-2 show the locations of the selected well development sites for the two plays. Development sites were readily recognized within the more densely drilled areas of the play core. In such areas, a typical site included approximately 6 wells and 1 mi^2 of area. To ensure some data on the margins of the play, sites were commonly used with only one or two wells. Where wells are not evenly spaced in such marginal sites, well spacing was arbitrarily set to 1,000 feet (ft). Marginal sites are indicated by black dots on Exhibit 2-1 and Exhibit 2-2 and provide much more uncertain estimates of TRR/mi^2.

Exhibit 2-1. Well development sites used in the evaluation of uTRR/mi^2 for the Marcellus play



Note: Green dots are sites for which three or more wells were available. Black dots indicate recovery calculated from 1 or 2 wells only. The 717 total sites aggregate EUR estimates for 3,706 wells.

Exhibit 2-2. Well development sites used in the evaluation of uTRR/mi² in the Utica play



Notes: Green dots are sites for which three or more wells were available. Black dots indicate recovery calculated from 1 or 2 wells only. The 752 total sites aggregate EUR estimates from 2,577 wells.

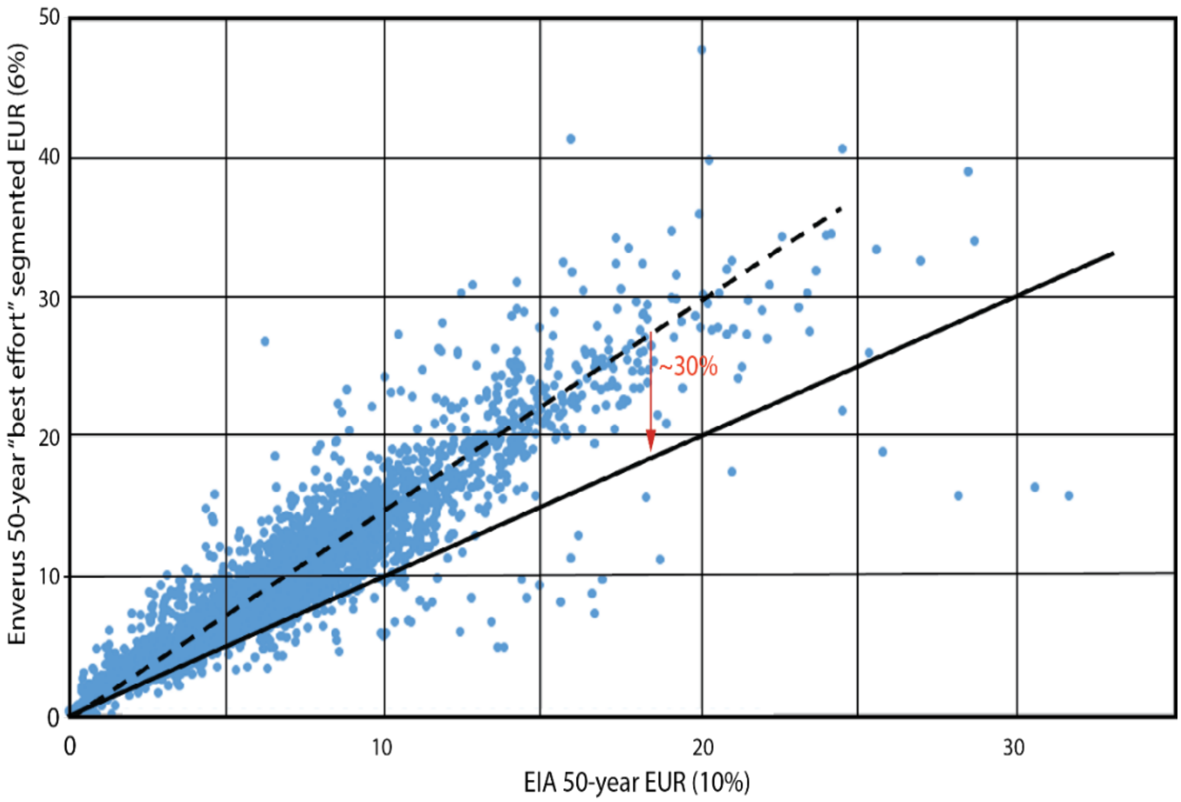
2.3 NORMALIZATION TO UNIT AREA

Per well productivity is commonly normalized to account for variability in well lateral length (a common convention is bcfg/1,000 ft lateral). To further normalize productivity to arrive at uTRR/mi^2, SSAE measured the characteristic well spacing within each "site" using equal area projections. Final site area is the product of total lateral length of all wells and the well spacing.

2.4 EUR UNCERTAINTY

The value of this analysis is highly dependent on the reasonableness of well-level EUR estimates that form the basis for site uTRR. As a check, SSAE compared EURs for common sets of wells as provided by three sources: EIA, Enverus, and an industry collaborator. SSAE finds that the most salient parameter that drives differences in the EURs is the assumed decline rate at which further production decline transitions from hyperbolic to exponential. This parameter generally is intended to reflect the onset of lateral well interference—a phenomenon that is not well known or easily evaluated and will become better known as field developments continue to mature. The Enverus "best effort–segmented" approach that forms the base EURs for SSAE's analyses sets this threshold when decline rate reaches 6 percent. An industry collaborator set this value at 5 percent—a level that may be common within industry. [26] EIA typically sets this value to 10 percent. [27] Comparison of the Enverus EURs to those provided by EIA for more than 4,000 Marcellus wells showed the Enverus EURs to be ~30 percent greater (Exhibit 2-3). Comparison of EURs from 900 wells provided by the industry partner shows them to be, on average, 15 percent higher than the Enverus values. This analysis refers to values derived using the Enverus projection as the base data, but provide two alternative EURs ranging from +15 percent to -30 percent in attempt to capture the substantial uncertainty in EUR.

Exhibit 2-3. Comparison of 50-year EURs (in bcfge) for ~4,000 Marcellus wells provided by EIA and Enverus



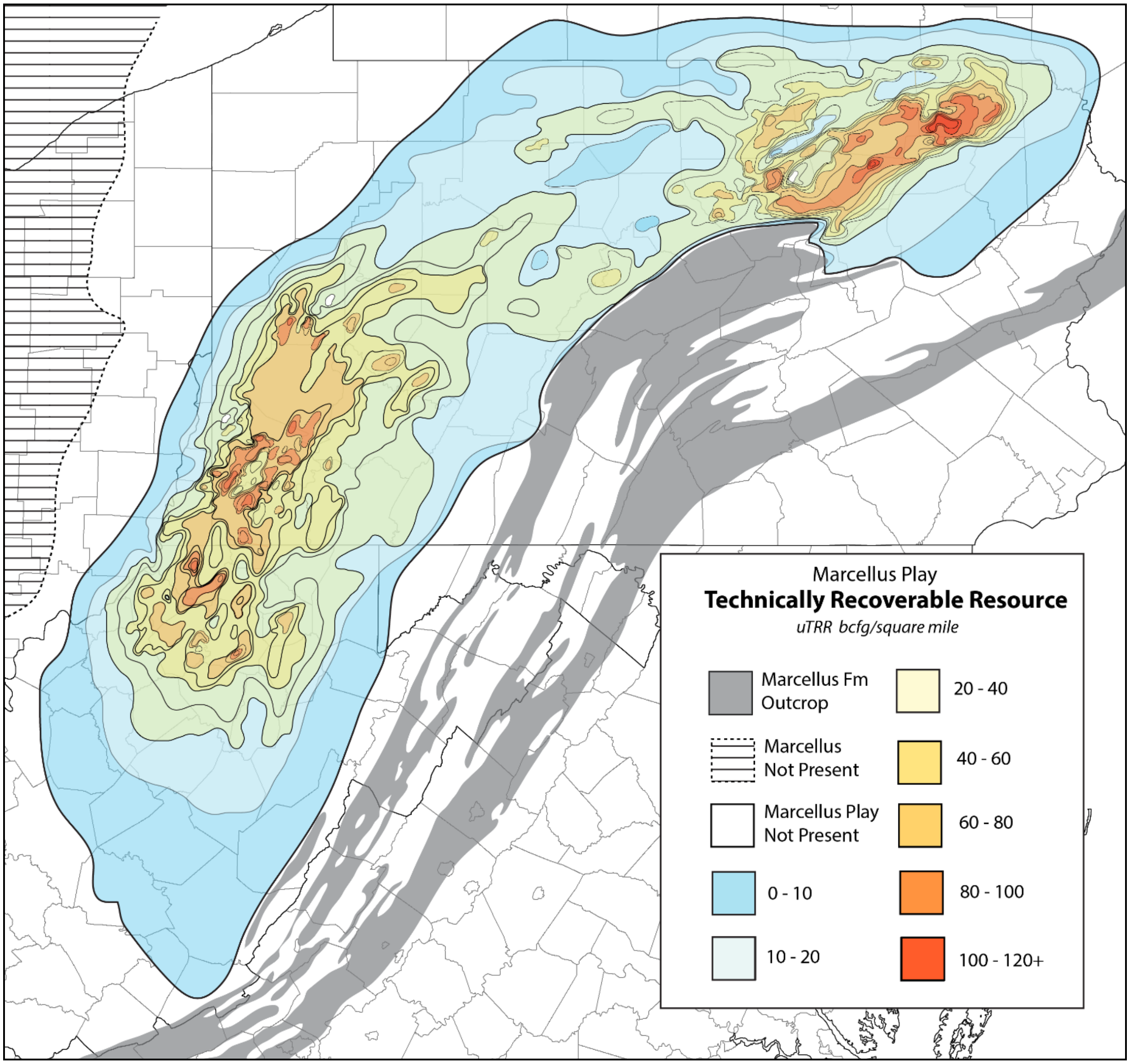
Note: Solid line indicates a match between the datasets. When a common transition to terminal decline is set at 6%, the projections are well aligned. However, when the standard EIA method of onset of terminal decline is set at a decline rate of 10%, the projections tend to differ (dashed lines) by approximately 30%.

3 RESULTS

Exhibit 3-1 and Exhibit 3-2 show maps of uTRR/mi^2 for the Marcellus and Utica plays. These maps show the recoverability that would be expected in the future for wells drilled at any location. The maps do not reflect actual past recovery, but instead the performance of those developments included in the data set. Certain past developments (those drilled before 2013 or featuring vertical wells) very likely did not achieve the performance that is depicted here. The maps reveal large areas within the cores of both plays typified by expected recovery of more than 50 bcfg/mi^2, with maximum values exceeding 100 bcfg/mi^2 in the Marcellus. Large areas along the play margins are characterized by potential recovery of less than 20 bcfg/mi^2. Where the data are most dense, substantial variability is noted over short distances. In the case of the Marcellus, these local variations trend parallel to the depositional strike of the basin and are inferred to largely reflect variability in productivity associated with geologic phenomena (Exhibit 3-3 and Exhibit 3-4). However, variability in operational practices between operators is also a factor. Such variability likely extends throughout the full extent of both plays, although data are not sufficient to reveal it everywhere.

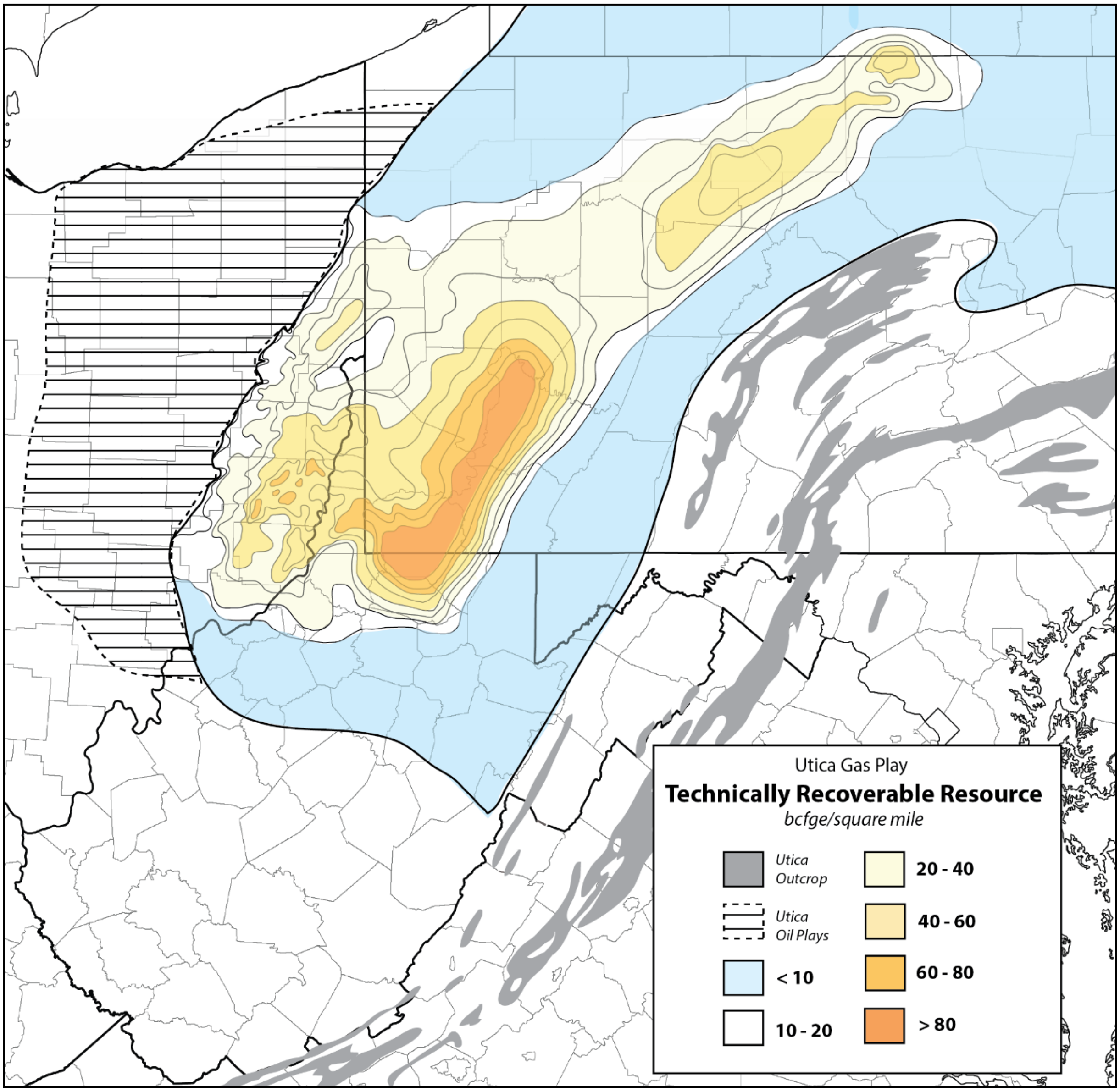
Summary statistics related to the evaluation of each play are shown in Exhibit 3-5. Notably, not only does average uTRR/mi^2 greatly exceed the values inherent in many prior assessments for play core areas, but the average cumulative production per mi^2 to date (Marcellus = 22.3 bcfg/mi^2; Utica = 15.5 bcfg/mi^2) exceeds those values as well. Exhibit 3-5 also provides information related to an initial review of the Geneseo/Burket play; however, data for that play were deemed insufficient for further analysis at present; also, potential interference between Geneseo/Burket and Marcellus wells requires further detailed evaluation. Summaries for select counties are shown in Exhibit 3-6 and Exhibit 3-7. Exhibit 3-8 compares the various assessments of expected resource density (rTRR/mi^2) for the Marcellus play for a selected site in Lycoming County, PA. Exhibit 4-1 compares the assessments for both Marcellus and Utica basin wide. New developments within the core regions of the Marcellus play as assessed by USGS are assigned to deliver ~10 bcfg/mi^2 or less. USGS has no sub-plays for the Utica, which is assigned a play average rTRR density of ~5 bcfg/mi^2. SSAE's data show that developments within the primary play fairway of the Marcellus play have already produced at an average rate of ~25 bcfg/mi^2 over an average production history of only 5 years. The data indicate that new developments within should ultimately deliver up to 60 bcfg/mi^2 in the play core and ~30 bcfg/mi^2 on the play margins. The situation is similar with respect to the Utica play, with average productivity to date of ~17 bcfg/mi^2 and ultimate productivity that will, on average, exceed 35 bcfg/mi^2 over the full area of the gas play. There is as yet very little data to support interpretations in the eastern (deep) portion of the Utica, but indications are that large areas could obtain recoveries of 100 bcfg/mi^2 as drilling and completion complications are resolved. [28] The Utica findings contain significant uncertainty; while the most promising acreage in the Marcellus has been explored, the findings of further drilling in the deep Utica might significantly alter the Utica assessment.

Exhibit 3-1. Estimated uTRR/mi^2 throughout the Marcellus play area



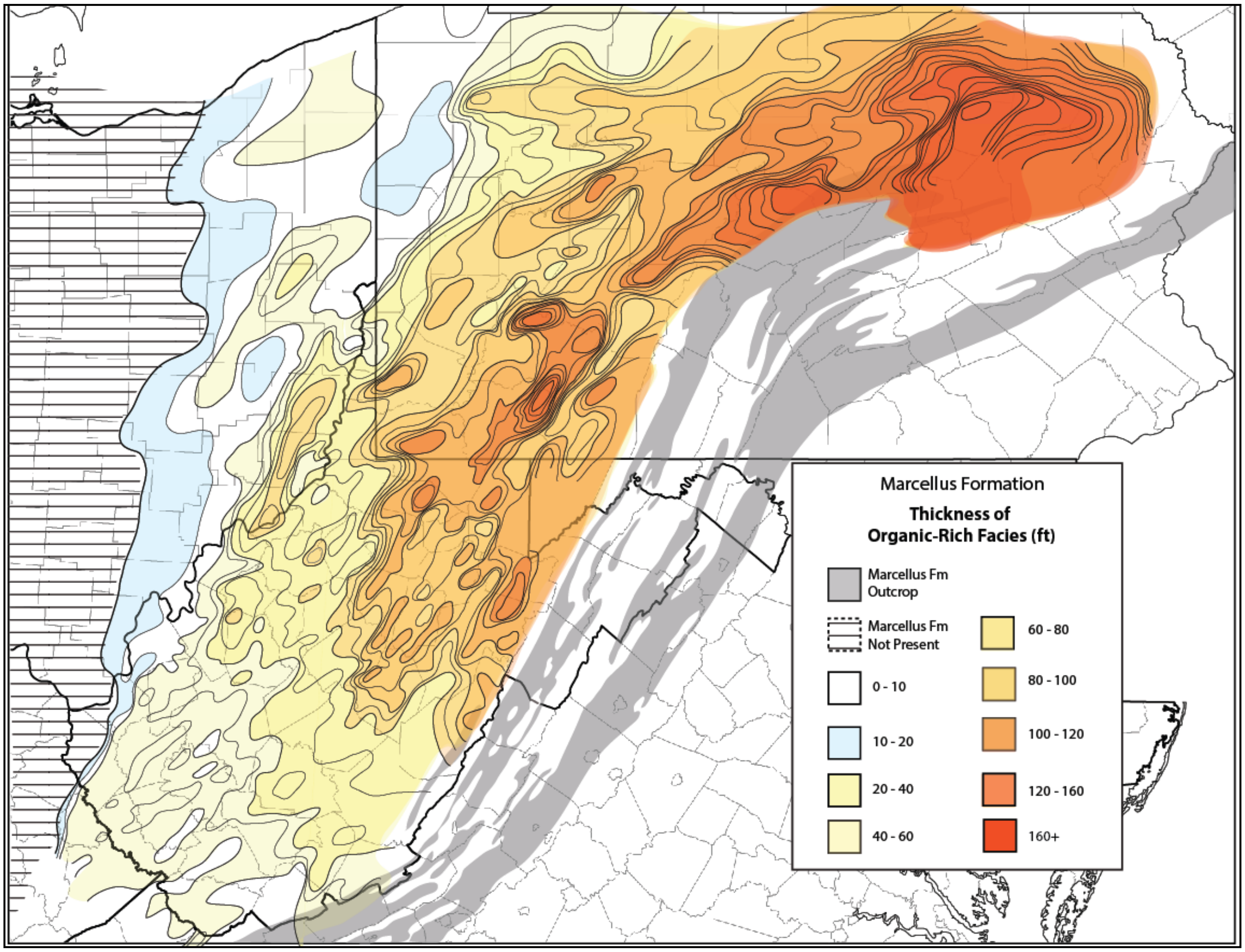
Note: The map indicates the potential recovery density at any undrilled location based on observed and predicted performance of 717 multi-well developments (Exhibit 2-1). Areas of high data density show significant lateral variation in expected areal recovery. This variation may represent non-geologic phenomena related to variability in well drilling and completion design and success; however, the alignment of these trends with depositional strike suggests strong contribution from geologic factors.

Exhibit 3-2. Estimated uTRR/mi² throughout the Utica gas play area



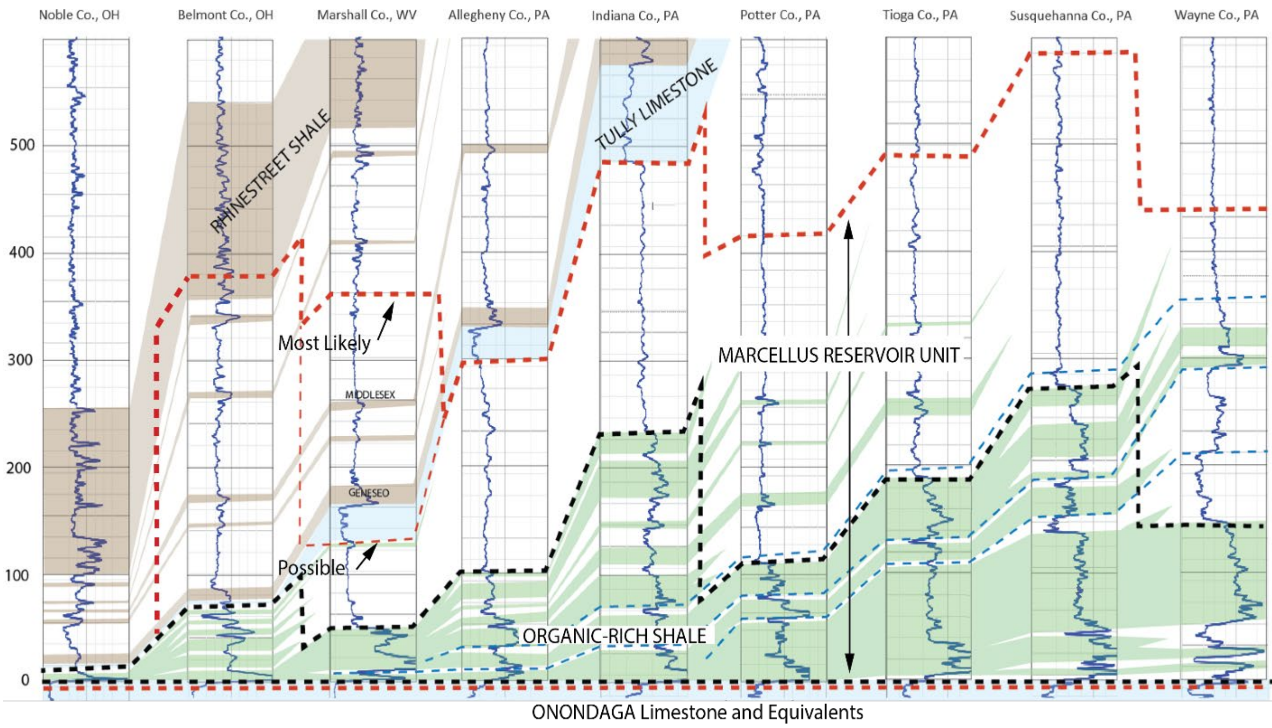
Note: The map indicates the expected recovery density at any undrilled location based on observed and predicted performance of 752 multi-well developments (Exhibit 2-2). Three clear sub-plays are evident. To the west is the wet gas and marginal dry gas play that has been the focus of most Utica gas well drilling to date. To the northeast is the dry gas area and to the southeast is the deep (highly over-pressured) dry gas area. Pressure gradients in this region have been estimated at 0.90 psi/foot or higher. The southwest area poses substantial drilling challenges but has witnessed several wells suggesting potential recovery of 100 bcf/mi² or higher. The ultimate assessment of Utica resources is highly uncertain and will remain dependent on further drilling results in this region.

Exhibit 3-3. Thickness of organic-rich sediments (gamma-ray above baseline) within the Marcellus play



Note: Linear trends are aligned with depositional strike and represent lateral facies transitions (Exhibit 3-4).

Exhibit 3-4. Cross-section of Marcellus Formation and Marcellus Reservoir Unit from northeastern PA to southwestern OH



Note: Intervals that exceed the gamma-ray baseline are in green. The eastward dilution of organic content results in marked changes in thicknesses shown in Exhibit 3-3.

Exhibit 3-5. Summary statistics for Utica and Marcellus play TRR density evaluation

Play	Wells	Months online	Avg spacing (ft)	Avg Hrz Length (ft)	Avg cum. gas/well (bcfge)	Avg EUR/well (bcfge)	Avg EUR per 1.000 ft	Avg drainage (acres)	% EUR produced to date
Marcellus	3,706	61.0	843	5,812	4.02	9.40	1.63	111	43%
Utica	2,577	54.6	970	8,176	4.53	9.58	1.12	182	47%
Geneseo-Burket	194	42.4	713	6,880	2.89	9.84	1.42	112	29%

Play	Sites	Avg wells per site	Avg site area (mi^2)	Avg cum. gas (bcfge)	Avg cum. gas per mi^2 (bcf)	Avg TRR per mi^2 (bcf)	% EUR to date
Marcellus	717	5.17	0.90	20.92	22.32	50.75	44%
Utica	752	3.43	0.96	15.49	15.45	31.43	49%
Geneseo-Burket	75	2.59	0.45	7.47	17.01	54.27	31%

Exhibit 3-6. Summary statistics for Marcellus play uTRR density evaluation for select counties

State	County	A	B	C	D	E	F	G	H
PA	Susquehanna	54	328	6.1	58	938	1.10	35.1	76.7 / 53.7
PA	Sullivan	11	38	3.5	50	1027	0.71	31.4	73.1 / 51.2
PA	Wyoming	14	78	5.6	60	1088	1.30	31.0	69.8 / 48.9
PA	Greene	36	235	6.5	55	742	1.12	31.1	68.6 / 48.0
PA	Allegheny	12	59	4.9	56	857	1.06	28.7	65.5 / 45.6
PA	Washington	96	576	6.0	58	848	1.07	24.5	61.0 / 42.7
WV	Wetzel	13	97	7.5	57	777	1.03	26.0	60.5 / 42.5
WV	Marion	10	36	3.6	59	905	0.56	25.8	58.1 / 40.7
WV	Harrison	16	107	6.7	72	720	1.10	25.5	56.5 / 39.6
WV	Tyler	15	94	6.3	39	731	1.36	21.5	56.5 / 39.6
WV	Doddridge	25	183	7.3	51	728	1.50	24.6	55.5 / 38.9
PA	Bradford	58	221	3.8	70	930	0.67	26.4	55.4 / 38.8
WV	Monongalia	8	38	4.8	41	793	0.99	19.8	54.7 / 38.3
PA	Butler	36	158	4.4	59	791	0.60	19.9	52.8 / 36.9
PA	Lycoming	53	343	6.5	73	829	0.98	26.4	52.0 / 36.4
PA	Fayette	18	100	5.6	66	807	0.67	22.8	48.3 / 33.8
WV	Marshall	14	127	9.1	53	703	1.29	19.0	47.1 / 33.0
PA	Armstrong	10	55	5.5	60	926	1.13	16.6	47.0 / 32.9
WV	Taylor	10	48	4.8	58	913	0.87	17.9	46.3 / 32.4
PA	Westmoreland	10	54	5.4	79	708	0.70	21.8	42.7 / 29.9
WV	Ritchie	10	68	6.8	43	858	1.61	16.2	42.2 / 29.5
PA	Tioga	44	203	4.6	70	957	0.78	15.1	33.2 / 23.2
PA	Clinton	6	34	5.7	84	885	0.84	17.2	32.8 / 22.0
PA	Jefferson	12	31	2.6	70	848	0.46	12.7	29.7 / 20.8
PA	Elk	14	66	4.7	52	733	0.85	11.8	28.3 / 19.8
PA	Cameron	5	34	6.8	44	713	1.32	10.6	28.2 / 19.7

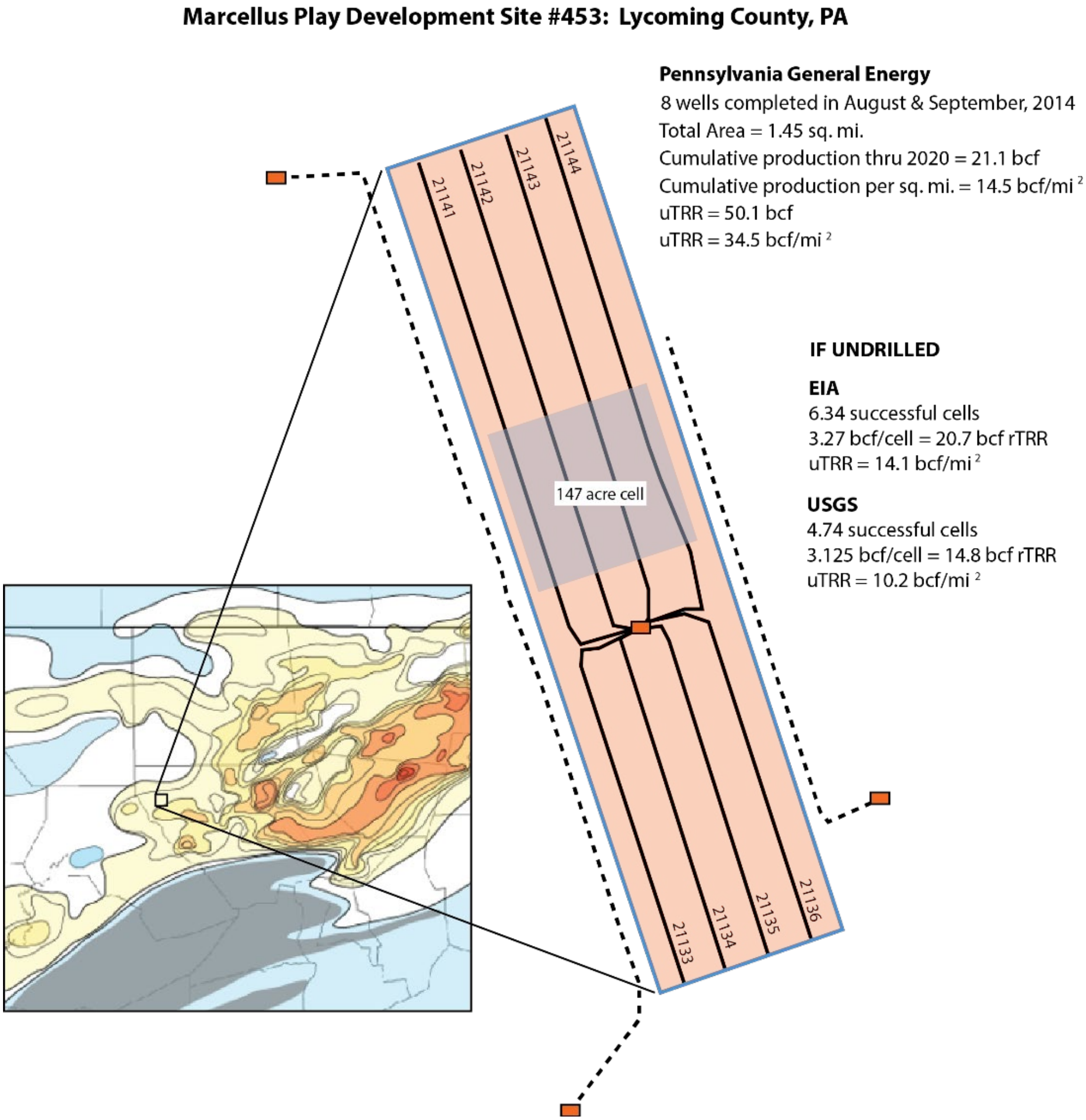
Note: A – number of sites; B – total number of wells; C – average number of wells per site; D – average months of production data/well; E – average spacing (ft); F – average site area (mi^2); G – average site productivity to date (cumulative reported production/mi^2); H – average site uTRR density (bcfge/mi^2) at base EUR and EUR -30%.

Exhibit 3-7. Summary statistics for Utica play uTRR density evaluation for select counties

State	County	A	B	C	D	E	F	G	H
PA	Westmoreland	3	4	1.3	41	1000	0.34	55.8	122.4 / 85.7
PA	Greene	10	17	1.7	30	1000	0.45	23.5	67.6 / 47.3
OH	Belmont	111	444	4.0	47	998	1.26	26.7	51.2 / 35.8
OH	Monroe	89	333	3.7	44	986	1.22	20.6	43.6 / 30.5
WV	Marshall	12	32	1.7	20	1479	1.34	13.7	40.9 / 28.6
PA	Cameron	4	17	4.3	13	1094	1.54	8.1	38.9 / 27.2
OH	Jefferson	51	161	3.2	38	1017	1.14	17.7	35.0 / 24.5
PA	Tioga	17	37	2.2	41	1248	0.89	16.8	33.6 / 23.5
PA	Potter	8	32	4.0	25	1047	1.05	12.2	33.5 / 23.4
PA	Elk	7	19	2.7	28	1084	0.90	8.9	27.8 / 19.5
OH	Guernsey	58	211	3.6	54	833	0.92	11.2	27.1 / 19.0
OH	Noble	44	171	3.9	60	882	1.06	14.7	26.5 / 18.6
OH	Harrison	90	364	4.0	60	865	1.00	12.9	25.0 / 17.5
OH	Columbiana	43	74	1.7	67	987	0.41	11.6	23.5 / 16.5
PA	Lawrence	21	53	2.5	69	1077	0.76	10.7	22.1 / 15.5
OH	Carroll	105	455	4.3	74	948	0.98	11.5	21.5 / 15.1
OH	Washington	6	11	1.8	59	1090	0.49	7.3	15.6 / 10.9
PA	Mercer	13	50	3.8	64	874	0.87	6.0	13.7 / 9.6
PA	Beaver	13	21	1.6	69	1619	0.55	7.2	12.3 / 8.6
OH	Mahoning	5	12	2.4	75	833	0.48	4.5	8.7 / 6.1

Note: A – number of sites; B – total number of wells; C – average number of wells per site; D – average months of production data/well; E – average spacing (ft); F – average site area (mi^2); G – average site productivity to date (cumulative reported production/mi^2); H – average site uTRR density (bcfge/mi^2) at base EUR and EUR -30%.

Exhibit 3-8. Example comparison of assessed/hypothetical uTRR for Marcellus acreage



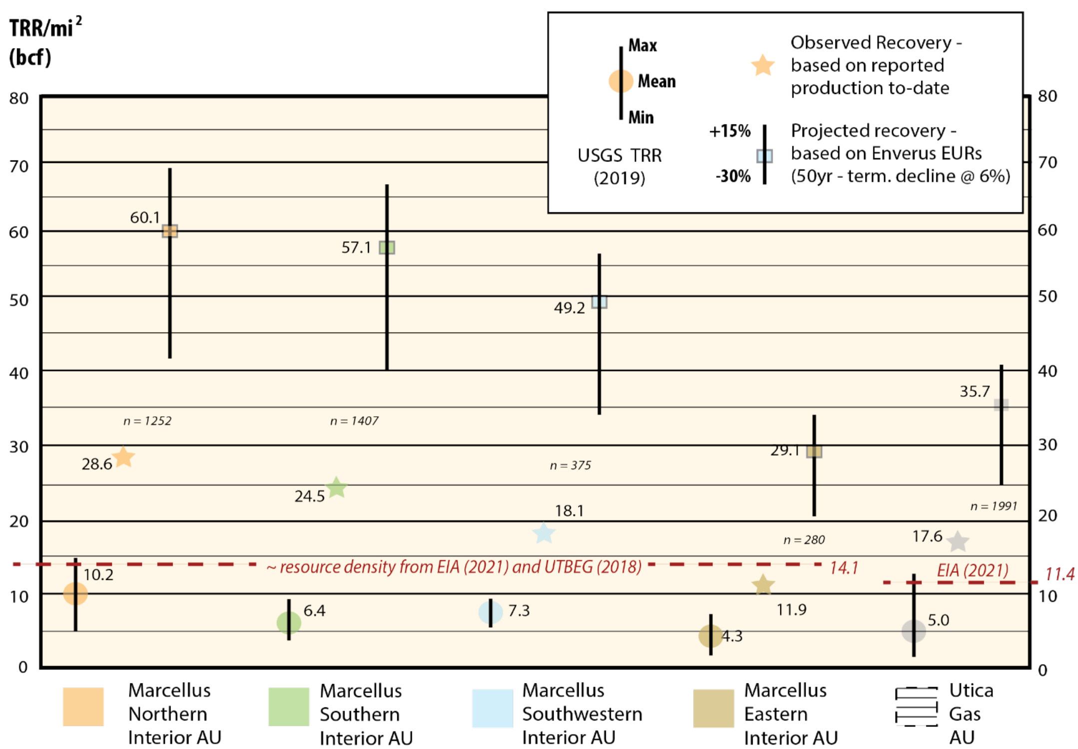
Note: This site was developed by 8 wells and has achieved cumulative production to date of 14.5 bcfg/mi^2 with predicted ultimate recovery of 34.5 bcfg/mi^2. This acreage, if it had not been developed, would be assigned 14.1 bcfg/mi^2 uTRR using EIA's approach and 10.2 bcfg/mi^2 uTRR using USGS's approach.

4 Discussion

The results of this analysis indicate that future well developments in the Marcellus and Utica plays are likely to continue to outperform many current projections. For example, if the average development site of the more than 1,000 that SSAE studied did not produce any additional gas, that site would routinely have produced roughly double the gas (in terms of bcfg/mi^2) as would be assigned to that same acreage if it were to be drilled by future wells. This observation is not based on any projection but is based on reported gas production to date. If SSAE allows that average site to continue to produce through a well life of 50 years, it is likely to produce 3–5 times the current assessment.

It is unclear why current assessments are as conservative as they appear to be. Documentation on assessment details is commonly limited. One likely factor is that assessment areas are often quite large and as a result, reflect an averaging of core and marginal areas. However, as shown in Exhibit 4-1, these differences persist even for Marcellus sub-plays that correspond more closely to core play regions. Perhaps a likely reason for this disconnect is the nature of the input data—including the use of poorly-performing (and vertical) wells that are unlikely to be representative of what future wells would achieve if drilled at the same location. There may also be a selective exclusion of newer wells that may be more representative of future performance. The following sections further discuss select issues related to the analysis.

Exhibit 4-1. Comparison of TRR/mi^2 results for the Utica play and for four main sub-plays of the Marcellus play based on the USGS partitioning

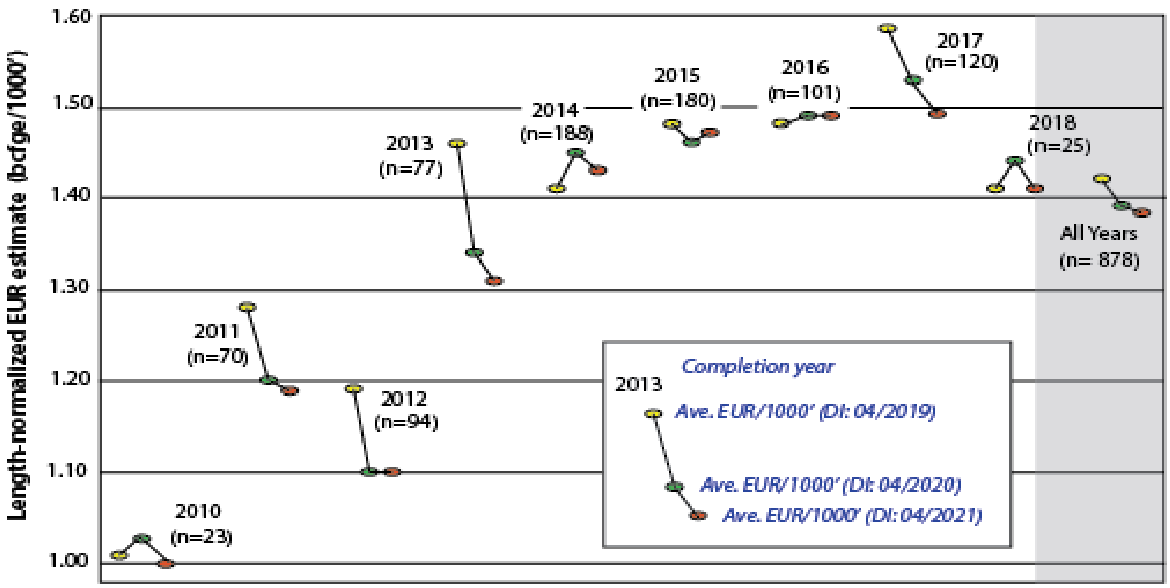


Note: The data show that prior assessments routinely assign lower recovery for remaining acreage within each area than has already been achieved by existing wells (stars) and much lower recovery than is expected to be ultimately recovered by existing wells (boxes).

4.1 EUR Stability

Another check on EUR reliability is to assess the annual change in projected EUR for wells. While individual well EURs may change significantly for a variety of sound reasons, if EURs are generally reliable after ~24 months of production data, then typical values within a large population of "mature" wells should change little with each passing year. To test the "stability" of the Enverus EUR projections, SSAE compared estimated EURs for 897 Marcellus wells as reported in the April 2019, April 2020, and April 2021 Enverus DrillingInfo data releases (Exhibit 4-2). The data show that the average EUR for all wells is virtually unchanged between 2019 and 2021 data releases. Within any given well vintage, there is a trend toward decrease in EUR, particularly for older wells. The data are consistent with generally lower EURs from wells of 2013 vintage and earlier, and also suggest that EURs are relatively stable once ~2 years of production data are available.

Exhibit 4-2. Review of the observed change from the Enverus per-well EUR (normalized per 1,000 ft of lateral length) estimates from April 2019 to April 2021 for 878 Marcellus wells in WV by date of well completion



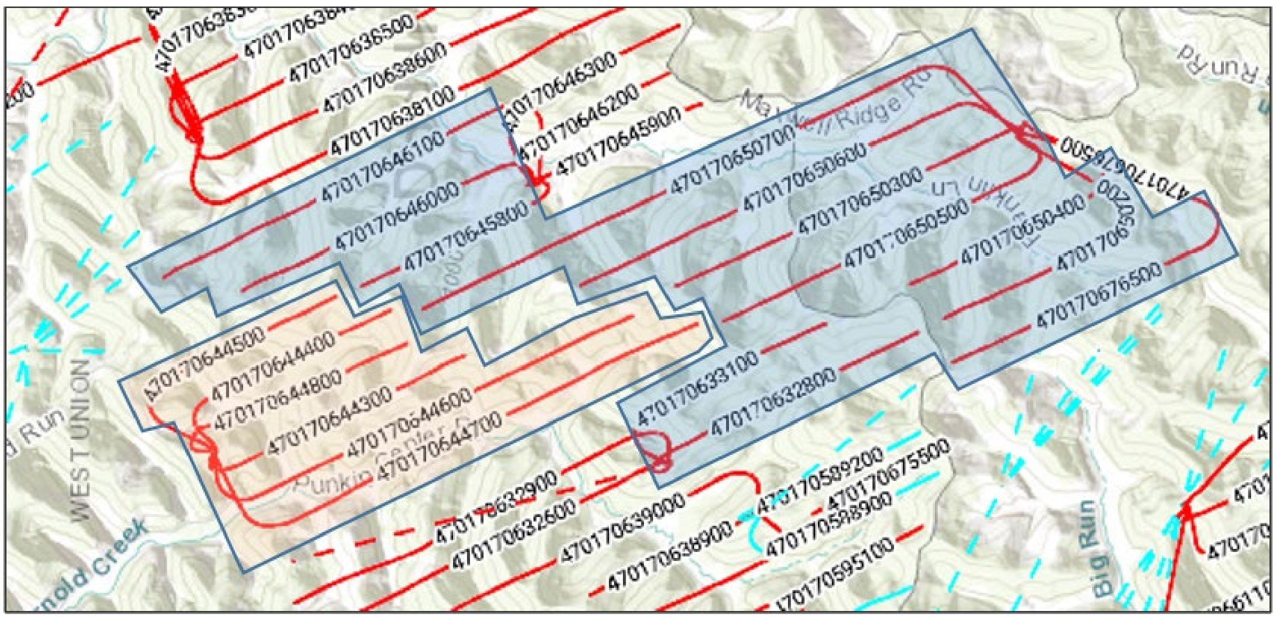
Note: The majority of older wells (completed before 2014) show a modest decrease (~10%) in EUR between the 2019 and 2021 estimates. Wells drilled since 2014 show generally stable EURs, including 25 wells completed as recently as 2018. For the full dataset, the variability is little changed (~2% decline) with subsequent time.

4.2 Calculation of Area/Well Spacing

Perhaps the most salient data uncertainty that impacts TRR/mi^2 is calculation of area. Drainage area is generally very poorly known and difficult to assess. Reported lateral length is often questionable, both seriously overestimated and underestimated, for various reasons. Where calculations suggest anomalous recovery/foot, lengths are cross-checked with known or inferred intended well paths to assign most likely values. For detailed production studies, determining the lateral length that is within the target formation is of interest. However, for this analysis, SSAE seeks to estimate the lateral dimension of acreage that is considered to have been developed by the well (i.e., unlikely to be considered available as targets for future wells). Minor inefficiencies due to drilling complications or lease boundary restrictions are considered an inherent part of the development process.

Well spacing was directly measured for all development sites and is considered generally reliable. However, measured well spacing is highly variable between developments (ranging <500–>1,500 ft) and this operational decision has significant implications for calculated TRR density. While the vast majority of the 1,469 sites employing well spacings that are relatively consistent when compared to neighboring developments, a few clear spacing outliers occur—likely part of case studies designed to gauge the economic implications of alternative spacings (Exhibit 4-3).

Exhibit 4-3. Example of adjacent coeval developments at alternative spacings



Note: Blue indicates wells spaced at 980 ft. Orange are wells spaced at 760 ft. For further details, see the Doddridge County site listed in Exhibit 4-4. The image is rotated so that north is to the left.

In Exhibit 4-4, SSAE elected eight examples of adjacent developments conducted by the same operator but with markedly contrasting well spacing. In these instances, the increase in TRR/mi^2 at the closer spacing ranged 10–83 percent. This value is aligned with the 64 percent increase in areal recovery reported from an early spacing experiment. [29] This, like many other issues, creates a conundrum relative to the concept of “technically recoverable.” Surely, tight well spacings are technically feasible and if routinely applied, would lead to substantially increased TRR. However, in practice, increased productivity must be balanced with increased costs as denser spacings also increase the cost to develop a unit area. While such economic considerations are ostensibly outside the purview of TRR assessment, as a practical matter, the assessment of TRR is intended to provide insight on what is likely to happen, not simply what could (technically) happen. Therefore, TRR assessment is designed to capture the prevailing industry practice into the future, which is likely to be (at the basin scale) continued development across a range of spacings. However, if one was to define TRR as what was truly recoverable with existing technologies, then a 50 percent increase in the estimate to reflect uTRR at close spacing would not be unrealistic.

Exhibit 4-4. Examples of apparent spacing experiments by industry

Play	County, State	Operator	Wells/ spacing 1 (ft)	Wells/ spacing 2 (ft)	TRR spacing 1 (bcfg/mi^2)	TRR spacing 2 (bcfg/mi^2)	Change
Marcellus	Susquehanna, PA	Cabot O&G	4 @ 1000	6 @ 600	100.9	150.7	+51%
Marcellus	Marshall, WV	HG Energy	5 @ 750	7 @ 600	51.8	70.1	+35%
Marcellus	Marshall, WV	HG Energy	6 @ 742	6 @ 500	23.1	40.6	+76%
Marcellus	Doddridge, WV	EQT	10 @ 980	6 @ 760	36.5	64.1	+76%
Marcellus	Ritchie, WV	Antero	12 @ 1,000	8 @ 670	46.4	79.9	+72%
Marcellus	Greene, PA	EQT	8 @ 715	6 @ 500	95.4	125.6	+32%
Marcellus	Washington, PA	EQT	9 @ 667	10 @ 523	50.8	92.8	+83%
Marcellus	Washington, PA	Range	7 @ 960	7 @ 527	36.4	39.4	+10%
Utica	Carroll, OH	E&P Ohio, LLC	6 @ 1,090	8 @ 645	14.6	25.1	+65%

4.3 Estimation of rTRR

Exhibit 3-1 and Exhibit 3-2 reflect the TRR on a per mi^2 basis. The mapped values are the recovery expected if wells perform as recent wells have and are allowed to produce for 50 years. To obtain an estimate of rTRR, dTRR/mi^2 estimates for acreage associated with existing wells must be estimated and subtracted. Exhibit 4-5 and Exhibit 4-6 display compiled estimates for total area, drilled area, and remaining area for various regions (counties or parts of counties where TRR varied significantly within a county) within the Marcellus play, and calculated estimates for dTRR and rTRR. Exhibit 4-7 provides the same information for the Utica play. Exhibit 4-8 summarizes these data. Using the base case scenario, total rTRR is 693 tcfg from 873 tcfg uTRR for the Marcellus play. For the Utica gas play, total rTRR is 684 tcfg from 725 tcfg uTRR. Of the total rTRR for both plays of 1,377 tcfg, 1,015 tcfg occur in PA, 259 tcfg are in WV, and 90 tcfg are in Ohio (OH) (with an additional 13 tcfg in a portion of New York [NY]). Note however, that Utica and total resources are highly driven by Utica assessments in the deep dry Utica of Westmoreland, Greene, Armstrong, and Allegheny counties, PA, which are based on very few wells to date and, therefore, are quite uncertain.

Exhibit 4-5. Generalized estimation of remaining TRR in the Marcellus play in WV and OH

State	Area Name	Total Area (mi^2)	Developed (mi^2)	Undrilled (mi^2)	Recovery (drilled) (tcf/mi^2)	Recovery (undrilled) (tcf/mi^2)	dTRR (base - tcfge)	dTRR (+15%) (tcfge)	dTRR (-30%) (tcfge)	rTRR (base) (tcfge)	rTRR (+15%) (tcfge)	rTRR (-30%) (tcfge)
WV	Harrison	416	69.2	346.8	0.050	0.045	3.5	4.1	2.5	15.29	17.59	10.71
WV	Doddridge	320	131.3	188.7	0.060	0.053	8.0	9.2	5.6	9.80	11.27	6.86
WV	Barbour - West	271	12.0	259.0	0.042	0.038	0.5	0.6	0.4	9.65	11.09	6.75
WV	Lewis - North	200	2.9	197.1	0.055	0.044	0.2	0.2	0.1	8.50	9.78	5.95
WV	Marshall	307	111.2	195.8	0.043	0.042	4.9	5.6	3.4	8.06	9.27	5.64
WV	Preston - West	318	4.2	313.8	0.023	0.023	0.1	0.1	0.1	7.07	8.13	4.95
WV	Monongalia - East	229	1.5	227.5	0.031	0.031	0.0	0.1	0.0	6.91	7.95	4.84
WV	Taylor	173	14.5	158.5	0.052	0.042	0.8	0.9	0.5	6.52	7.50	4.57
WV	Wetzel - East	120	18.5	101.5	0.065	0.064	1.2	1.4	0.9	6.37	7.32	4.46
WV	Marion - East	210	8.8	201.2	0.030	0.030	0.3	0.3	0.2	5.91	6.80	4.14
WV	All Others	2,947	16.9	2930.1	0.002	0.002	0.0	0.0	0.0	5.74	6.60	4.02
WV	Lewis - South	189	0.4	188.6	0.030	0.030	0.0	0.0	0.0	5.55	6.38	3.88
WV	Monongalia - West	132	27.3	104.7	0.062	0.052	1.7	2.0	1.2	5.33	6.13	3.73
WV	Randolph - West	300	1.1	298.9	0.018	0.018	0.0	0.0	0.0	5.27	6.06	3.69
WV	Marion - West	100	8.8	91.2	0.065	0.058	0.6	0.7	0.4	5.18	5.96	3.63
WV	Ritchie - Northeast	200	75.4	124.6	0.052	0.040	4.0	4.6	2.8	4.88	5.62	3.42
WV	Tyler - East	210	122.4	87.6	0.058	0.055	7.2	8.3	5.1	4.72	5.43	3.31
WV	Gilmer - Rest	220	1.6	218.4	0.022	0.022	0.0	0.0	0.0	4.71	5.42	3.30
WV	Upshur - South	275	5.7	269.3	0.017	0.017	0.1	0.1	0.1	4.49	5.16	3.14
WV	Ritchie - Southwest	252	0.0	252.0	0.018	0.018	0.0	0.0	0.0	4.45	5.11	3.11
WV	Wetzel - Central	120	55.4	64.6	0.069	0.068	3.9	4.5	2.7	4.30	4.95	3.01
WV	Gilmer - Northeast	120	0.3	119.7	0.035	0.035	0.0	0.0	0.0	4.11	4.72	2.87
WV	Wetzel - West	119	8.5	110.5	0.035	0.035	0.3	0.4	0.2	3.79	4.36	2.65
WV	Braxton	511	0.0	511.0	0.007	0.007	0.0	0.0	0.0	3.51	4.03	2.45
WV	Calhoun	279	0.8	278.2	0.012	0.012	0.0	0.0	0.0	3.27	3.76	2.29
WV	Preston - East	330	0.3	329.7	0.010	0.010	0.0	0.0	0.0	3.23	3.72	2.26
WV	Webster	553	0.2	552.8	0.005	0.005	0.0	0.0	0.0	2.71	3.11	1.90
OH	Monroe	120	11.4	108.6	0.027	0.024	0.3	0.4	0.2	2.56	2.94	1.79
WV	Upshur - North	80	6.8	73.2	0.028	0.028	0.2	0.2	0.1	2.01	2.31	1.41
WV	Tyler - West	48	0.2	47.8	0.034	0.034	0.0	0.0	0.0	1.59	1.83	1.12
WV	Pleasants - West	101	0.0	101.0	0.015	0.015	0.0	0.0	0.0	1.48	1.71	1.04
OH	Washington	60	0.0	60.0	0.020	0.020	0.0	0.0	0.0	1.18	1.35	0.82
WV	Barbour - East	70	0.1	69.9	0.017	0.017	0.0	0.0	0.0	1.16	1.34	0.81
WV	Pleasants - East	30	2.7	27.3	0.037	0.037	0.1	0.1	0.1	0.99	1.14	0.69
WV	Greenbrier	500	1.1	498.9	0.002	0.002	0.0	0.0	0.0	0.98	1.12	0.68
WV	Roane	484	2.4	481.6	0.002	0.002	0.0	0.0	0.0	0.94	1.09	0.66
WV	Fayette - Northeast	420	0.0	420.0	0.002	0.002	0.0	0.0	0.0	0.82	0.95	0.58
WV	Hancock	83	0.1	82.9	0.010	0.010	0.0	0.0	0.0	0.81	0.93	0.57
OH	Belmont	50	0.4	49.6	0.015	0.015	0.0	0.0	0.0	0.73	0.84	0.51
WV	Wirt	233	0.0	233.0	0.003	0.003	0.0	0.0	0.0	0.69	0.79	0.48
WV	Clay	342	0.0	342.0	0.002	0.002	0.0	0.0	0.0	0.67	0.77	0.47
WV	Brooke - North	44	3.2	40.8	0.014	0.014	0.0	0.1	0.0	0.56	0.64	0.39
WV	Ohio - West	86	55.7	30.3	0.018	0.018	1.0	1.2	0.7	0.53	0.61	0.37
WV	Wood - East	180	0.0	180.0	0.003	0.003	0.0	0.0	0.0	0.53	0.61	0.37
WV	Kanawha - Northeast	250	0.0	250.0	0.002	0.002	0.0	0.0	0.0	0.49	0.56	0.34
WV	Ohio - East	20	10.6	9.4	0.045	0.045	0.5	0.6	0.3	0.42	0.48	0.29
OH	Jefferson	20	0.2	19.8	0.012	0.012	0.0	0.0	0.0	0.23	0.27	0.16
WV	Brooke - South	45	37.3	7.7	0.025	0.025	1.0	1.1	0.7	0.19	0.22	0.13
	TOTAL						40.6	46.7	28.4	178.9	205.7	125.2

Note: TRR are taken from mapped values (Exhibit 3-1). Three rTRR and dTRR values are given to represent uncertainty in the primary well-level EUR estimates as described in the text.

Exhibit 4-6. Generalized estimation of remaining TRR in the Marcellus play in PA and NY

State	Area Name	Area (mi^2)	Developed (mi^2)	Undrilled (mi^2)	Recovery (drilled) (tcf/mi^2)	Recovery (undrilled) (tcf/mi^2)	dTRR (base - tcfge)	dTRR (+15%) (tcfge)	dTRR (-30%) (tcfge)	rTRR (base) (tcfge)	rTRR (+15%) (tcfge)	rTRR (-30%) (tcfge)
PA	Allegheny	730	40.7	689.3	0.065	0.065	2.7	3.1	1.9	43.91	50.50	30.74
PA	Westmoreland - East	828	13.0	815.0	0.035	0.035	0.5	0.5	0.3	27.96	32.15	19.57
PA	Clearfield	1145	23.0	1122.0	0.021	0.024	0.5	0.6	0.3	26.39	30.35	18.47
PA	Armstrong	653	36.9	616.1	0.043	0.043	1.6	1.9	1.1	25.96	29.86	18.17
PA	Sullivan	450	34.3	415.7	0.065	0.063	2.3	2.6	1.6	25.66	29.51	17.97
PA	Indiana	827	4.6	822.4	0.030	0.030	0.1	0.2	0.1	24.18	27.81	16.93
PA	Washington - SE	657	310.3	346.7	0.075	0.062	23.7	27.3	16.6	21.07	24.23	14.75
PA	Bradford - SE	577	234.2	342.8	0.082	0.061	19.6	22.5	13.7	20.49	23.57	14.35
PA	Lycoming - NE	400	85.2	314.8	0.068	0.057	5.9	6.8	4.1	17.58	20.22	12.31
PA	Jefferson	652	9.7	642.3	0.028	0.028	0.3	0.3	0.2	17.63	20.27	12.34
PA	Susquehanna	823	360.2	462.8	0.079	0.035	29.0	33.4	20.3	15.87	18.26	11.11
PA	Bradford - NW	570	109.8	460.2	0.051	0.033	5.7	6.6	4.0	14.88	17.12	10.42
PA	Fayette - East	540	3.0	537.0	0.027	0.027	0.1	0.1	0.1	14.21	16.34	9.95
PA	Tioga - NW	680	52.5	627.5	0.022	0.022	1.2	1.4	0.8	13.53	15.56	9.47
PA	Elk	828	32.8	795.2	0.023	0.017	0.8	0.9	0.5	13.25	15.24	9.27
PA	Beaver	370	15.7	354.3	0.035	0.035	0.6	0.6	0.4	12.15	13.97	8.51
PA	Centre - NW	500	6.6	493.4	0.025	0.025	0.2	0.2	0.1	12.09	13.90	8.46
PA	Potter	600	8.0	592.0	0.020	0.020	0.2	0.2	0.1	11.60	13.34	8.12
PA	Butler - South	300	78.0	222.0	0.057	0.052	4.5	5.2	3.2	11.31	13.01	7.92
PA	Lycoming - NW	400	91.3	308.7	0.043	0.035	4.0	4.6	2.8	10.59	12.18	7.41
PA	Greene - West	280	130.3	149.7	0.075	0.068	10.0	11.5	7.0	9.98	11.47	6.98
PA	Cambria	688	0.7	687.3	0.015	0.015	0.0	0.0	0.0	10.10	11.62	7.07
PA	Clinton	550	15.2	534.8	0.030	0.019	0.5	0.5	0.3	9.96	11.45	6.97
PA	Tioga - SE	350	105.0	245.0	0.050	0.041	5.4	6.2	3.8	9.84	11.32	6.89
PA	Fayette - West	250	45.4	204.6	0.047	0.046	2.2	2.5	1.5	9.22	10.60	6.46
PA	Westmoreland - West	200	23.3	176.7	0.052	0.052	1.2	1.4	0.9	9.00	10.35	6.30
PA	McKean	550	20.4	529.6	0.017	0.017	0.4	0.4	0.2	8.82	10.15	6.18
PA	Greene - East	296	130.3	165.7	0.051	0.051	6.8	7.8	4.7	8.28	9.52	5.80
PA	Clarion	501	7.6	493.4	0.017	0.017	0.1	0.2	0.1	8.22	9.45	5.75
PA	Butler - North	340	5.2	334.8	0.020	0.020	0.1	0.1	0.1	6.56	7.55	4.59
PA	Somerset	500	2.2	497.8	0.013	0.013	0.0	0.0	0.0	6.34	7.29	4.44
PA	Wyoming - SE	280	0.0	280.0	0.020	0.020	0.0	0.0	0.0	5.49	6.31	3.84
PA	Luzerne	350	0.0	350.0	0.014	0.014	0.0	0.0	0.0	4.80	5.52	3.36
NY	Broome	245	0.0	245.0	0.017	0.017	0.0	0.0	0.0	4.08	4.69	2.86
NY	Steuben	210	0.0	210.0	0.017	0.017	0.0	0.0	0.0	3.50	4.02	2.45
PA	Cameron	300	11.9	288.1	0.012	0.012	0.1	0.2	0.1	3.39	3.90	2.37
PA	Washington - NE	200	80.4	119.6	0.035	0.027	2.9	3.3	2.0	3.16	3.64	2.21
PA	Wyoming - NW	117	83.2	33.8	0.075	0.072	6.4	7.3	4.5	2.39	2.74	1.67
PA	Forest	220	2.4	217.6	0.010	0.010	0.0	0.0	0.0	2.13	2.45	1.49
NY	Tioga	138	0.0	138.0	0.015	0.015	0.0	0.0	0.0	2.03	2.33	1.42
NY	Chemung	126	0.0	126.0	0.015	0.015	0.0	0.0	0.0	1.85	2.13	1.30
PA	Blair - West	140	0.7	139.3	0.012	0.012	0.0	0.0	0.0	1.64	1.88	1.15
NY	Delaware	126	0.3	125.7	0.012	0.012	0.0	0.0	0.0	1.48	1.70	1.03
PA	Bedford	70	0.1	69.9	0.010	0.010	0.0	0.0	0.0	0.68	0.79	0.48
PA	Lawrence	40	1.4	38.6	0.010	0.010	0.0	0.0	0.0	0.38	0.43	0.26
PA	Warren	50	0.2	49.8	0.005	0.005	0.0	0.0	0.0	0.24	0.28	0.17
PA	Venango	20	0.3	19.7	0.010	0.010	0.0	0.0	0.0	0.19	0.22	0.14
	TOTAL						**139.4**	**160.4**	**97.6**	**514.1**	**591.2**	**359.9**

Note: TRR are taken from mapped values (Exhibit 3-1). Three rTRR and dTRR values are given to represent uncertainty in the well-level EUR estimates as described in the text.

Exhibit 4-7. Generalized estimation of rTRR in the Utica play

State	Area Name	Total Area (mi^2)	Developed (mi^2)	Undrilled (mi^2)	Recovery (drilled) (tcf/mi^2)	Recovery (undrilled) (tcf/mi^2)	dTRR (base) (tcfge)	dTRR (+15%) (tcfge)	dTRR (-30%) (tcfge)	rTRR (Tcfge)	rTRR (+15%)	rTRR (-30%)
PA	Greene	576	6.7	569.3	0.095	0.095	0.7	0.75	0.46	53.00	60.95	37.10
PA	Westmoreland - West	400	2.2	397.8	0.120	0.120	0.3	0.31	0.19	46.78	53.79	32.74
PA	Armstrong	653	0.5	652.5	0.055	0.055	0.0	0.03	0.02	35.17	40.45	24.62
PA	Potter	850	11.1	838.9	0.035	0.035	0.4	0.45	0.28	28.78	33.09	20.14
PA	Allegheny - West	580	0.4	579.6	0.050	0.050	0.0	0.02	0.01	28.40	32.66	19.88
PA	Tioga	700	22.0	678.0	0.042	0.042	0.9	1.08	0.66	27.91	32.09	19.53
PA	Washington - West	657	0.0	657.0	0.042	0.042	0.0	0.00	0.00	27.04	31.10	18.93
PA	Butler	789	1.5	787.5	0.035	0.035	0.1	0.06	0.04	27.01	31.06	18.91
PA	Elk	828	10.6	817.4	0.030	0.030	0.3	0.37	0.23	24.03	27.64	16.82
PA	Fayette - West	200	0.0	200.0	0.120	0.120	0.0	0.00	0.00	23.52	27.05	16.46
PA	Indiana	640	0.3	639.7	0.035	0.035	0.0	0.01	0.01	21.94	25.23	15.36
PA	Clearfield	700	0.0	700.0	0.030	0.030	0.0	0.00	0.00	20.58	23.67	14.41
PA	Westmoreland - East	400	0.0	400.0	0.050	0.050	0.0	0.00	0.00	19.60	22.54	13.72
WV	Monongalia - West	181	0.4	180.6	0.100	0.100	0.0	0.04	0.03	17.70	20.36	12.39
PA	Cameron	396	10.4	385.6	0.045	0.045	0.5	0.55	0.33	17.00	19.55	11.90
PA	Washington - East	200	1.6	198.4	0.085	0.085	0.1	0.16	0.10	16.53	19.00	11.57
PA	Jefferson	652	0.0	652.0	0.025	0.025	0.0	0.00	0.00	15.97	18.37	11.18
OH	Belmont	532	219.1	312.9	0.054	0.050	12.1	13.88	8.45	15.33	17.63	10.73
WV	Marion	310	0.0	310.0	0.050	0.050	0.0	0.00	0.00	15.19	17.47	10.63
PA	Clarion	601	0.0	601.0	0.025	0.025	0.0	0.00	0.00	14.72	16.93	10.31
WV	Marshall	307	30.1	276.9	0.050	0.050	1.5	1.76	1.07	13.57	15.60	9.50
PA	Allegheny - East	150	0.0	150.0	0.090	0.090	0.0	0.00	0.00	13.23	15.21	9.26
OH	Columbiana	450	30.7	419.3	0.031	0.030	1.0	1.11	0.68	12.33	14.18	8.63
OH	Monroe	456	136.4	319.6	0.042	0.038	5.8	6.72	4.09	11.90	13.69	8.33
OH	Jefferson	408	121.8	286.2	0.040	0.040	5.0	5.72	3.48	11.22	12.90	7.85
WV	Wetzel	359	1.9	357.1	0.030	0.030	0.1	0.07	0.04	10.50	12.07	7.35
PA	Beaver	435	7.0	428.0	0.025	0.025	0.2	0.21	0.13	10.49	12.06	7.34
PA	Fayette - East	200	0.0	200.0	0.050	0.050	0.0	0.00	0.00	9.80	11.27	6.86
OH	Harrison	402	129.1	272.9	0.038	0.032	5.0	5.75	3.50	8.56	9.84	5.99
PA	Lawrence	358	18.0	340.0	0.025	0.025	0.5	0.53	0.32	8.33	9.58	5.83
WV	Monongalia- East	180	0.4	179.6	0.045	0.045	0.0	0.02	0.01	7.92	9.11	5.54
WV	Tyler	258	3.6	254.4	0.030	0.030	0.1	0.13	0.08	7.48	8.60	5.24
OH	Washington	300	3.0	297.0	0.022	0.022	0.1	0.08	0.05	6.40	7.36	4.48
OH	Noble	370	50.4	319.6	0.020	0.020	1.0	1.18	0.72	6.26	7.20	4.38
PA	Clinton	200	0.0	200.0	0.030	0.030	0.0	0.00	0.00	5.88	6.76	4.12
PA	McKean	300	4.2	295.8	0.020	0.020	0.1	0.10	0.06	5.80	6.67	4.06
WV	Ohio	106	0.6	105.4	0.050	0.050	0.0	0.03	0.02	5.17	5.94	3.62
PA	Venango	300	0.3	299.7	0.015	0.015	0.0	0.01	0.00	4.41	5.07	3.08
OH	Guernsey	250	76.7	173.3	0.025	0.025	2.0	2.25	1.37	4.25	4.88	2.97
OH	Mahoning	200	3.9	196.1	0.022	0.022	0.1	0.10	0.06	4.23	4.86	2.96
PA	Mercer	300	12.6	287.4	0.015	0.015	0.2	0.22	0.13	4.23	4.86	2.96
WV	Hancock	83	0.0	83.0	0.050	0.050	0.0	0.00	0.00	4.07	4.68	2.85
OH	Carroll	280	108.9	171.1	0.025	0.022	2.8	3.19	1.94	3.69	4.24	2.58
PA	Forest	200	0.4	199.6	0.015	0.015	0.0	0.01	0.00	2.93	3.37	2.05
WV	Harrison	100	0.0	100.0	0.010	0.010	0.0	0.00	0.00	0.98	1.13	0.69
WV	Doddridge	100	0.0	100.0	0.010	0.010	0.0	0.00	0.00	0.98	1.13	0.69
OH	Trumbull	50	3.9	46.1	0.012	0.012	0.0	0.05	0.03	0.54	0.62	0.38
WV	Pleasants	60	7.2	52.8	0.010	0.010	0.1	0.08	0.05	0.52	0.60	0.36
PA	Bradford	50	0.2	49.8	0.010	0.010	0.0	0.00	0.00	0.49	0.56	0.34
OH	Morgan	40	0.5	39.5	0.011	0.011	0.0	0.01	0.00	0.43	0.49	0.30
WV	Taylor	40	0.0	40.0	0.010	0.010	0.0	0.00	0.00	0.39	0.45	0.27
OH	Tuscarawas	30	3.6	26.4	0.012	0.012	0.0	0.05	0.03	0.31	0.36	0.22
WV	Ritchie	30	0.0	30.0	0.010	0.010	0.0	0.00	0.00	0.29	0.34	0.21
PA	Lycoming	20	0.0	20.0	0.015	0.015	0.0	0.00	0.00	0.29	0.34	0.21
	TOTAL						**41.0**	**47.1**	**28.7**	**684.1**	**786.67**	**478.84**

Note: TRR are taken from mapped values (Exhibit 3-2). Three rTRR values are given to represent uncertainty in the well-level EUR estimates as described in the text.

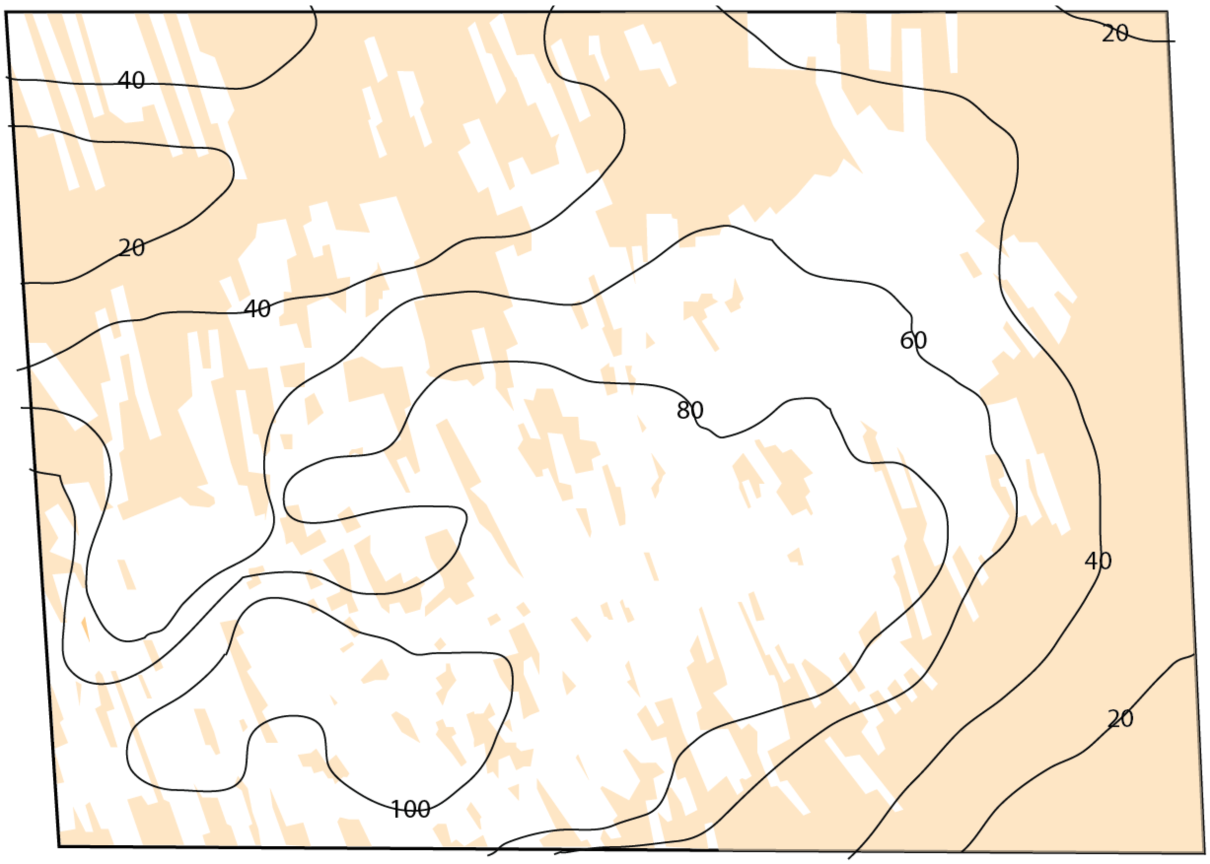
Exhibit 4-8. Summary of TRR estimates (tcfg) for the Marcellus and Utica shale gas plays

Play	State	dTRR			rTRR			uTRR		
		base	*+15%*	*-30%*	*base*	*+15%*	*-30%*	*base*	*+15%*	*-30%*
Marcellus	PA	139.4	160.4	97.6	501.2	576.3	350.8	640.6	736.7	448.4
	WV	40.3	46.4	28.2	174.2	200.3	122.0	214.5	240.6	148.2
	OH	0.3	0.3	0.2	4.7	5.4	3.3	5.0	5.7	3.5
	NY	0.0	0.0	0.0	12.9	14.9	9.1	12.9	14.9	9.1
	Basin	**180.0**	**207.1**	**126.0**	**693.0**	**796.7**	**485.2**	**873.0**	**997.9**	**609.2**
Utica gas	PA	4.2	4.8	2.9	513.9	591.0	359.8	518.1	595.8	362.7
	OH	34.9	40.1	24.4	85.4	98.3	59.8	120.3	138.3	84.2
	WV	1.9	2.1	1.3	84.8	97.5	59.4	86.6	99.6	60.7
	Basin	**41.0**	**47.0**	**28.6**	**684.1**	**786.8**	**479.0**	**725.0**	**833.7**	**507.6**

Note: Three values are given to reflect uncertainty in EUR calculations largely driven by selection of decline curve cutoffs as discussed in the text.

For the dTRR calculation, drilled area is determined by summing the estimated lateral lengths for all wells in the area (including active, inactive, completed, plugged and abandoned, etc.) and multiplying by the common well spacing as determined from the detailed evaluation of Marcellus development described above. In this sense, the gas volumes associated with drilled wells include past production, gas yet to be produced in existing wells, and resources associated with unsuccessful wells for which the resources were not produced for either operational, logistical, or economic reasons. The remaining undrilled area is assigned a TRR/mi^2 value typical of that area to determine approximate rTRR. In the most heavily drilled counties, the TRR/mi^2 is lower for undeveloped acreage than for developed acreage due to preferential drilling in the most productive regions. An example from Susquehanna County, PA, is provided in Exhibit 4-9. This area is among the most intensively drilled in the Marcellus play. Note that apparently undrilled "patches" remain within the area of intensive development. It is not clear how many of these are actual undrilled areas and how many reflect reporting deficiencies related to well directional surveys; however, it is likely that many are real and that some of those are sufficiently small or irregular such that they could not justify future wells. The primary causes of these minor "undrained" areas are not certain, but include abnormal lease geometries or restrictions, changes in prominent well azimuth, and later wells within a development being unable to reach the planned lateral length. Exhibit 4-10 and Exhibit 4-11 provide another example from Marcellus development in western Doddridge County, WV. SSAE has not evaluated this issue quantitatively—for this analysis, SSAE accommodates this inefficiency by reducing the undrilled acreage by 2 percent (to reflect future spatial inefficiency) and by a corresponding 2 percent increase in drilled acreage. This may be a conservative estimate. SSAE does not assign acreage that has not been drilled due to various regulatory issues as unrecoverable, so these volumes are included in the estimates (for example, much of Allegheny County, PA, and select counties in southern NY).

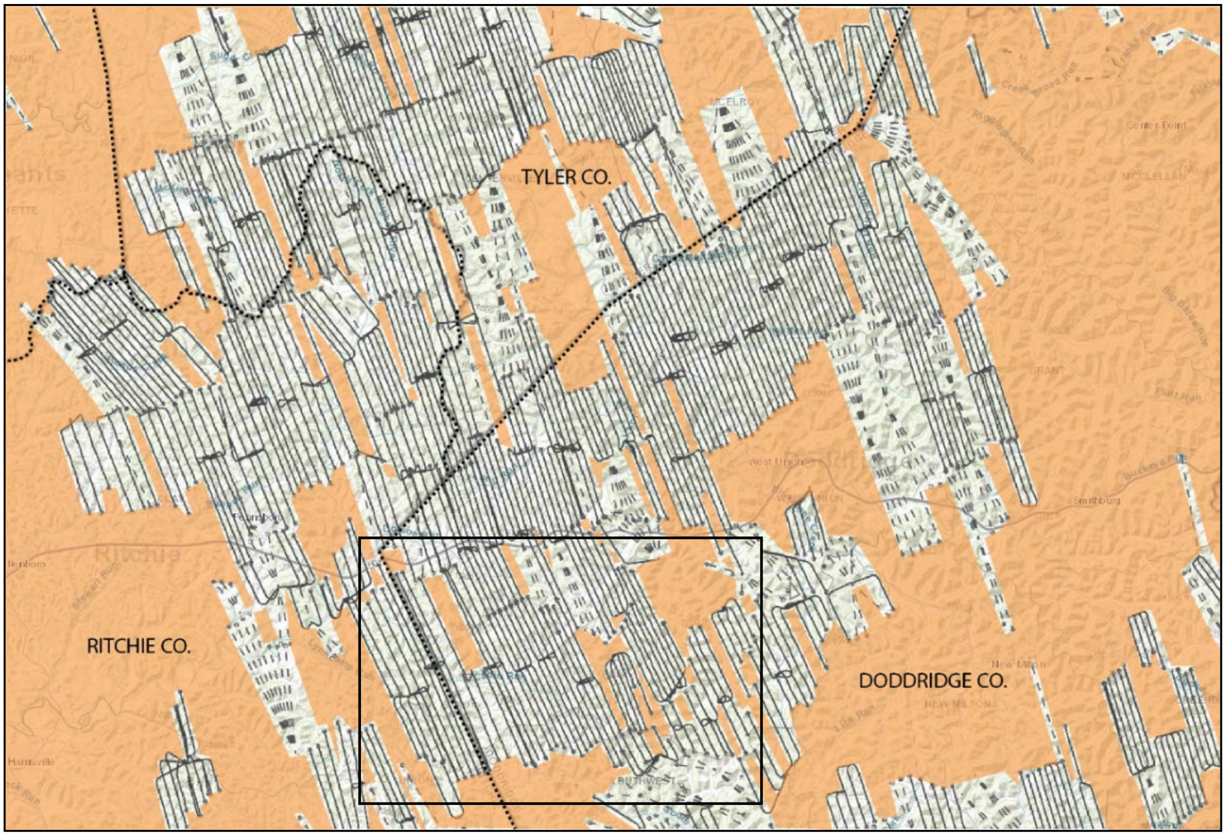
Exhibit 4-9. Case study for assessment of change in recoverability between drilled (white) and remaining (orange) acreage within the Marcellus play in Susquehanna County, PA



Note: Contours are expected recovery (50-year base case EURs in bcfg/mi^2). For this county, the estimated evaluation of uTRR (see Exhibit 4-6) was set at 79 bcfg/mi^2 for drilled acreage and 35 bcfg/mi^2 for remaining acreage.

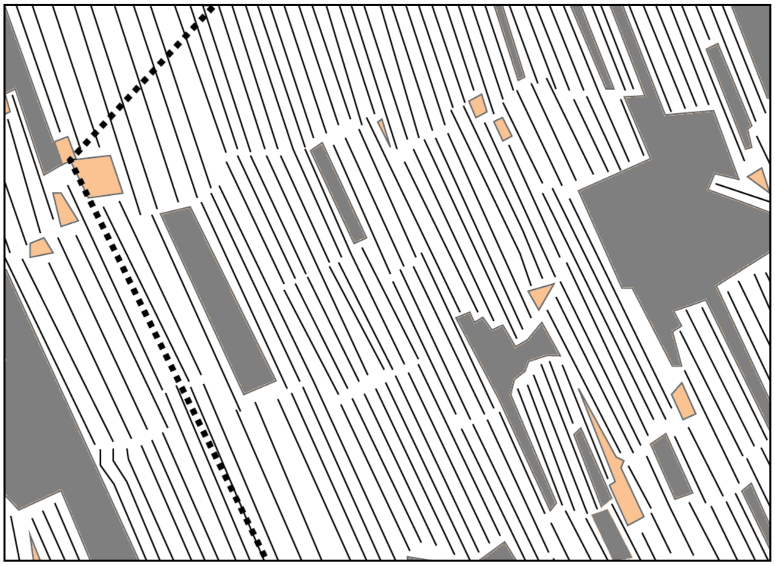
Comparison of dTRR estimates (equal to uTRR minus rTRR) with reported cumulative production and reserves provides an order-of-magnitude check on the general calculation. These values should be similar with the exception of any resources associated with "failed" wells (wells for which acreage was consumed but TRR was not converted to production or reserves). For the Marcellus, total cumulative production through 2020 was 54.0 tcfg and reserves were 139.4 tcfg (total of 193.4 compared with 180.1 tcfg dTRR). [11] For the Utica, the values are 13.2 tcfg cumulative production and 34.4 tcfg reserves (total of 47.2 compared to 41 tcfg dTRR). This discrepancy is less if the dTRR +15 percent values of 207 tcfg (Marcellus) and 47 tcfg (Utica) are used, which may be more representative of reserve calculations reported by industry.

Exhibit 4-10. Approximate determination of undrilled Marcellus acreage in western Doddridge, southern Tyler, and northern Ritchie counties, WV



Note: After subtracting drilled acreage from total acreage, all remaining (orange) areas are "undrilled." Area indicated by box shown in detail in Exhibit 4-11. NOTE: dashed drill paths based on surface and bottom-hole locations only and do not reflect actual drill paths.

Exhibit 4-11. Example local area showing areas determined to be undrilled



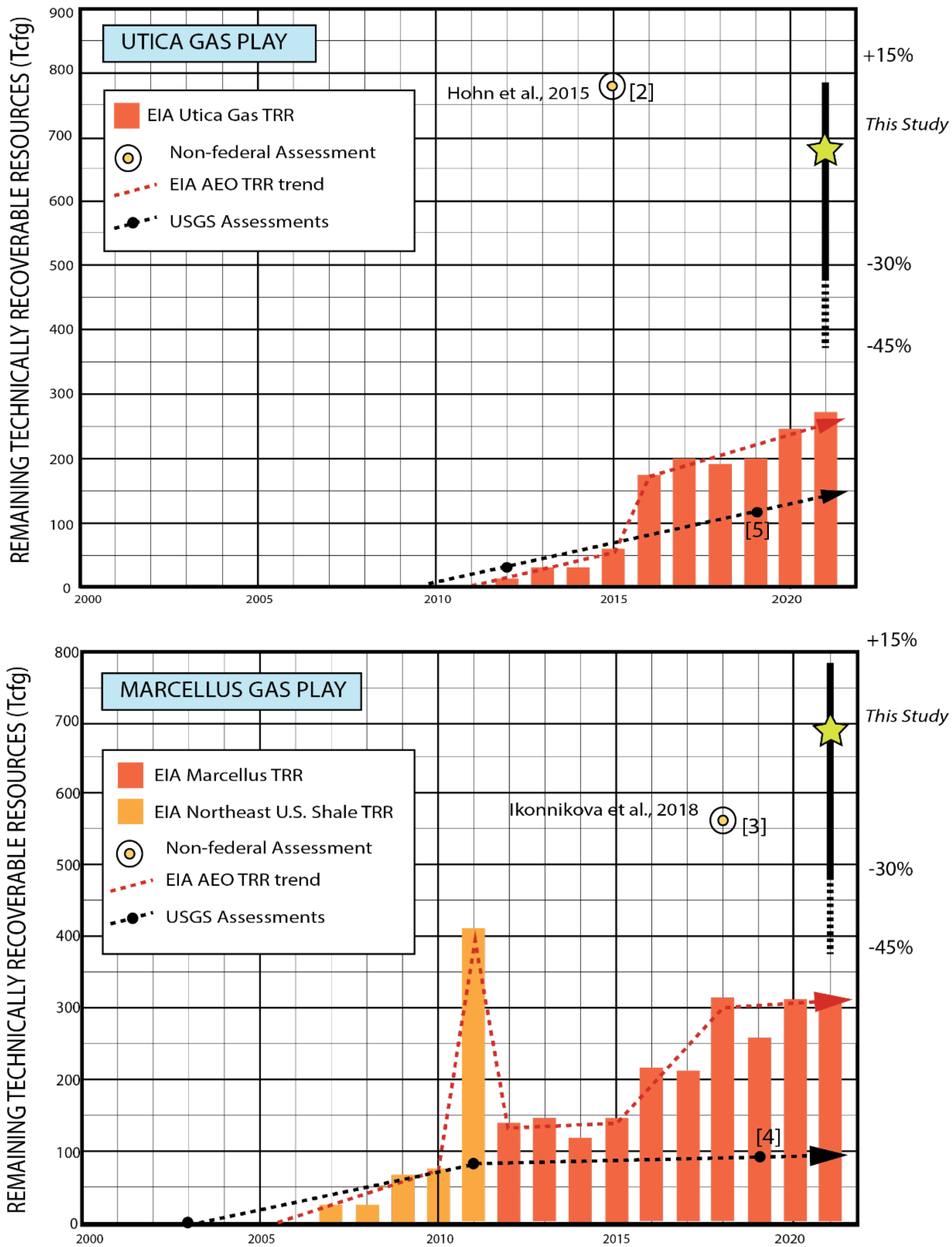
Note: Black lines are well paths. Location is indicated by boxed area in Exhibit 4-10.

5 SUMMARY

Recent assessments of the Marcellus and Utica shale gas plays have indicated continuing uncertainty in future resource availability for these key resource elements. By reference to carefully screened well performance data from 6,283 wells grouped into 1,469 developments that have been normalized to indicated recoverable resources per mi^2, both total potential and remaining undeveloped TRRs have been estimated at high spatial resolution. This evaluation suggests that while the general magnitude of both plays have been clearly identified in a range of prior studies, [9, 16, 14] both plays may have been undervalued in oft-cited federal assessments (Exhibit 5-1).

Although both plays now include large numbers of drilled and producing wells, very few of those wells have produced for more than eight years. Those that have produced longer were completed using practices that are much different and less effective than those currently in use and likely to be used in the future. Thus, these findings remain estimates with significant uncertainty. That uncertainty is based primarily on the method used to assign EURs to individual wells. Based on review of EUR assessments between three EUR sources, SSAE selected the Enverus (April 2020) release as the base scenario for this evaluation and suggest that uncertainty spans a range from base +15 percent to base -30 percent.

Exhibit 5-1. Modified version of Exhibit 1-2 and Exhibit 1-3 showing estimates of rTRR (with noted uncertainties) from this study



Note: The black line reflects nominal range in EUR uncertainty from +15% to -30% as described in the text. Dashed extension of the uncertainty to -45% reflects an additional -15% designed to reflect potential non-drillable acreage due to various logistical issues or general drilling inefficiency. Results remain significantly higher than prevailing federal assessments as generally aligned with previous public-sector studies.

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