Resource Analysis to Improve Recovery of Unconventional Oil and Gas

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U.S. Department of Energy

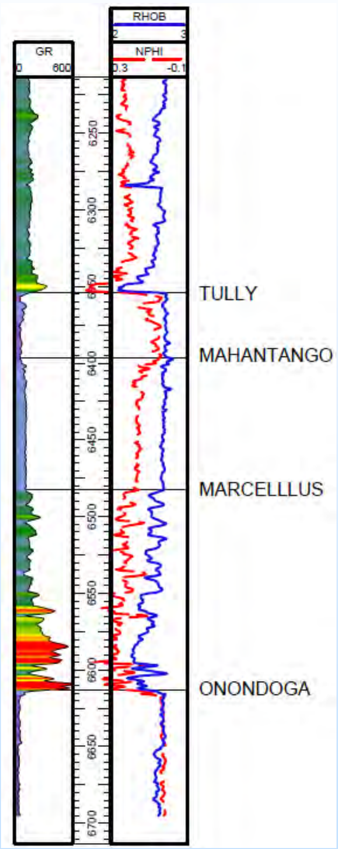
National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

Discussion Agenda

- **Scope and Overview**
- **Pilot Project**
  - Study Area
  - Data
  - Results and Findings
- **Next Steps/Ongoing Work**
- **Questions/Discussions**



Source: Ikonnikova, S. (2018). EIA Energy Forecasting Forum - April 2018

Scope and Objectives

Detailed Analysis of Industry Performance in Marcellus Shale

- **Evaluate region-specific industry performance data with the goal of identifying R&D needs conducive to improving the recovery of oil and gas in unconventional reservoirs.**

  – Apply regression-style techniques to develop a model capable of predicting EUR based on available data parameters.

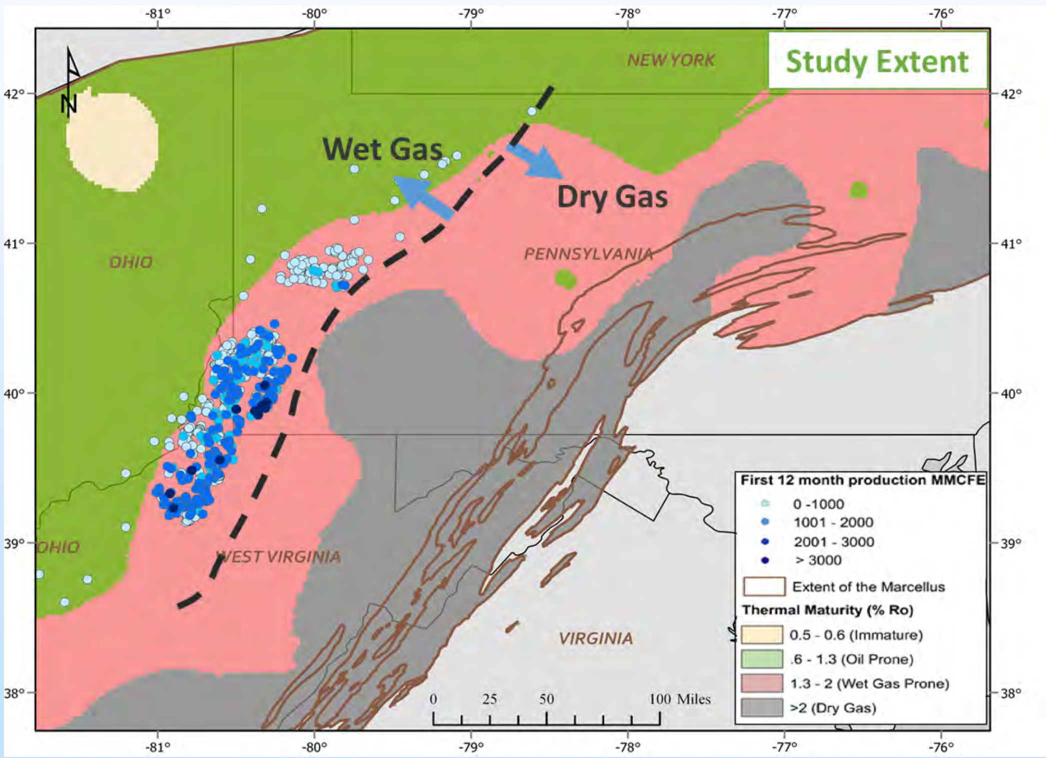
  – Test several machine learning regression algorithms and assess relevance in O&G applications.

  – Use sensitivity analysis or other means to quantify the relative contribution of each input parameter on productivity.

  – Identify most critical research needs and pass that information to fundamental researchers.

Pilot Evaluation – Western Marcellus

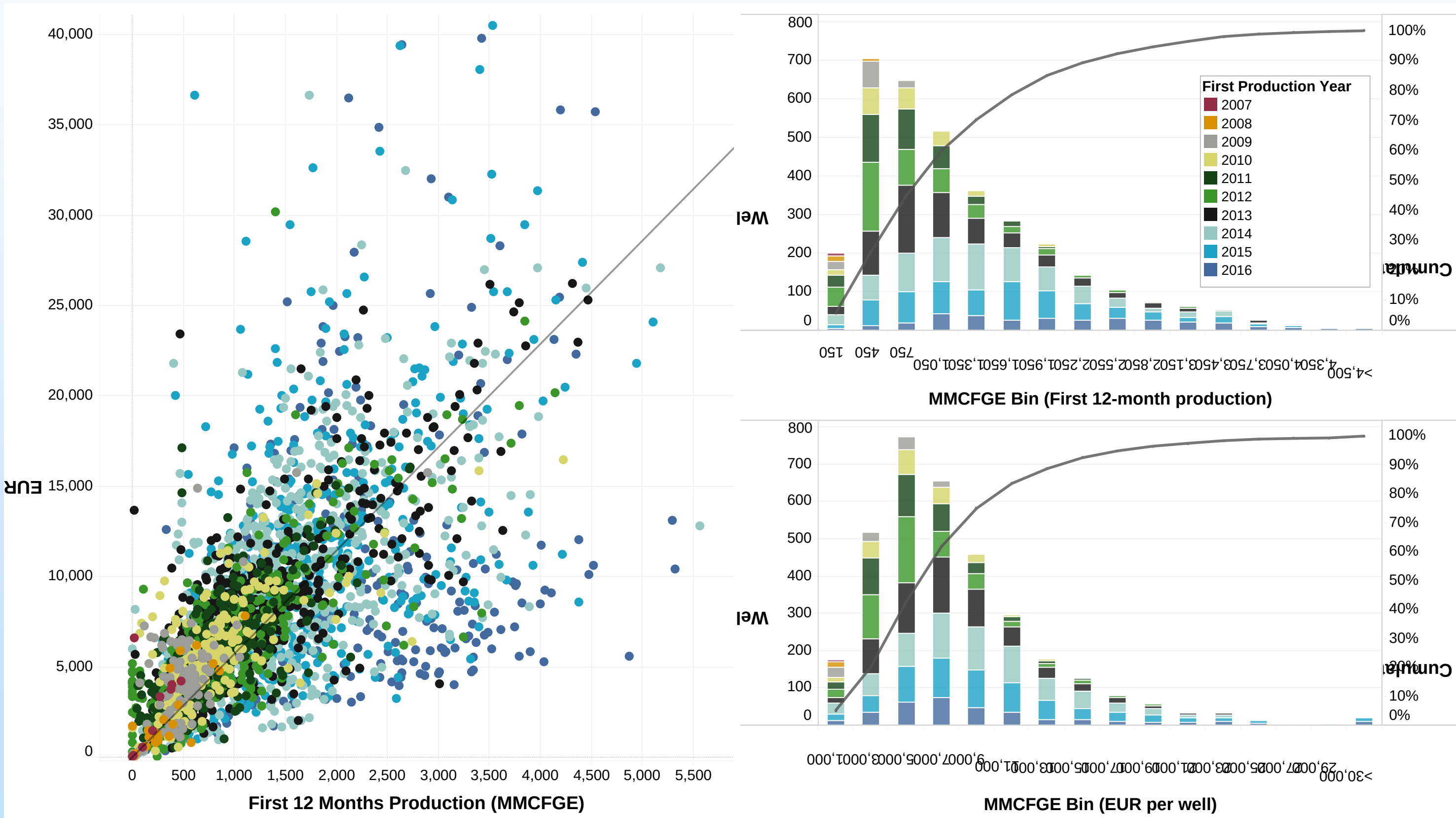
Western Marcellus Shale – Wet Gas Region; 2007 Through 2016 1st Production Year Wells



Type	Name	Source
Geology	Surface Hole Latitude	DrillingInfo (DI)
	Surface Hole Longitude	DI
	GR	Well Logs, DI
	Thickness	Well Logs, DI, Lit. Review
	R_o (VR)	Core Data, DI, Lit. Review
	True Vertical Depth	DI
	First 12m GOR	Calculated
Technology	Perf. Interval Length	DI
	Total Additive Per ft	DI
	Total Fluid Per ft	DI
	Total Proppant Per ft	DI
	Azimuth	DI
	Spacing	DI
	Pad Drilled (Y/N)	DI
Prod.	First 12m Production	DI

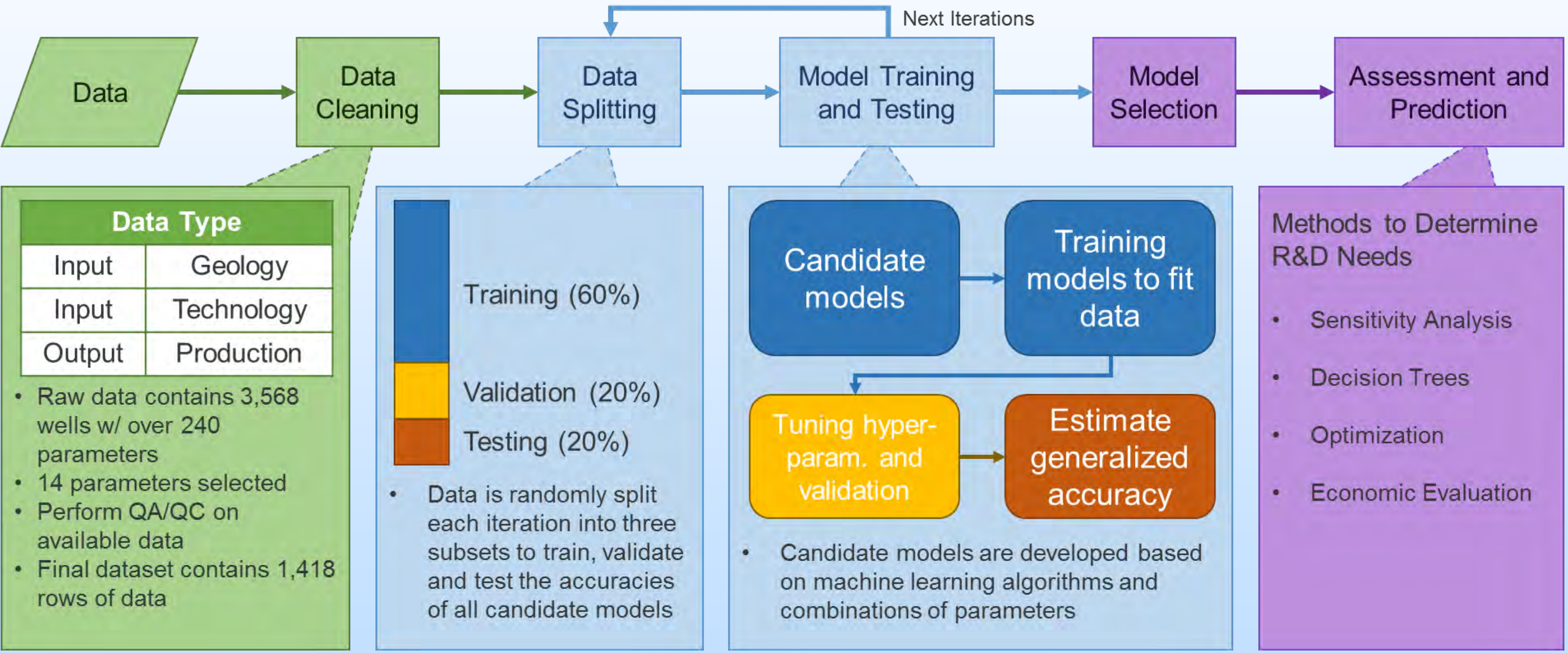
Justification for Use of 1st Year Production

- Not a predicted value.
- Explicitly measured.
- Strongly correlated to predicted EUR.
- Better parameter for pilot-testing machine learning.



Machine Learning Framework

To Evaluate the Impact of Technology and Geology Parameters on Well Productivity

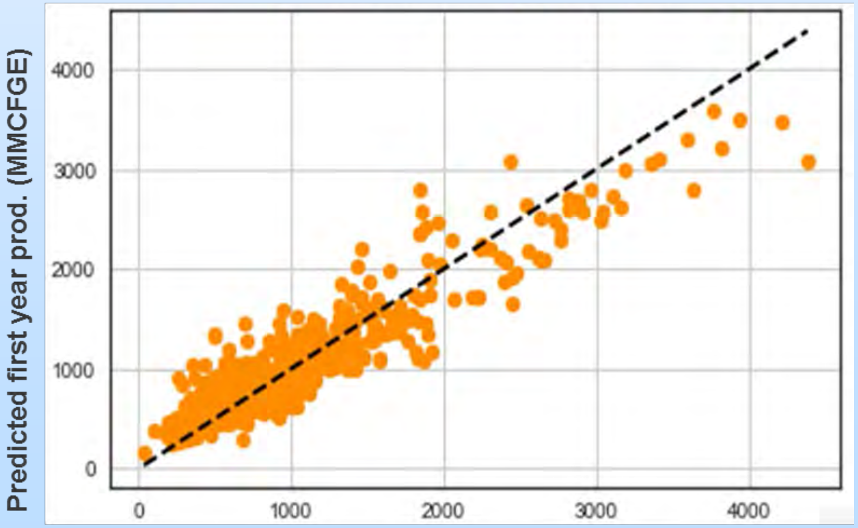


Modeling Training Results Overview

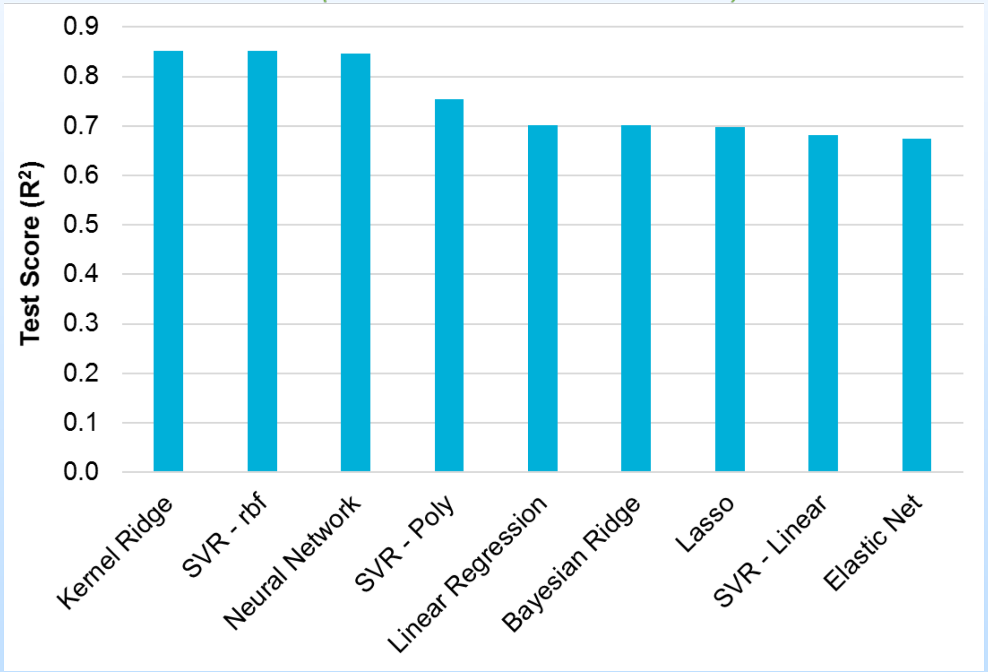
Western Marcellus Predictive Model

- Nine algorithms with various parameter combinations (up to a total of 14) were tested in this study to compare model performance.
- Non-linear algorithms performed better, indicating complexity in predicting production.

Model performance (Kernel Ridge)



Algorithms Evaluated and Testing Score
(All 14 Parameters Included)

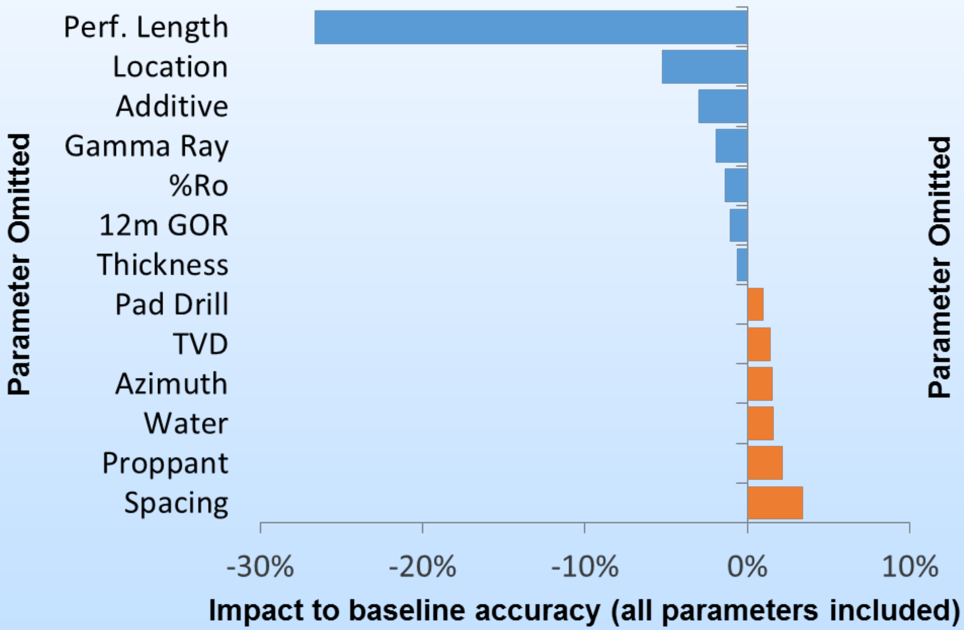


Assessing Parameter Impact on Accuracy

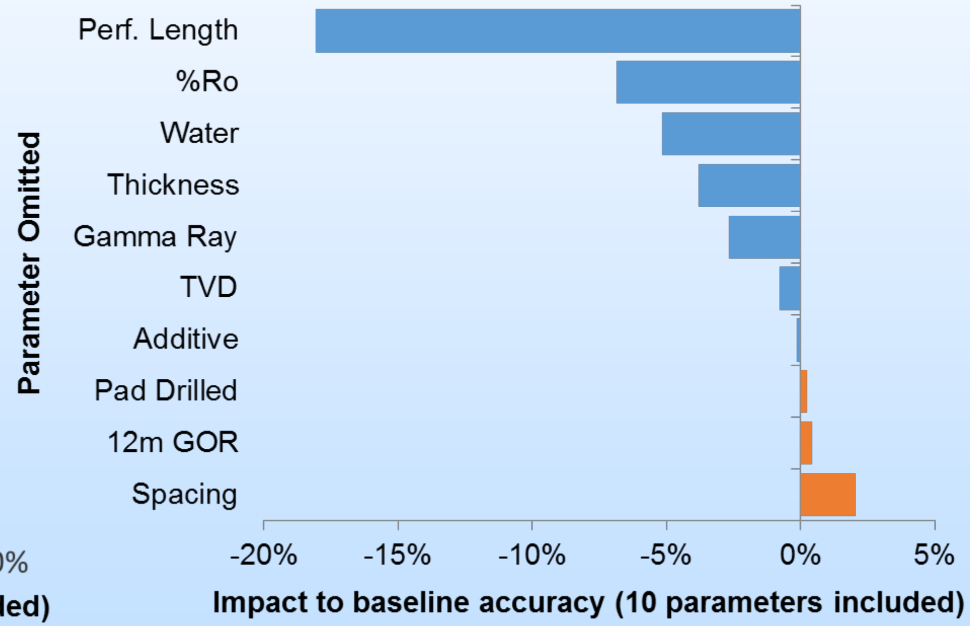
R^2 Loss Evaluation on Down-Selected Parameter Set

Initial Model Parameter Set
(All 14 Parameters Included)

Finalized Model Parameter Set
(10 Parameters Included)



Initial R^2 = 0.85



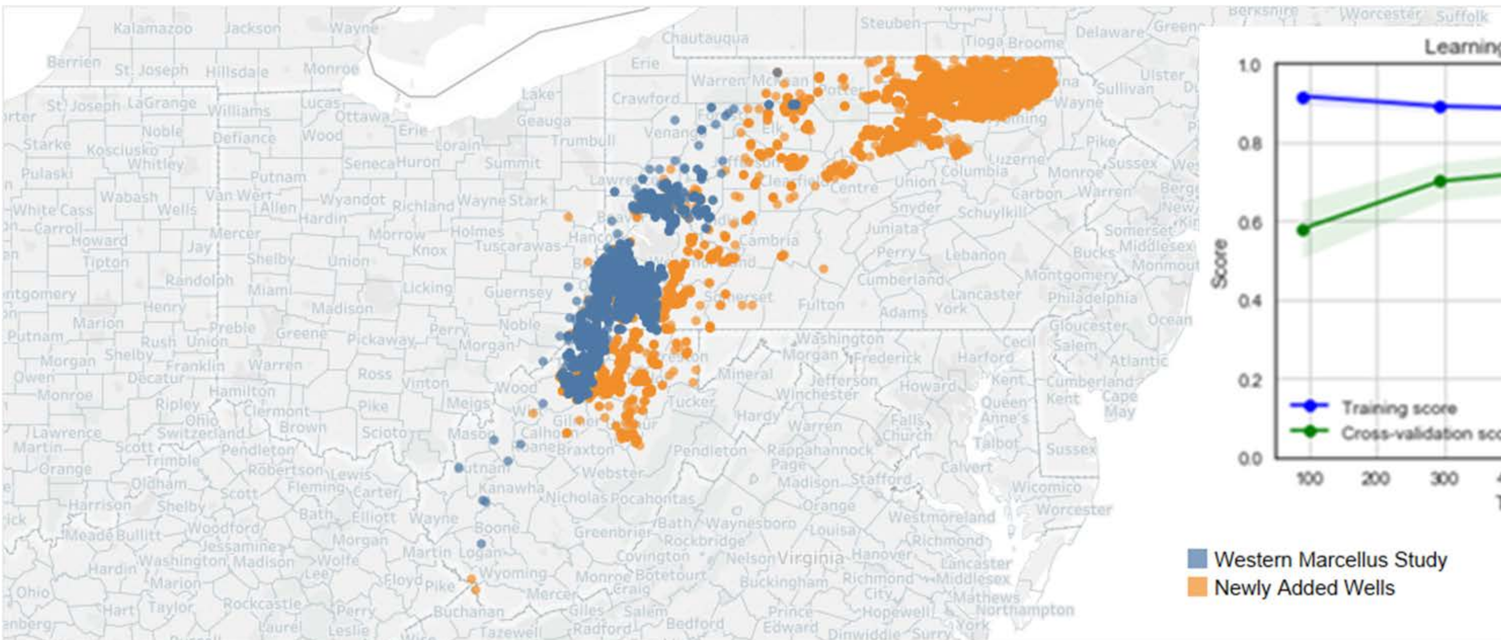
Initial R^2 = 0.83

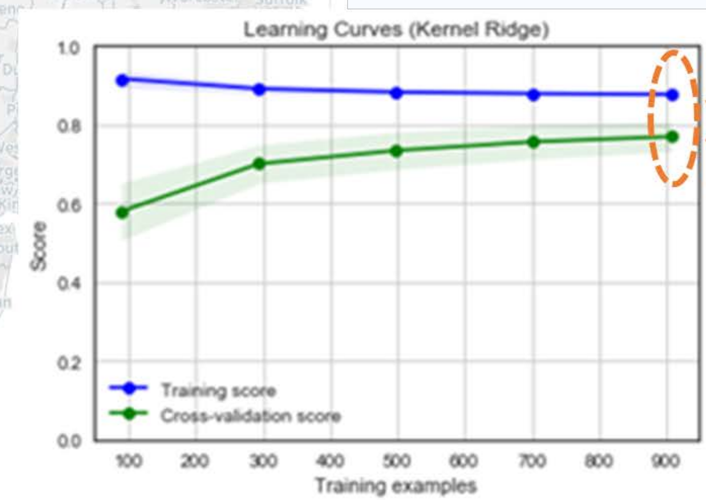
Pilot Study Conclusions

- Publicly available data can be used to develop reasonably performing regression models that can predict well productivity.
- Geology and technology parameters are needed in combination, in order to fully explain variance in well productivity.
- There is a need for expanded data sets, both in number of samples and in number of parameters in each sample.
- Early sensitivity analysis shows that there is room for optimization in all wells analyzed.

Next Steps/Ongoing Work

Expanded Study Area and Well Counts





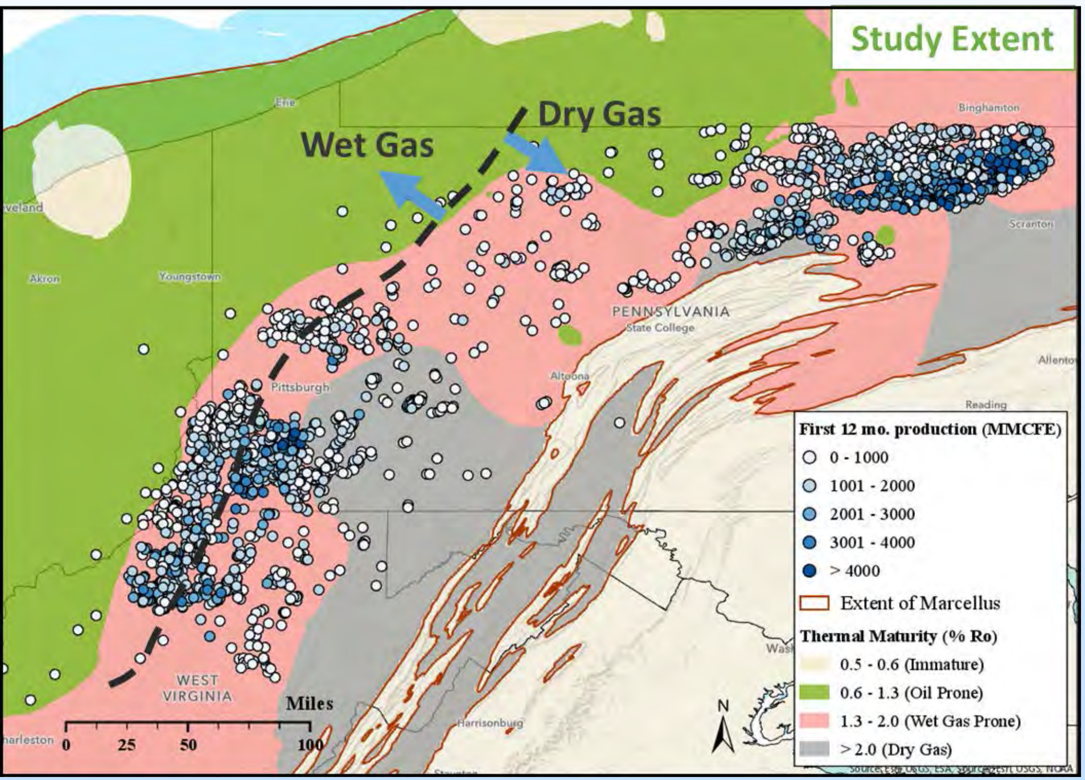
The data was downloaded from Drilling Info at Marcellus formation on May 18, 2018

Type of Data	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	**Total**
Newly Added Wells	2	15	121	451	845	1,107	1,035	854	550	406	937	6,323
Western Marcellus Study	8	26	117	212	365	488	641	694	624	393		3,568
												9,891

More data could reduce training vs. validation gap

Expanded Evaluation – Marcellus Shale

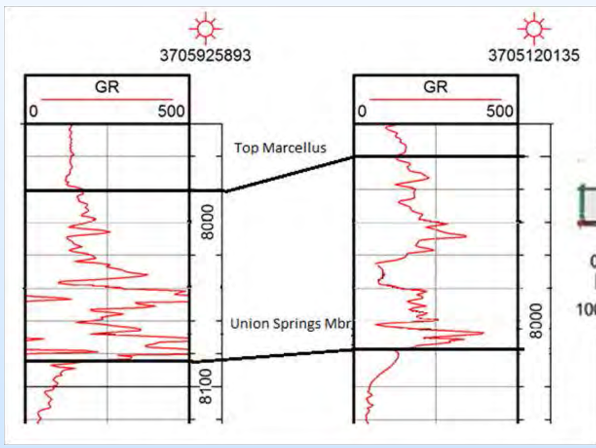
Marcellus Shale – 2007 Through 2017 1st Production Year Wells

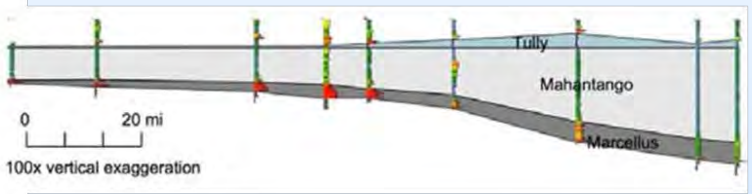


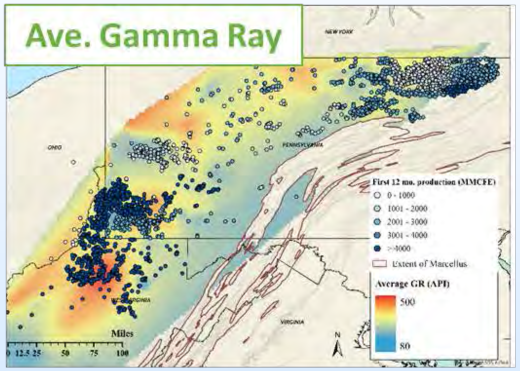
Type	Name	Source
Geology	Surface Hole Latitude	DrillingInfo (DI)
	Surface Hole Longitude	DI
	GR, Porosity, Res, Den	Well Logs, DI
	Thickness	Well Logs, DI, Lit. Review
	R_o (VR)	Core Data, Lit. Review
	True Vertical Depth	DI
	Upper, Lower, All Marcellus	Well Logs
	First 12m GOR	Calculated
Technology	Perf. Interval Length	DI
	Total Additive Per ft	DI
	Total Fluid Per ft	DI
	Total Proppant Per ft	DI
	Azimuth	DI
	Spacing	DI
	Pad Drilled (Y/N)	DI
Prod.	First 12m Production	DI

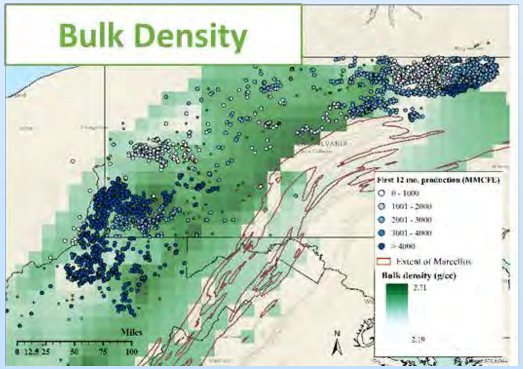
Expanding the Geologic Dataset

Data Acquisition and Interpretation → **Stratigraphic Property Assessment** → **Geologic Property Contouring**









- Well log correlation
- Core data
- Lit. data

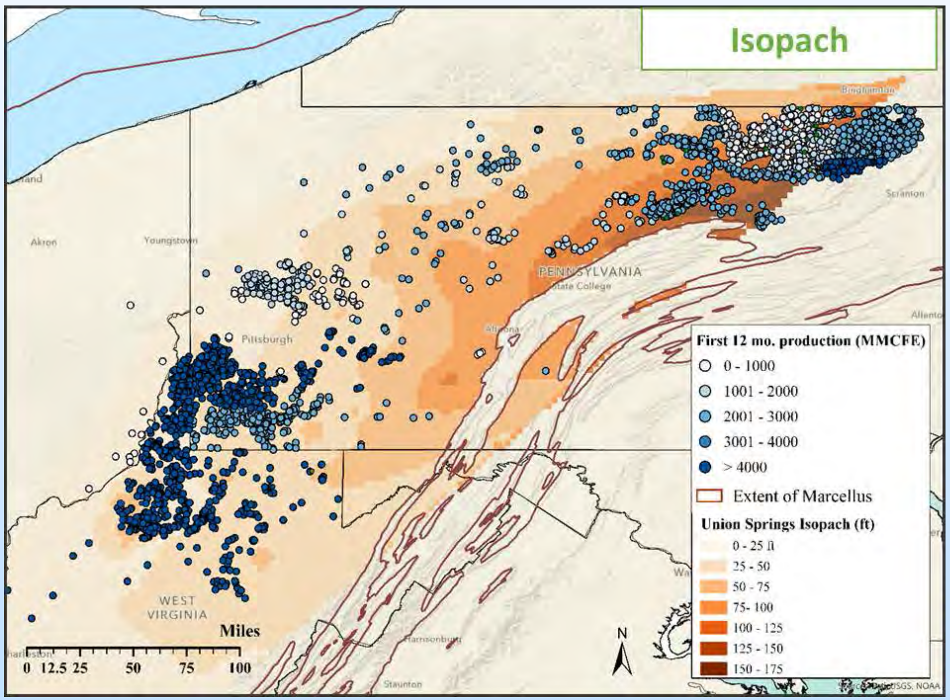
- Parameter values
- Thickness

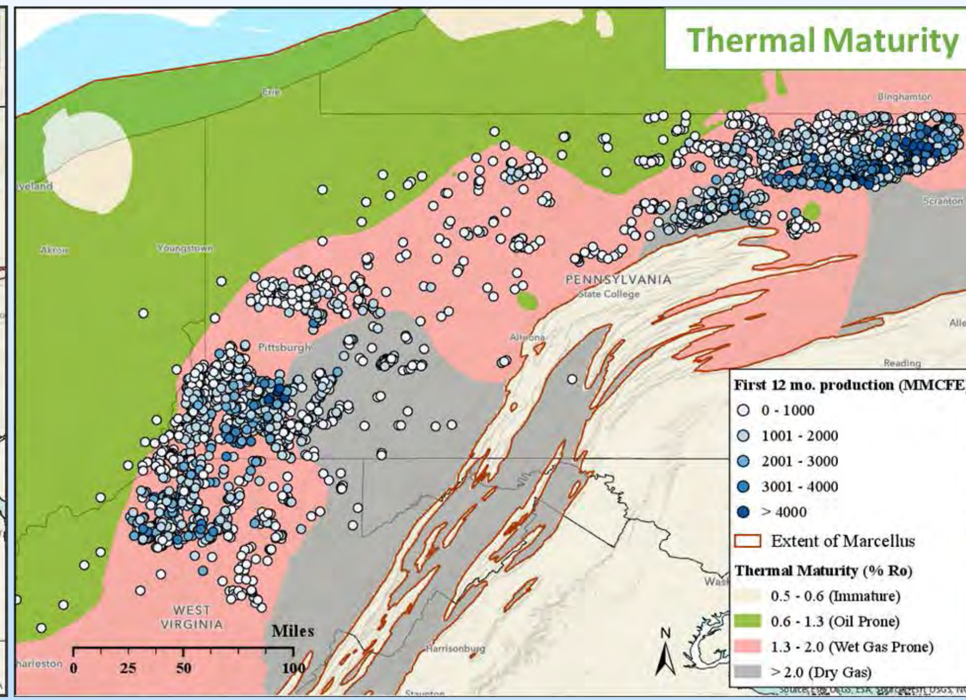
- Depth
- Zonal segregation

Preliminary – Geologic Assessment

Isopach and Thermal Maturity

- Well log interpretation completed to assess geologic factors across play.

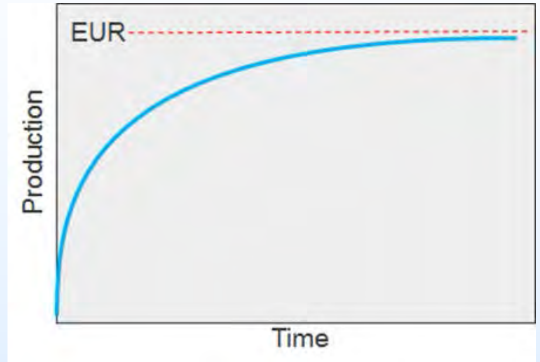


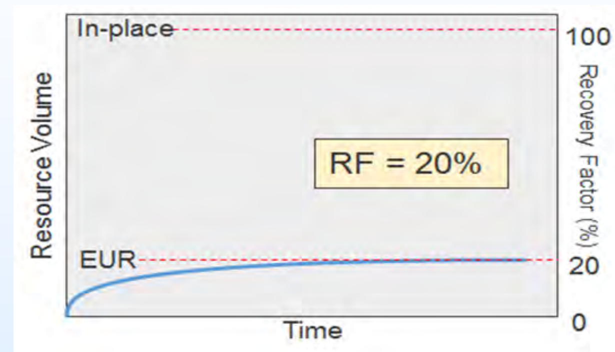


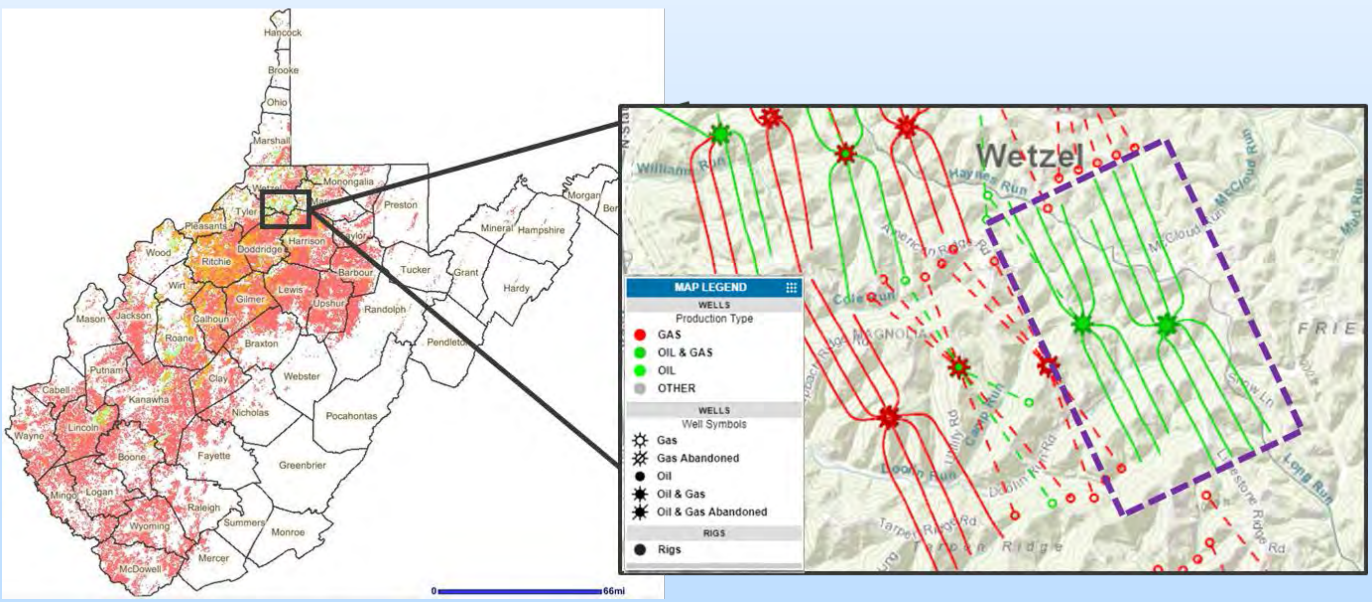
Recovery Factor (RF) Assessment

Marcellus Shale – West Virginia

- **RF is the ratio of the EUR of a specific entity (i.e., well, lease area, or play) divided by the total in-place resource.**







- Acquire OGIP data.
- Evaluate RF for areas totally developed or nearly developed.
- Use info to inform the regression analysis if possible.
- Analyze the data parameters to determine their individual impact on well productivity (EUR) and RF.
- Collaboration with the West Virginia Geologic Survey.

Boswell, R. 2017 - Recovery Efficiency in UOG Development

Desired data sets

- **Only partial understanding can be attained from publicly-available data/information alone.**
  - State reporting requirements strongly influence data availability and quality across plays

- **Expanded datasets would enable for refined models, and enable better determination of parameters influencing production.**

- **Desired datasets:**
  - Well logs (i.e. .las files)
  - Completion-related information (i.e. stage count, total perforations, and pressures)
  - Additive type, proppant size and type
  - Well orientation (toe-up vs. toe down; % in zone)
  - Well spacing
  - Pre-stimulation pay-zone pore pressures
  - Geochemical and geophysical data
  - Natural fracture extent
  - Others…

Acknowledgements

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- ShangMin Lin
- Aranya Venkatesh

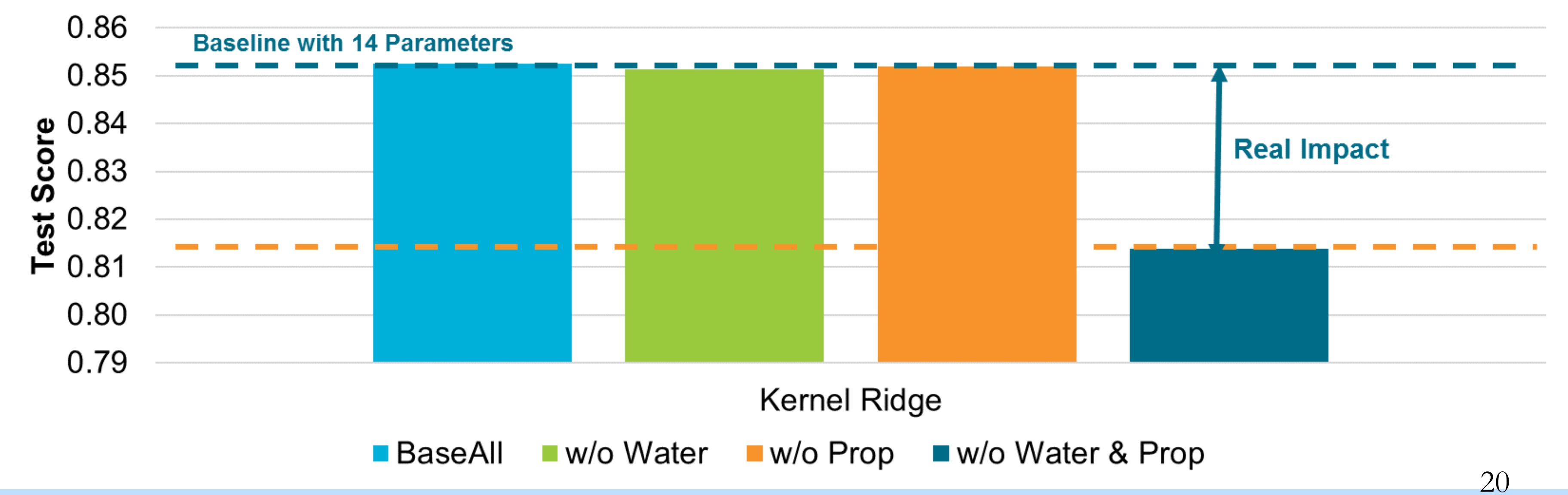
Questions ?

Backup Slides

Impact of Correlated Parameters on Accuracy

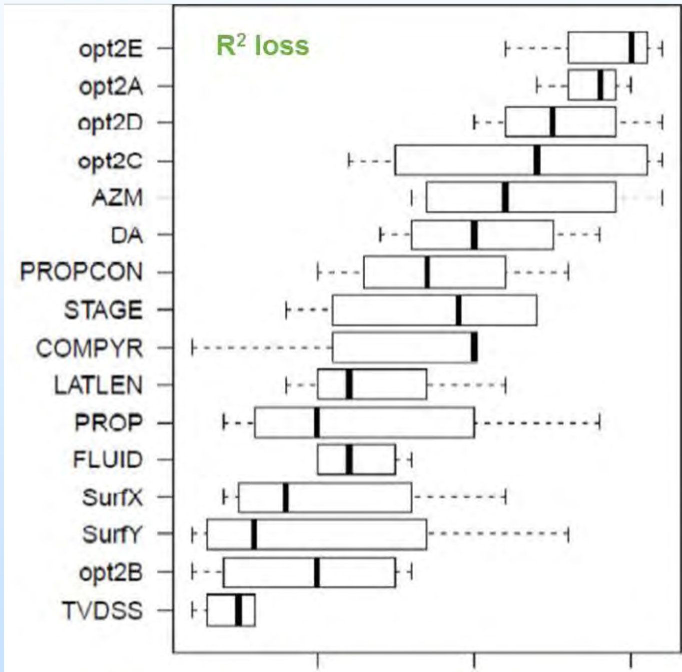
Water and Proppant Correlation

- Volumes of water and proppant injected were found to be strongly correlated.
- Should either of the two parameters be excluded in model training, the other compensates, suggesting that neither parameter has importance.
- But, when both parameters are removed, the test scores drop considerably.



Variation in Parameter Impact on Accuracy

Comparison of Different Studies Predicting Production

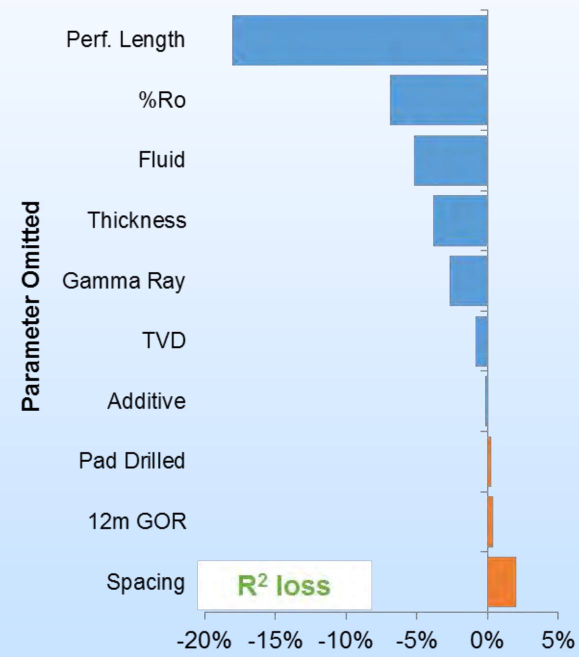


Wolfcamp shale – Delaware Basin, Texas
Battelle / Baker Hughes - 2015

Rank	Feature	% Degree of Influence
1	Net Thickness (ft)	100
2	No- Stages	41
3	Easting-End Point	40
4	Cluster per Stage	39
5	Propp (lbs-ft)	36
6	Lateral Length (ft)	29
7	Shot Density (shots-ft)	26
8	Max- Prop- Conc-(lb-gal)	25
9	MD (End)	24
10	Treatment Pressur (psi)	23
11	Average TVD	21
12	Treatment Rate (bbl-min)	21
13	Clean Vol- (bbls-ft)	16
14	Northing-End Point	15
15	Langmuir Vol- (scf-ton)	10
16	Azimuth (End)	10
17	Porosity %	9
18	Langmuir Pressure (psi)	6
19	Slurry Vol- (bbls-ft)	6
20	TOC %	6
21	Water Saturation %	
22	Deviation (End)	
23	Inclination (End)	

Fuzzy Pattern Recognition

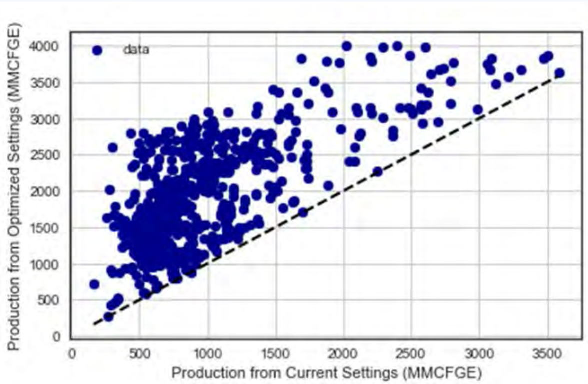
Focused Marcellus Region – Appalachian Basin
WVU / Intelligent Solutions - 2017

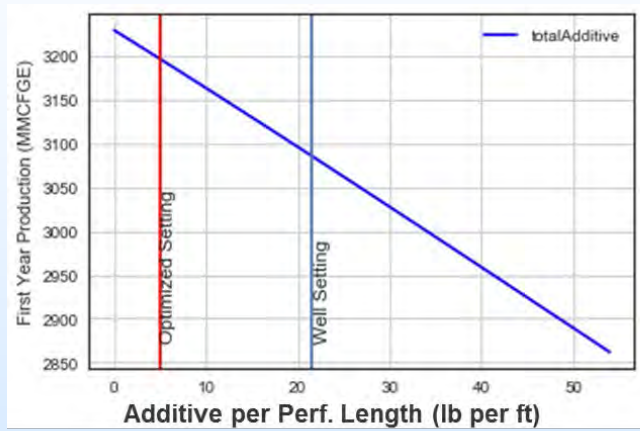


Western Marcellus – Appalachian Basin
NETL - 2018

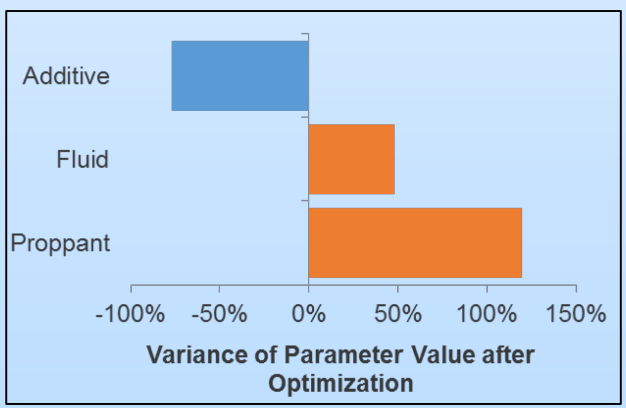
Optimization of Well Design

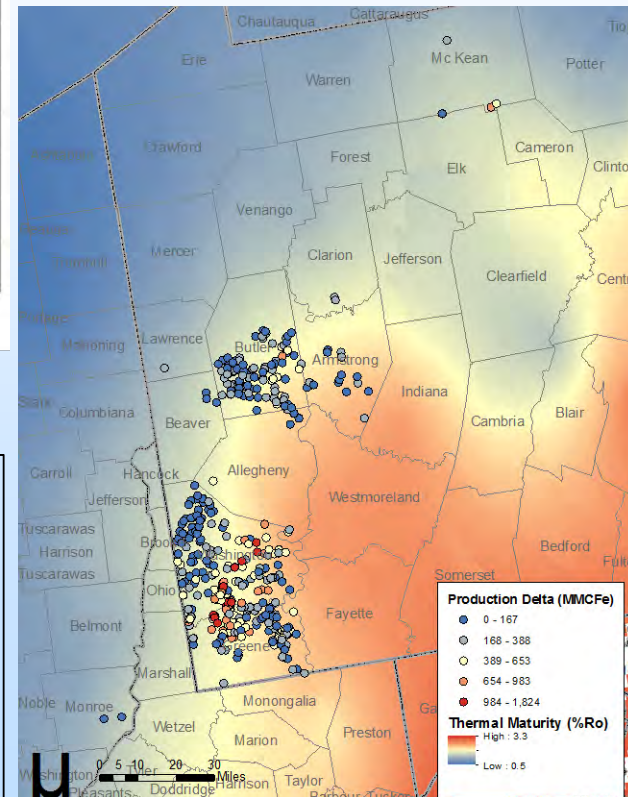
Modifying Additive, Fluids, and Proppant per Perforated Interval Length





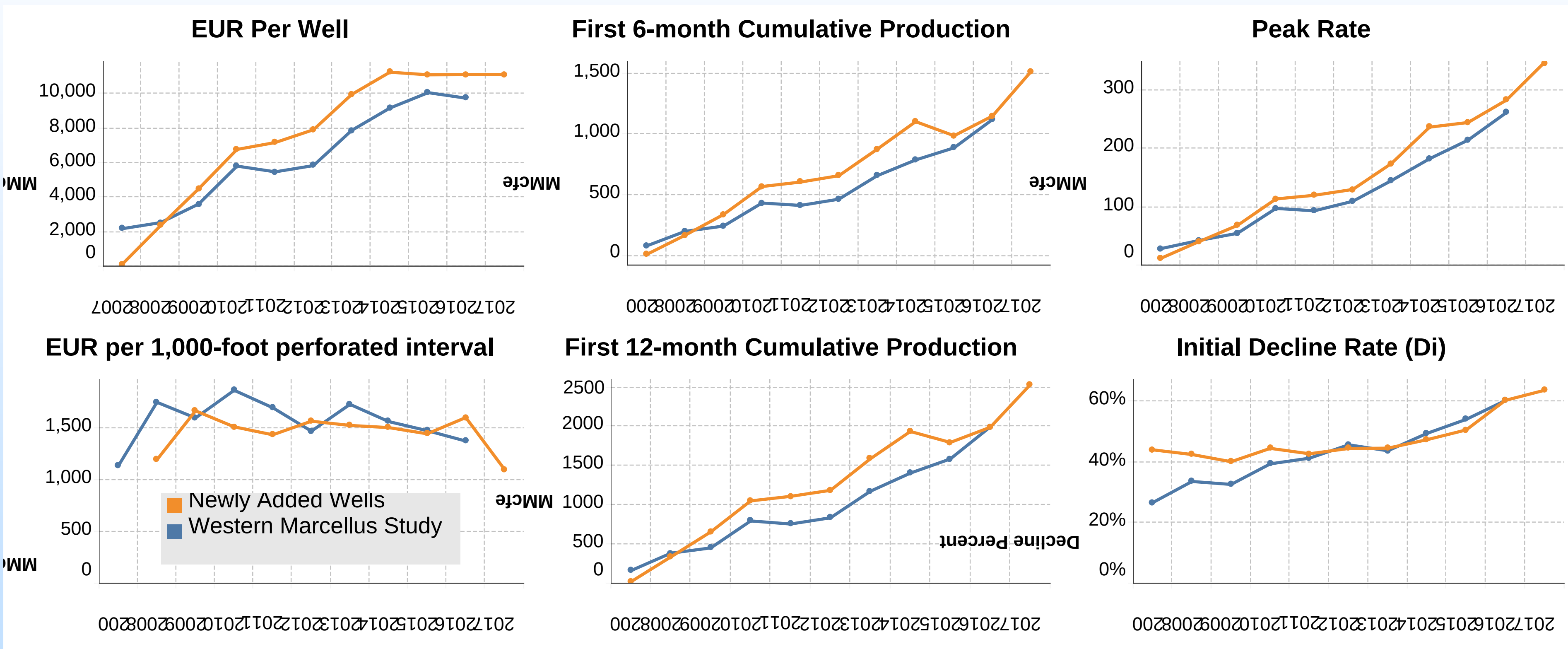
- Most wells in the preliminary test showed that the design can be improved.
- Increasing parameter values does always yield best results.
- Additive was decreased to optimize well design for a case-study well.





Production Performance Summary

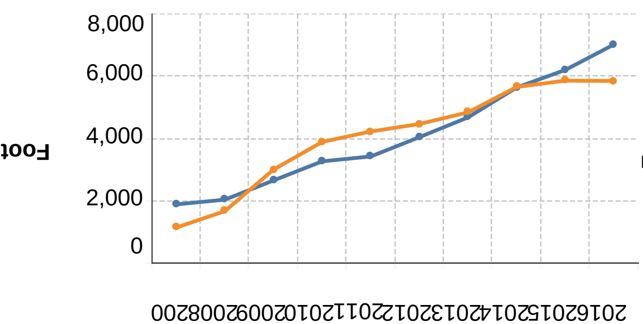
Marcellus Shale – All Wells (2007 – 2017)



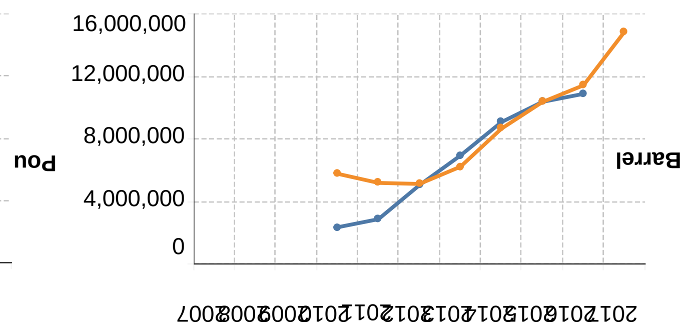
Well Completion/Design Summary

Marcellus Shale – All Wells (2007 – 2017)

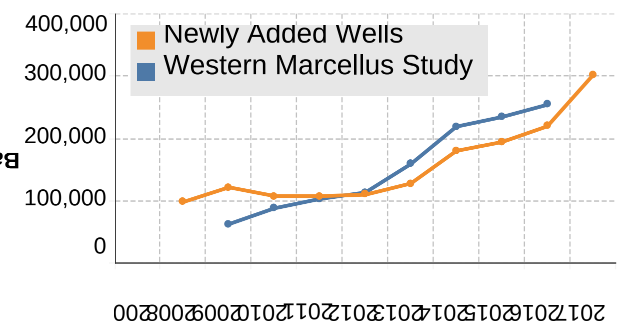
Peforated Interval Length



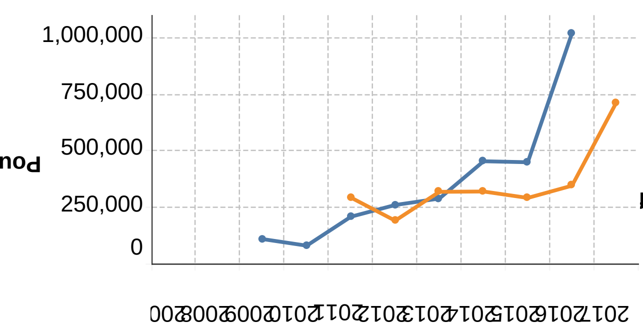
Total Proppant



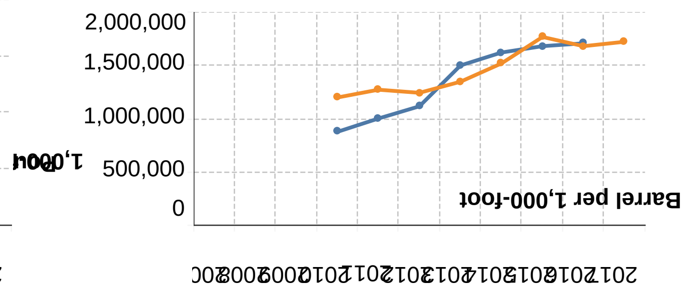
Total Water



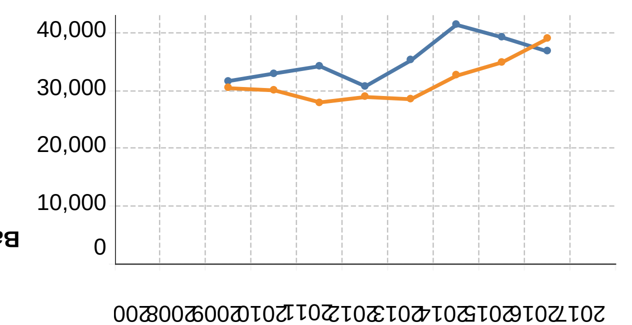
Total Additive Injected



Proppant per 1,000-foot perforated interval



Water per 1,000-foot perforated interval



Recovery Factor (RF) Assessment

- RF is a concept not readily applied to UOG.
- EUR is a function of the marriage of technology and geology.
  - Technology changes with time (future >>> past).
  - Geology changes with location (core >>> margins).
  - Assessments can get EUR very wrong for either (both) reasons.
- In-place volumes subject to great uncertainty.
- RF is better with gas. Also better with depth/pressure.
- RF is likely better than we think in core areas and worse than we think at the margins.
- Minor improvements in RF can be directly translated into immense and tangible economic and national security benefits.

Table 1: Major Shale Gas Plays: Reserves, Recovery Factors, Production Potential, Well-Productivities – 2013

Plays	Barnett	Fayetteville	Haynesville	Marcellus
Gas-in-place[1], bcf/sq. mile	50	30	77	18
Year-end Output, bcfd	5.31	2.87	3.87	10.90
Cumulative Production, tcf	14.7	4.2	8.5	6.7
Reserves(EUR)[2], tcf	20	9	12	140
Recovery Factor, %	6.1	11.2	1.7	9.3
Production Potential[3], bcfd	5.64(2011)	2.88(2012)	7.0(2011)	24
Peak Well-Productivity, Mcfd/well	438 (2008)	833 (2010)	3,382 (2010)	
Present Well-Productivity, Mcfd/well	303	610	1,195	1,050
Year-end Producing Wells	17,494	4,704	3,238	10,369
Current 180-day Well IPs, MMcfd	1.9	2.1	9.5	4.9
Well-Productivity Decline Rate, %/year	7	10	35	
Well EUR, bcf/well	2.2	3.0	3.5	1.6
Well-Productivity by 2020, Mcfd/well	190	306	102	

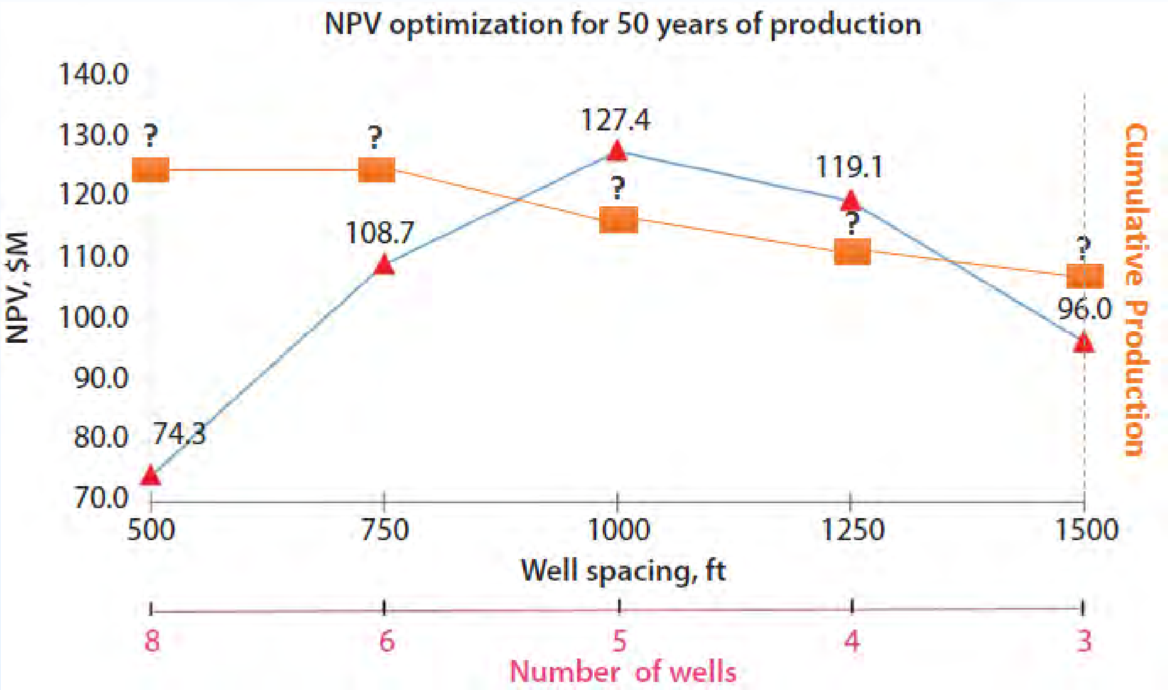
Sandrea and Sandrea, OGJ, 2014

Basin	Formation/Play	Age	Oil In-Place ($MBbls/Mi^2$)	Oil Recovery ($MBbls/Mi^2$)	Oil Recovery Efficiency (%)
Williston	Bakken ND Core	Mississippian-Devonian	12,245	1,025	8.4%
	Bakken ND Ext.	Mississippian-Devonian	9,599	736	7.7%
	Bakken MT	Mississippian-Devonian	10,958	422	3.9%
	Three Forks ND	Devonian	9,859	810	8.2%
	Three Forks MT	Devonian	10,415	376	3.6%
Maverick	Eagle Ford Play #3A	Late Cretaceous	22,455	1,827	8.1%
	Eagle Ford Play #3B	Late Cretaceous	25,738	2,328	9.0%
	Eagle Ford Play #4A	Late Cretaceous	45,350	1,895	4.2%
	Eagle Ford Play #4B	Late Cretaceous	34,505	2,007	5.8%
Ft. Worth	Barnett Combo - Core	Mississippian	25,262	377	1.5%
	Barnett Combo - Ext.	Mississippian	13,750	251	1.8%
Permian	Del. Avalon/BS (NM)	Permian	34,976	648	1.9%
	Del. Avalon/BS (TX)	Permian	27,354	580	2.1%
	Del. Wolfcamp (TX Core)	Permian-Pennsylvanian	35,390	1,193	3.4%
	Del. Wolfcamp (TX Ext.)	Permian-Pennsylvanian	27,683	372	1.3%
	Del. Wolfcamp (NM Ext.)	Permian-Pennsylvanian	21,485	506	2.4%
	Midl. Wolfcamp Core	Permian-Pennsylvanian	53,304	1,012	1.9%
	Midl. Wolfcamp Ext.	Permian-Pennsylvanian	46,767	756	1.6%
	Midl. Cline Shale	Pennsylvanian	32,148	892	2.8%

ARI/AEO, 2013

Shale Well Production Economic Model

- Well spacing/design typically based on spacing patterns that yield the highest NPV.
- Coupling data-driven predictive model with cash flow model enables economic evaluation of well/pad/lease optimization.
- Enables comparison of improving recovery (DOE mission) vs. maximizing profitability/NPV (Industry mission).



Influencing Factors

- Well spacing and SRV.
- Well interference.
- Over-capitalized field development.
- Economic vs. technically recoverable.

Parameter Overview by Well Vintage

Average Values

Parameter	Unit	Well First Production Year										Percentage Change Min to Max
		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	
Perforated lateral length	foot	2,712	2,258	2,821	3,313	3,441	4,090	4,712	5,555	6,098	6,612	193%
Water used for hydraulic fracturing	bbl/1,000 foot perforated	NA	NA	27,824	34,573	33,317	29,529	35,939	41,853	39,685	42,983	54%
Proppant used for hydraulic fracturing	pound/foot perforated	NA	NA	1,251	444	672	1,127	1,521	1,733	1,711	1,975	345%
Additive used for hydraulic fracturing	pound/foot perforated	15	25	72	58	63	81	61	99	66	143	850%
Well azimuth trajectory*	degree	139	139	128	132	131	137	139	140	138	140	10%
Well spacing	foot	601	2,709	1,617	1,360	1,083	1,251	1,283	1,167	1,313	1,328	351%
GOR cumulative at 12 months	mcf/bbl	4,445	2,401	2,870	3,793	4,397	3,773	3,763	3,650	4,729	7,272	203%
True vertical depth	foot	7,088	6,799	7,528	7,868	7,768	7,435	7,469	7,494	7,588	7,804	16%
Thickness	foot	30	29	28	28	29	29	28	29	29	29	7%
Gamma ray	API	261	259	268	268	271	265	270	276	271	273	7%
Thermal maturity	% R_0	1.5305	1.5304	1.6007	1.6373	1.6305	1.5708	1.5894	1.5964	1.6238	1.6555	8%

Predictive Models for 12-mo Productivity

Comparative Analysis

		Team KeyLogic	MIT [1]	BEG UT Austin [2, 3]
Technology		Perforated Lateral Length, Proppant, Fluid (Water), Pad Drilled, Well Spacing	Lateral Length, Fluid (Water), Proppant	Well Location, Lateral Length, Proppant, Fluid (Water)
Geology		Thickness, VR, Gamma Ray, Depth, Location	Location	OGIP, Thickness, Porosity, Gravity, Pressure
Algorithm		Kernel Ridge	Regression-Kriging	Tree Regression, Random Forest, Model Based Recursive Partitioning (MBRP)
Prediction		12 Month Cumulative Gas	12 Month Cumulative Gas	12 Month Cumulative Gas, EUR
Scores	MASE	0.28 (Lower the Better)	0.62	---
	R^2	0.83 (Higher the Better)	---	0.68-0.72 [3]
Key Take Aways		• Using a comprehensive geology data set instead of location data (latitude and longitude) will provide more accurate production outlooks • Initial results suggested that well completion designs can still be optimized to improve the overall production	• RK modelling can be used to develop supply curves for different economic scenarios or optimize design parameters at different well locations • To prevent overly optimistic potential well production projections, the chosen modeling method must consider the influence of location	• Lateral length does not significantly affect recovery factor • Completion type and well spacing were revealed to be the most significant factors affecting productivity • Recovery factor can be increased in the low to mid productivity range

[1] Montgomery and O'Sullivan, Spatial variability of tight oil well productivity and the impact of technology, *Applied Energy* 195 (2017)

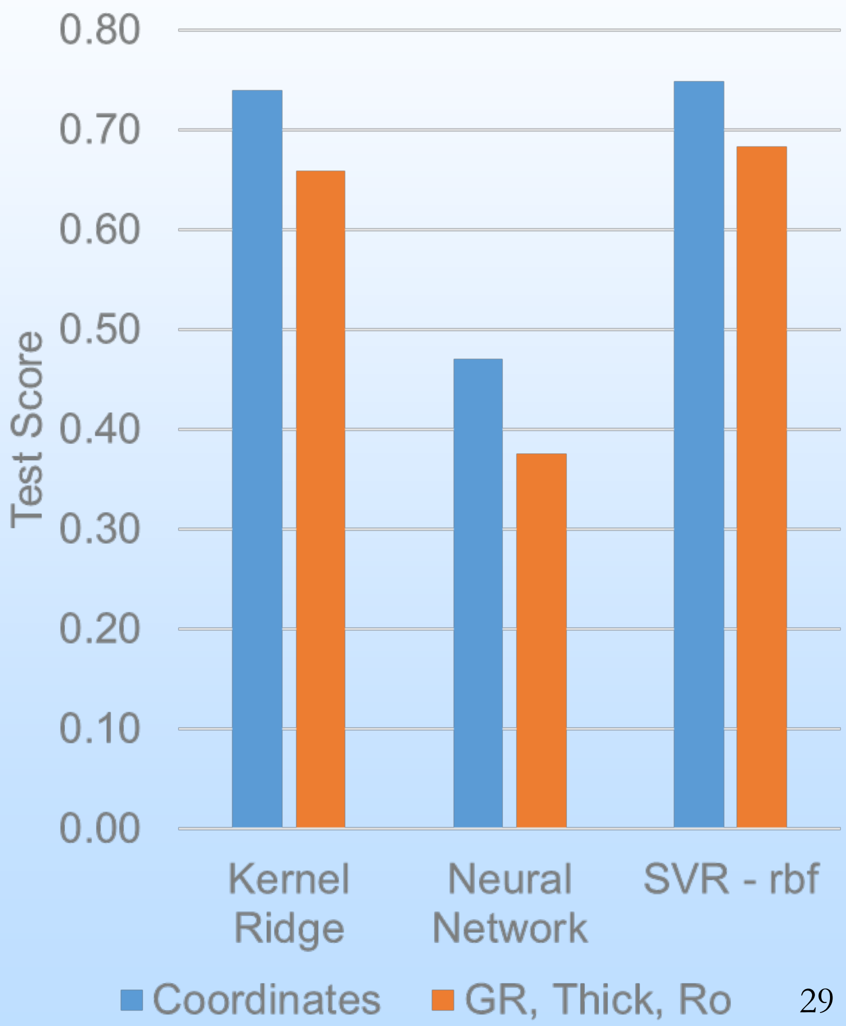
[2] Ikonnikova, S., Vankov, E., Gülen, G., Browning, J., "Understanding Shale Resource Production: What are the Key Variables?" presented at *SPE/IAEE Hydrocarbon Economics and Evaluation Symposium,* Houston, Texas, United States, 2016.

[3] Ikonnikova, S., Vankov, E., Smye, K., Browning, J., Gülen, G., Tinker, S., McDaid, G., Scanlon, B., "Evolution of Shale Oil and Gas Drilling Technology and its Implications," *Bureau of Economic Geology (BEG), The University of Texas at Austin*, Houston, Texas, United States, 2018 (Draft).

Geology

Differences Between Coordinates and Geology (gamma ray, thickness, R_o)

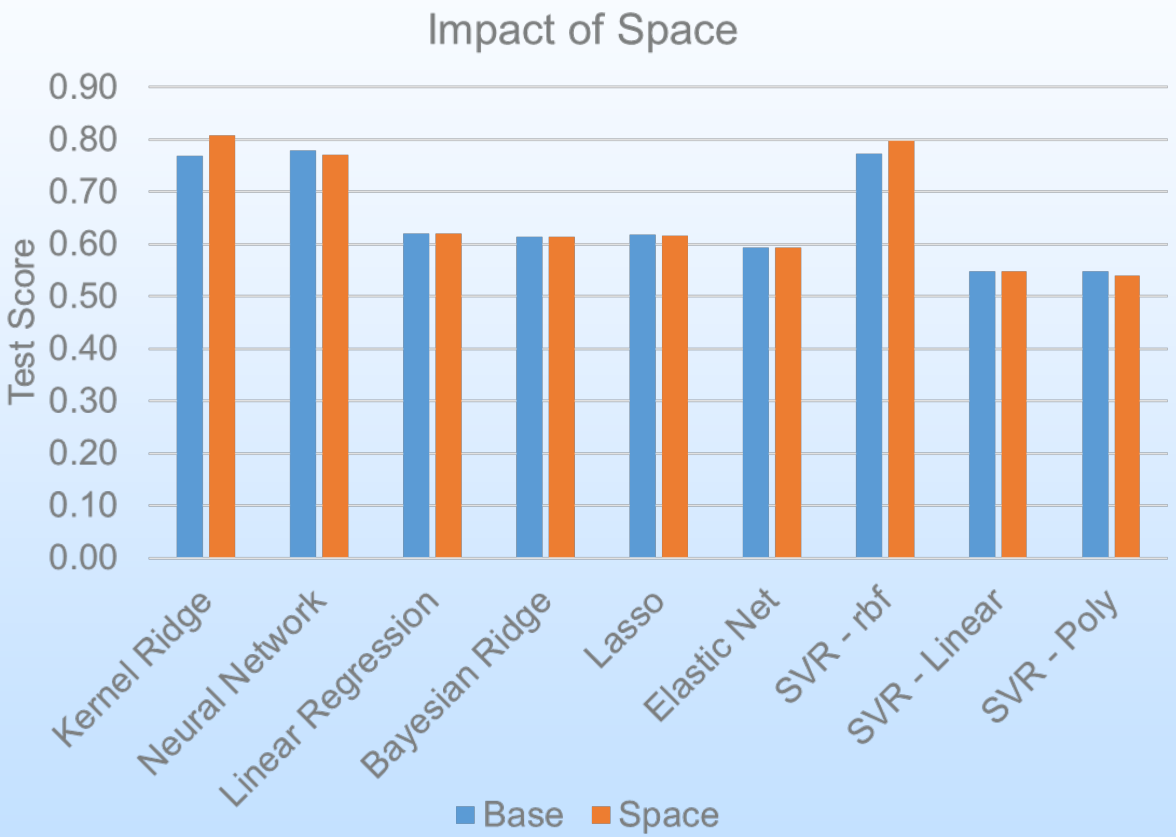
- **Algorithms trained exclusively with either (1) spatial coordinates, or (2) GR, thickness, and R_o.**
- **Production varies spatially, likely due to changes in geologic quality.**
  - Most studies use coordinates (lat/long) as a proxy for geology.
  - For this study, the geologic assessment enabled extrapolation of geologic parameters to entire study area.
  - Extrapolation imposes less certainty than explicit well-specific measurements.
- **Results indicate that geologic parameters acquired (despite extrapolation) have similar test score trend as using coordinates.**



Effect of Spacing

"Distance to Nearest Well" and "Pad Drill"

- **Accuracy remains after removing both spacing related parameters.**
  - It is known that wells can interfere when drilling too close to each other.
- **Possible conclusions:**
  - Noisy data about well spacing (i.e., not accurately reflecting well spacing).
  - Wells in the dataset are at spacings that are not causing interference or "frac hits."
- **R&D Pursuit: Evaluation of optimal spacing in Marcellus to maximize production and improve RF.**
  - Parent/Child well impacts.



Note: This baseline does not include coordinates and azimuth

Desired Datasets

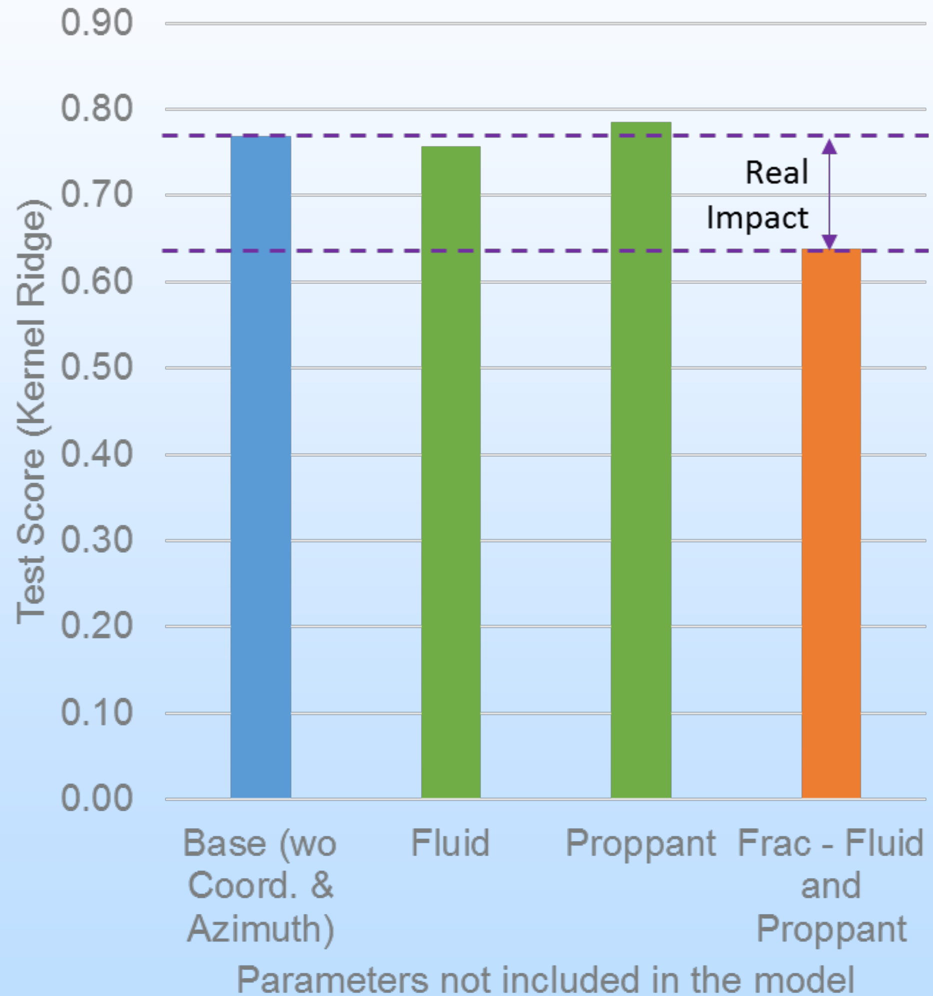
- **Only partial understanding can be attained from publicly available data/information alone.**
  - State reporting requirements strongly influence data availability and quality across plays.
- **Expanded datasets would enable for refined models, and enable better determination of parameters influencing production.**
- **Desired datasets:**
  - Well logs (i.e., .las files)
  - Completion-related information (i.e. stage count, total perforations, and pressures)
  - Additive type, proppant size and type
  - Well orientation (toe-up vs. toe down; % in zone)
  - Pre-stimulation pay-zone pore pressures
  - Lateral trajectory data
  - Geochemical and geophysical data
  - Natural fracture extent
  - Others…

Methods to Determining R&D Needs

Parameter Impact Assessment

Requires Various Approaches to Extract Actual Parametric Impact

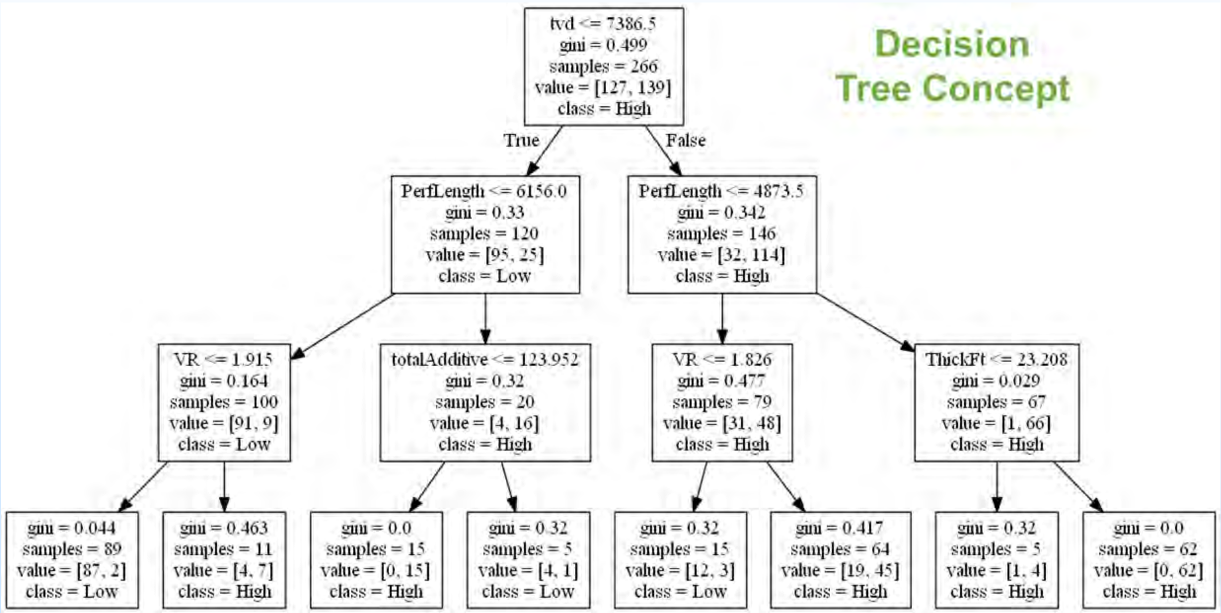
- **Removing Fluid or Proppant alone does not show significant impact to the overall accuracy.**
- **However, removing both parameters shows the real impact of fracture fluid and proppant.**
- **This problem is non-linear and certain parameters are likely collinear and/or have high degree interaction.**
- **Simple one-at-a-time sensitivity tests not suitable for identifying the parameter importance.**
  - Monte-Carlo variance-based approach.
  - Sobol total index approach
  - Decision tree analysis.



Decision Tree Analysis

Exploration of Parameters that Contribute to “Extreme” Well Performance

- **Dataset with low and high performing wells.**
  - <25th percentile (low) and >75th percentile (high).
- **Used key features to “classify” wells.**
- **Preliminary results show that:**



TVD	Perf. length	Thickness	VR		Well quality
Low	Low		Low	➡	Low
High	High	High			High

- All left branches at each node = True, all right branches at each node = False.
- gini is a ‘score’ for each node (zero when all cases in a node are classified into a single category).
- Value represents number of samples classified into each category [Low, High].

Literature Review

Machine Learning for Unconventional Oil and Gas Applications

Study	Region	Methods	Data used	Key parameters/ findings
Zhou et al	West Virginia	Multiple linear regression, principal components analysis and k-means	Fracture fluid, proppant, true vertical depth (TVD) , lateral length (LL), stages, treatment rate, thermal maturity (TM), thickness	Stages, lateral length
Izadi et al	Bakken	Multiple linear regression, boosted tree models	well location, LL, azimuth, stages, fracturing fluid, proppant type and volumes	Well location, proppant quantity
Schuetter et al	Wolfcamp shale	R^2-loss for model selection, decision trees	Latitude and longitude, TVD, LL, proppant quantity and concentration, stages	TVD, proppant quantity, LL
Montgomery and O'Sullivan	Williston Basin	Multiple linear regression, fixed-effects regression, kriging	Latitude and longitude, LL, water, proppant volumes	Location data,
Mohaghegh et al	Marcellus	Neural networks, Monte Carlo simulation, optimization	TVD, thickness, porosity, TOC, LL , clusters per stage, clean volume, proppant quantity per ft LL	Net thickness, well spacing, LL,
Mishra et al	Literature review	Decision trees, gradient boosting machine, support vector machine, neural networks, kriging	1) cross-validation typically not been done in O&G studies 2) most studies analyze only a handful of regression models 3) these studies typically ignore records with missing data points 4) they do not typically evaluate relative variable importance.	