CO2 Pipeline Cost Analysis Utilizing a Modified FE/NETL CO2 Transport Cost Model Tool

Martin K. Dubois[1], Dane McFarlane[2], Tandis S. Bidgoli[3]

1 - Martin K. Dubois, Improved Hydrocarbon, LLC (Joint PI, Integrated CCS for Kansas, DE-FE0029474)

2 - Dane McFarland, Great Plains Institute

3 – Kansas Geological Survey (PI, Integrated CCS for Kansas)

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Abstract

Costs and specifications for multiple large-scale CO2 pipeline scenarios were derived using a modified FE/NETL CO2 Transport Cost Model (Grant and Morgan, 2014). Transportation analysis is a component of a Phase I CarbonSAFE project, Integrated CCS for Kansas (ICKan), administered by the Kansas Geological Survey. One plan evaluated is gathering 10.9 million tonnes/yr (MT/yr) CO2 from 32 Midwest ethanol plants, combining it with 2.5 MT/yr CO2 from a Kansas coal-fired power plant, and transporting the CO2 to a saline aquifer site for CCS and to CO2 enhanced oil recovery markets in Kansas, Oklahoma and Texas. Economies of scale would reduce transportation costs for both, especially critical for the CCS project.

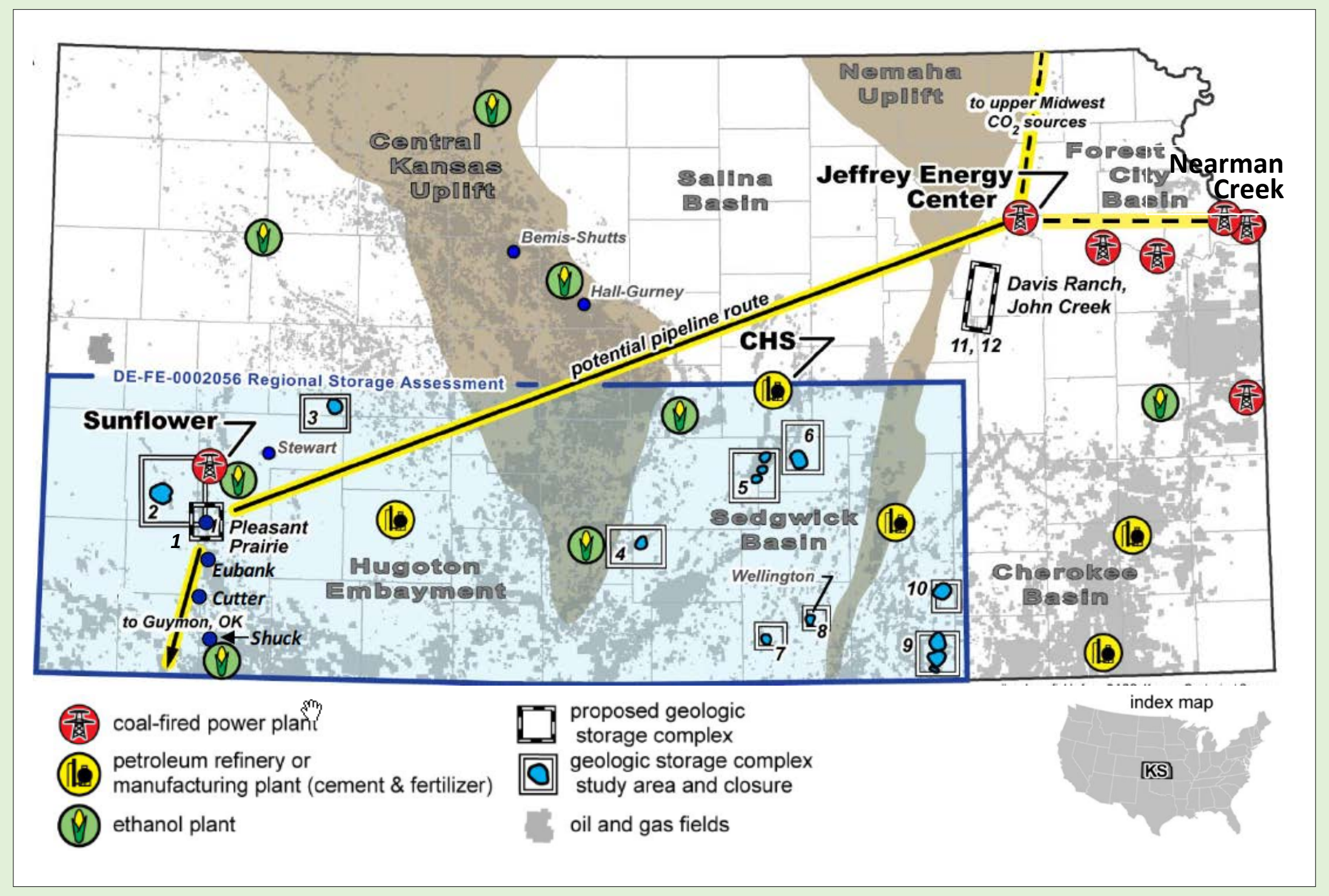
For a single point to point pipeline, the NETL Cost Model takes inputs, including length, CO2 capacity, pressure, project financing, and other parameters, and calculates capital and operating costs, and technical specifications such as pipeline diameter and pumping stations required. Calculations are by spreadsheet formulas and Excel VBA functions. The model was modified to evaluate multiple segments of a complex gathering and transportation system in one operation. Without changing or modifying the NETL spreadsheets or VBA code, a VBA macro was added that collects input parameters from a list of pipeline segments and calculates and records model outputs for each segment.

Modifications of the FE/NETL CO2 Transport Cost Model are discussed and the analyses of several CO2 pipeline scenarios are presented. The modified tool provides efficient high-level analysis of complex infrastructure required for large-scale CO2 transportation from multiple sources.

Integrated CCS for Kansas

Goals & Objectives

1. Identify and address major technical and nontechnical challenges of implementing CO_2 capture and transport and establishing secure geologic storage for CO_2 in Kansas
2. Evaluate and develop a plan and strategy to address the challenges and opportunities for commercial-scale CCS in Kansas



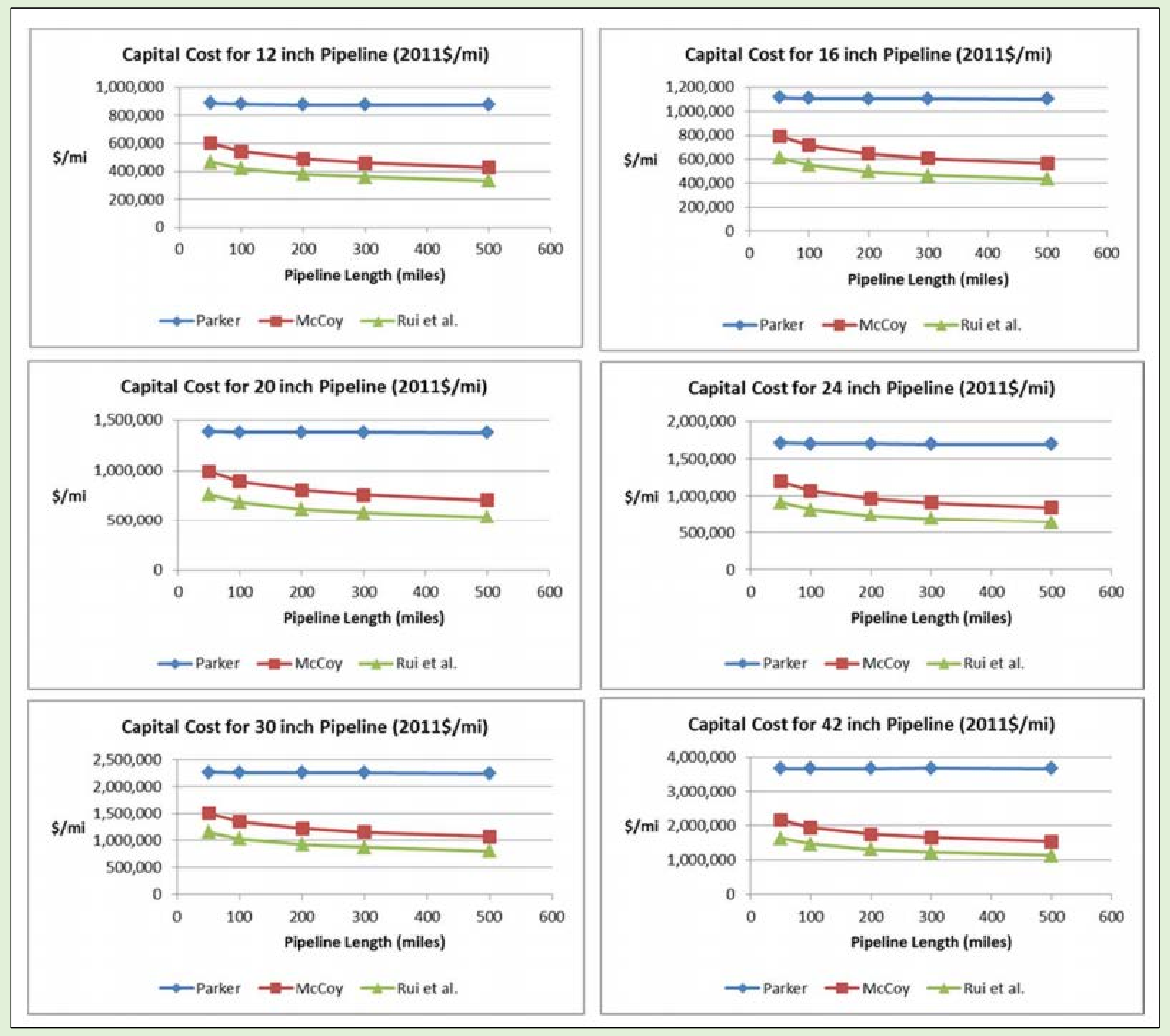
Base Case Scenario

1. Capture 50 million tonnes CO_2 from one of three Jeffrey Energy Center's 800 MWe plants over a 20 year period (2.5Mt/yr)
2. Compress CO_2 and transport 300 miles to Pleasant Prairie Field in SW Kansas for storage in saline aquifer below oil zones
   - Alternative: 50 miles to Davis Ranch and John Creek Fields.
3. ***Evaluate transport cost savings through scaling by combining with transportation infrastructure for CO2 from Ethanol in Upper Midwest***

FE/NETL Transport Cost Model

Why use the FE/NETL Transport Cost Model?

- **Needed an efficient tool** to evaluate multiple pipeline scenarios in a high-level review of transportation options.
- The Morgan and Grant (2014) cost model is well-documented and thoughtfully applies publicly available costing data and equations from reliable, peer-reviewed sources.
- The **Cost Model was easily adapted** to our needs for evaluating capital and operating costs for **multiple pipeline segments** by creating additional Excel VBA macro functionality to interact with the NETL cost model.



Pipeline cost estimates by diameter in 2011$/mi. Parker (2004), **used in Cost Model** give highest pipeline capital costs followed by McCoy and Rubin (2008) and Rui et al. (2011).

FE/NETL Stated Objectives:

- Develop a mathematical model that estimates the costs of transporting liquid CO2 using a pipeline – **Point to point** pipeline (Engineering model)
- Model calculates break-even first year CO2 price for transporting CO2 (Financial Model)

Engineering model

- **User specifies** length, CO2 volume/yr, pipeline capacity factor, input and outlet pressure, and change in elevation. User can specify the number of booster stations.
- **Outputs:** minimum and nominal pipeline diameter, capital costs by category (materials, labor, misc., surge tanks, control systems, booster pumps), and operating costs (pipeline O&M, equipment and pumps O&M, and electrical costs).

Financial model *(financial model not used in study)*

- **User specifies:** start year (2011), length of construction period (3 years) and length of operations (30 years)
- **User specifies** financial parameters: debt/equity ratio (45%/55%), cost of debt (5.5%/yr), desired rate of return on equity (12%/yr), escalation rate (3%/yr), tax rate (38%), project contingency (15%) depreciation method
- **Output:** Model generates cash flow of revenues and calculates break-even first year CO2 price

Modifications to Cost Model

For calculating many pipeline network segment costs in one operation, created additional Excel VBA macro functionality to interact with the NETL cost model without modifications to the NETL spreadsheets or VBA code.

- Added a **new worksheet** to the Cost Model workbook **(see Poster Panel 2)** with columns for user input parameters and cost model output
- **Created a VBA macro** that collects inputs from a list of pipeline segments copied into the new worksheet.
- Changed binning on pipe diameters so minimum nominal size 4"
- New macro inputs the parameters for each segment to the Cost Model.
- Records model outputs for each segment individually in the new worksheet.

Model inputs and outputs

Inputs (by segment)	**Outputs (by segment)**
length (miles)	minimum pipeline ID (inches)
number of booster pumps	pipeline nominal diameter (inches)
annual CO2 transport (Mt/yr)	materials costs
capacity factor	labor costs
input pressure (psig)	ROW-damage costs
output pressure (psig)	miscellaneous costs
change in elevation (feet)	CO2 surge tanks costs
	pipeline control system costs
	pump costs
	Total capital cost
	pipeline O&M
	other equipment and pumps O&M
	electricity costs for pumps
	Total annual operating expenses

Additional Work

Changes to improve the model:

- **Update to current dollars**. The Cost Model reports in 2011 dollars.
- **Surge tank cost** and application needs to be better understood and possible modifications applied. In the current model, a single surge tank at a set cost is applied for each pipeline segment.
- The **control system cost** is a single flat rate per pipeline segment, and is rather low. This needs to be modified.
- Need to add an **additional booster pump** at the end of each segment that joins another segment. Current model is a point-to-point pipeline with the downstream ending at an injection well rather than needing to be boosted to pipeline pressure.
- Comparison with detailed costs from "real-life" examples could guide other improvements.

References

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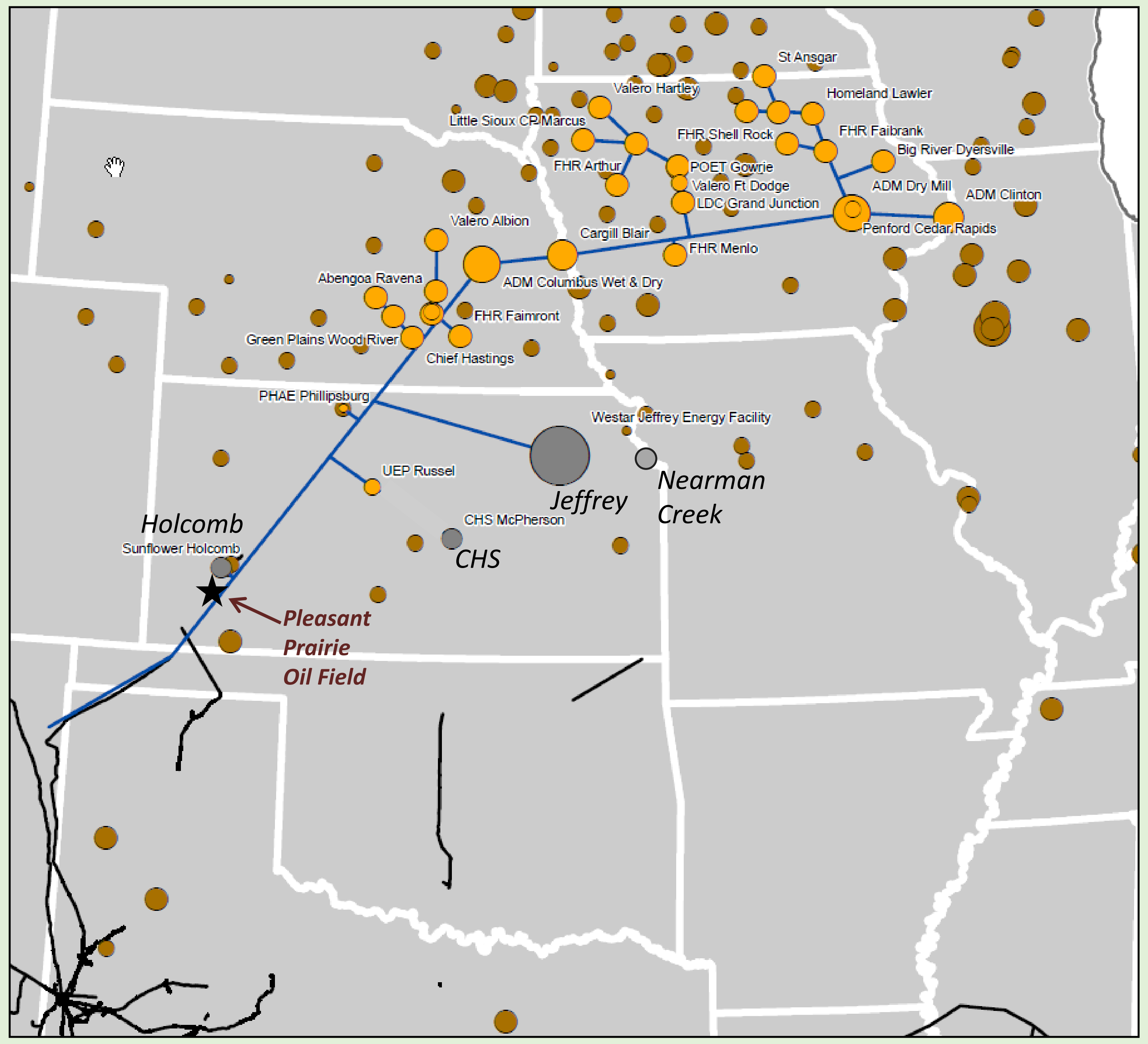
Contacts

Dubois – mdubois@ihr-llc.com
McFarlane - dmcfarlane@gpisd.net
Bidgoli - tbidgoli@kgs.ku.edu

CO2 Volumes and Network Design



Large-scale gathering and transportation system connecting 32 ethanol plants and delivering CO2 to Kansas, Oklahoma and Texas. Bubbles are sized according to CO2 volume. Ethanol plants are yellow (in the evaluated scenario) and brown (not in the scenario). Gray circles are ICKan industry partners, one of which is shown to be connected under this scenario. Pleasant Prairie is one of the storage sites considered in the project. Black line segments are existing CO2 pipeline infrastructure.

Work Flow

1. Ethanol production data for Midwest facilities from US Dept. of Energy, EIA, 2017
2. The volume of CO2 calculated at a rate of 6.624 lbs. CO2/gallon ethanol (Dubois et al., 2002).
3. Import Ethanol plant data to ArcGIS. Choose ethanol plants to tine into system.
4. Selection criterion: Larger ethanol plants, distance, and contacts made by Eric Mork, EBR Development LLC, a collaborator on the ethanol pipeline option.
5. Obtain distances for segments from ArcGIS and build the input file for the modified FE/NETL Cost Model.
6. Run model and optimize for capital cost (mainly nominal pipe diameter) and operating costs by varying:
   - Pressure drop from input to output
   - Number of booster stations
7. Include industry partner sources in some scenarios

Company	Ethanol Plant	State	Ethanol Capacity (MGPY)	CO2 output (Tonne/yr)
ABSOLUTE ENERGY	ST ANSGAR	IA	110	330,449
ADM	CEDAR RAPIDS DRY MILL	IA	300	901,224
ADM	CLINTON	IA	237	711,967
BIG RIVER UNITED	DYERSVILLE	IA	100	300,408
CARGILL INC	FORT DODGE	IA	113	339,461
FLINT HILLS	FAIRBANK	IA	100	300,408
FLINT HILLS	ARTHUR	IA	100	300,408
FLINT HILLS	MENLO	IA	100	300,408
FLINT HILLS	SHELL ROCK	IA	100	300,408
FRONTIER	GOWRIE	IA	60	180,244
GOLDEN GRAIN	MASON CITY	IA	107	321,436
HOMELAND ENERGY	LAWLER	IA	100	300,408
LITTLE SIOUX	MARCUS	IA	92	276,375
LOUIS DREYFUS	GRAND JUNCTION	IA	100	300,408
PENFORD PRODUCTS	CEDAR RAPIDS	IA	45	135,183
VALERO	ALBERT CITY	IA	110	330,449
VALERO	CHARLES CITY	IA	110	330,449
VALERO	FORT DODGE	IA	110	330,449
VALERO	HARTLEY	IA	110	330,449
PRAIRIE HORIZON	PHILLIPSBURG	KS	40	120,163
US ENERGY PARTNERS	RUSSELL	KS	55	165,224
ABENGOA BIOENERGY	RAVENNA	NE	88	264,359
ADM	COLUMBUS DRY MILL	NE	313	940,277
ADM	COLUMBUS WET MILL	NE	100	300,408
AVENTINE	AURORA WEST	NE	108	324,440
CARGILL	BLAIR	NE	210	630,857
CHIEF ETHANOL	HASTINGS	NE	70	210,285
FLINT HILLS	FAIRMONT	NE	100	300,408
GREEN PLAINS	CENTRAL CITY	NE	100	300,408
GREEN PLAINS	WOOD RIVER	NE	110	330,449
NEBRASKA ENERGY	AURORA	NE	45	135,183
VALERO	ALBION	NE	100	300,408
		Total from Ethanol		***10,943,860***

Thirty-two ethanol plants considered in a large-scale CO2 gathering system. The abbreviation MGPY is million gallons per year.

	Mwe	Approx. CO2 Emitted (Mt/yr)	Est. Vol. Available (Mt/yr)
Jeffrey Energy Center	2400	12.5	2.5
Dearman Creek	261	1.2	?
Holcomb Station	350	1.8	?
CHS refinery	NA	1.4	0.76

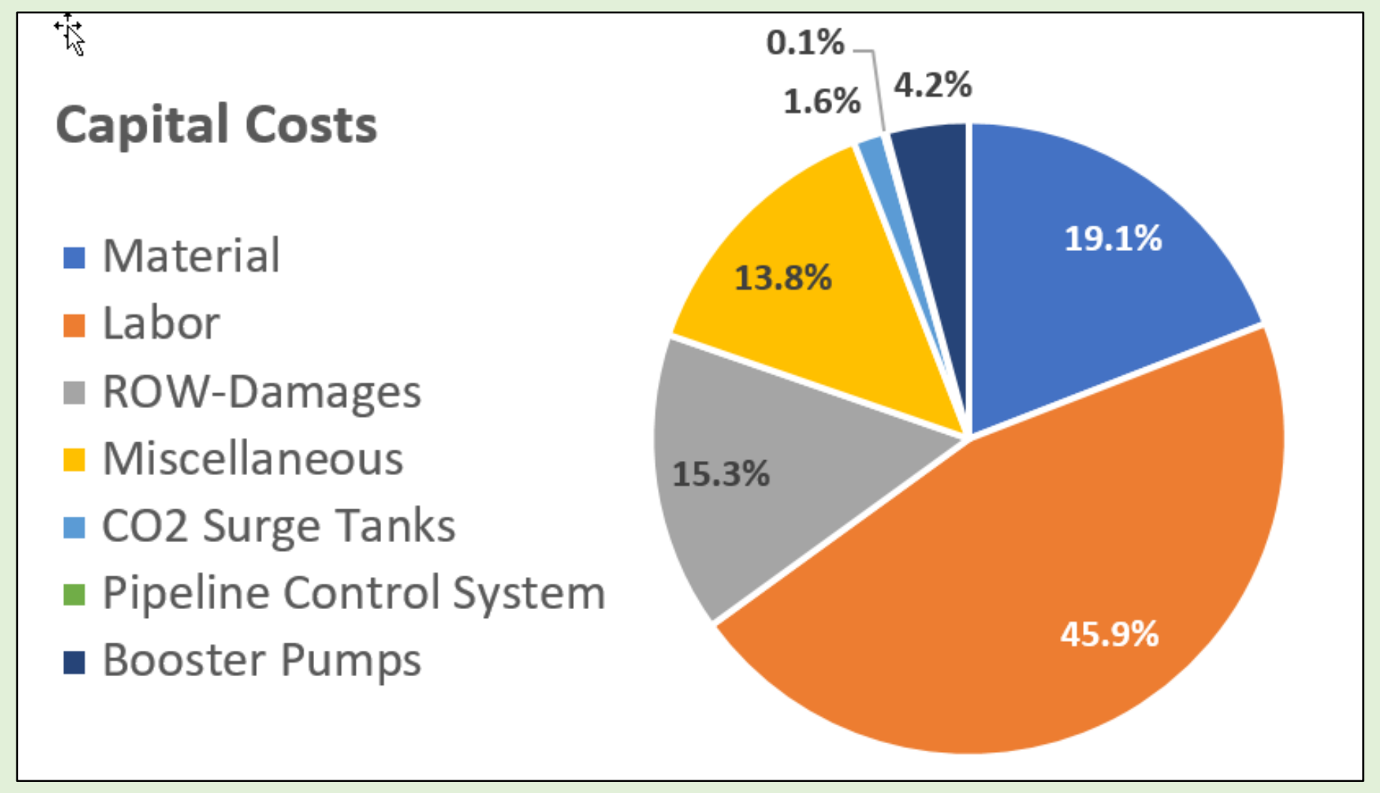
Industry partner CO2 source data. Abbreviations include Mwe – megawatt electric and MT/yr – million tonnes/year.

Model Inputs and Outputs

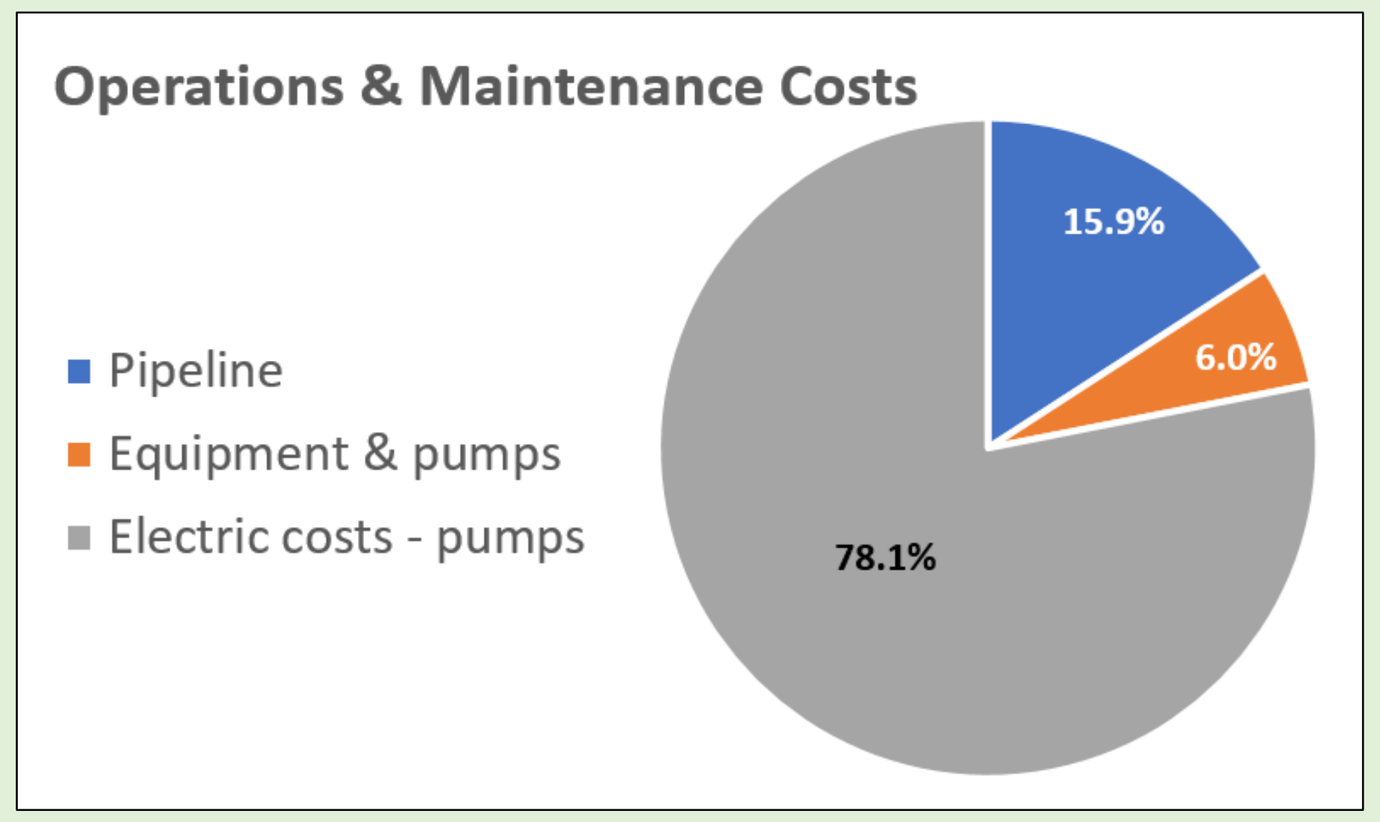
INPUTS								OUTPUTS													
								Pipeline Diam.		Capital Cost								Annual O&M Cost			
Segment ID	Length (X1.2)	# of Pumps	Annual CO2	Capacity factor	Input Pressure	Outlet Pressure	Change in Elev.	Minimum Pipeline Inner Diameter	Pipeline Nominal Diameter	Material	Labor	ROW-Damages	Miscellaneous	CO2 Surge Tanks	Pipeline Control system	Pumps	Total Capital	Pipeline O&M	Pipeline related equipment and pumps	Electricity costs for pumps	Total annual operating expenses
#	mi	#	MT/yr	dec.	psig	psig	ft	in	in	$M	$M	$M	$M	$M	$M	$M	$M	$K	$K	$K	$K
20	44.6	2	1.24	0.8	2200	1600	0	7.0	8	$4.9	$19.1	$3.9	$5.3	$1.2	$0.11	$0.93	$35.5	$378	$92	$413	$883
13	47.8	2	0.30	0.8	2200	1600	0	4.1	6	$4.2	$19.1	$3.1	$4.5	$1.2	$0.11	$0.35	$32.6	$405	$68	$100	$573
16	43.0	2	0.30	0.8	2200	1600	0	4.0	6	$3.8	$17.2	$2.8	$4.0	$1.2	$0.11	$0.35	$29.6	$364	$68	$100	$533
26	0.7	1	0.14	0.8	2200	1600	0	1.5	4	$0.1	$0.6	$0.1	$0.2	$1.2	$0.11	$0.13	$2.5	$6	$59	$23	$88
11	8.6	1	1.06	0.8	2200	1600	0	5.2	6	$0.8	$3.7	$0.6	$0.9	$1.2	$0.11	$0.41	$7.8	$73	$71	$177	$320
27	3.5	1	0.14	0.8	2200	1600	0	2.0	4	$0.3	$1.7	$0.2	$0.4	$1.2	$0.11	$0.13	$4.1	$30	$59	$23	$112
12	21.5	1	0.60	0.8	2200	1600	0	5.0	6	$1.9	$8.8	$1.4	$2.1	$1.2	$0.11	$0.27	$15.9	$182	$65	$100	$347
23	31.9	2	0.98	0.8	2200	1600	0	6.0	6	$2.8	$12.9	$2.1	$3.0	$1.2	$0.11	$0.77	$23.0	$270	$85	$328	$683
30	46.1	2	0.30	0.8	2200	1600	0	4.1	6	$4.1	$18.4	$3.0	$4.3	$1.2	$0.11	$0.35	$31.5	$391	$68	$100	$559
29	63.0	2	2.18	0.8	2200	1600	0	9.3	12	$10.6	$31.3	$9.2	$10.8	$1.2	$0.11	$1.51	$64.7	$534	$115	$729	$1,378
3	25.6	1	0.30	0.8	2200	1600	0	3.9	4	$1.9	$9.8	$1.3	$1.8	$1.2	$0.11	$0.18	$16.4	$217	$61	$50	$328
31	0.6	1	0.34	0.8	2200	1600	0	2.0	4	$0.1	$0.6	$0.1	$0.2	$1.2	$0.11	$0.19	$2.5	$5	$62	$57	$123
15	15.5	1	1.91	0.8	2200	1600	0	7.3	8	$1.7	$6.9	$1.4	$2.0	$1.2	$0.11	$0.67	$14.0	$132	$81	$318	$531
14	18.7	1	2.09	0.8	2200	1600	0	7.8	8	$2.1	$8.2	$1.6	$2.3	$1.2	$0.11	$0.73	$16.3	$158	$83	$348	$590
5	32.6	2	2.39	0.8	2200	1600	0	8.4	12	$5.5	$16.4	$4.8	$5.7	$1.2	$0.11	$1.64	$35.4	$277	$120	$797	$1,194
7	48.0	2	0.33	0.8	2200	1600	0	4.3	6	$4.2	$19.2	$3.2	$4.5	$1.2	$0.11	$0.37	$32.8	$407	$69	$110	$586
8	8.8	1	0.81	0.8	2200	1600	0	4.7	6	$0.8	$3.8	$0.6	$0.9	$1.2	$0.11	$0.33	$7.9	$75	$68	$134	$276
22	37.1	2	1.25	0.8	2200	1600	0	6.8	8	$4.1	$15.9	$3.2	$4.5	$1.2	$0.11	$0.94	$30.0	$314	$92	$418	$824
6	49.8	2	0.28	0.8	2200	1600	0	4.0	6	$4.4	$19.9	$3.3	$4.6	$1.2	$0.11	$0.34	$33.9	$422	$68	$92	$582
24	29.5	1	0.32	0.8	2200	1600	0	4.2	6	$2.6	$11.9	$2.0	$2.8	$1.2	$0.11	$0.18	$20.8	$250	$62	$54	$365
4	14.7	1	0.30	0.8	2200	1600	0	3.5	4	$1.1	$5.8	$0.8	$1.1	$1.2	$0.11	$0.18	$10.3	$124	$61	$50	$236
1	17.9	1	0.12	0.8	2200	1600	0	2.6	4	$1.3	$7.0	$0.9	$1.3	$1.2	$0.11	$0.12	$12.1	$152	$59	$20	$231
10	24.0	1	0.26	0.8	2200	1600	0	3.7	4	$1.8	$9.2	$1.3	$1.7	$1.2	$0.11	$0.17	$15.4	$203	$61	$44	$308
2	48.9	2	0.17	0.8	2200	1600	0	3.3	4	$3.5	$18.4	$2.5	$3.3	$1.2	$0.11	$0.27	$29.3	$414	$65	$55	$534
21	36.4	2	0.30	0.8	2200	1600	0	3.9	4	$2.6	$13.8	$1.9	$2.5	$1.2	$0.11	$0.35	$22.5	$309	$68	$100	$478
25	35.6	2	0.33	0.8	2200	1600	0	4.0	6	$3.2	$14.3	$2.4	$3.4	$1.2	$0.11	$0.37	$24.9	$302	$69	$110	$482
17	466.9	15	13.44	0.8	2200	1600	0	19.9	24	$274.6	$490.4	$217.0	$152.7	$1.2	$0.11	$63.47	$1,199.4	$3,958	$2,593	$33,657	$40,208
18	75.4	3	7.25	0.8	2200	1600	0	14.4	16	$20.9	$49.8	$17.2	$16.9	$1.2	$0.11	$6.96	$113.1	$639	$333	$3,631	$4,603
19	272.4	9	6.62	0.8	2200	1600	0	14.9	16	$75.3	$179.0	$62.1	$60.5	$1.2	$0.11	$19.14	$397.4	$2,309	$820	$9,945	$13,074
28	91.0	3	0.71	0.8	2200	1600	0	6.1	8	$9.9	$38.5	$7.8	$10.7	$1.2	$0.11	$0.91	$69.3	$771	$91	$356	$1,218
0	180.7	5	2.50	0.8	2200	1600	0	10.5	12	$30.2	$89.2	$26.2	$30.7	$1.2	$0.11	$4.27	$181.9	$1,532	$225	$2,086	$3,843
9	26.6	1	0.59	0.8	2200	1600	0	5.2	6	$2.4	$10.8	$1.8	$2.5	$1.2	$0.11	$0.27	$19.1	$225	$65	$99	$390
	1867									**$488**	**$1,172**	**$390**	**$352**	**$40**	**$3.6**	**$107**	**$2,552**	**$15,827**	**$6,027**	**$54,628**	**$76,482**
	Total Length (miles)																**Total Capital Costs** *($Millions)*				**Total Operating Costs** *($Thousands)*

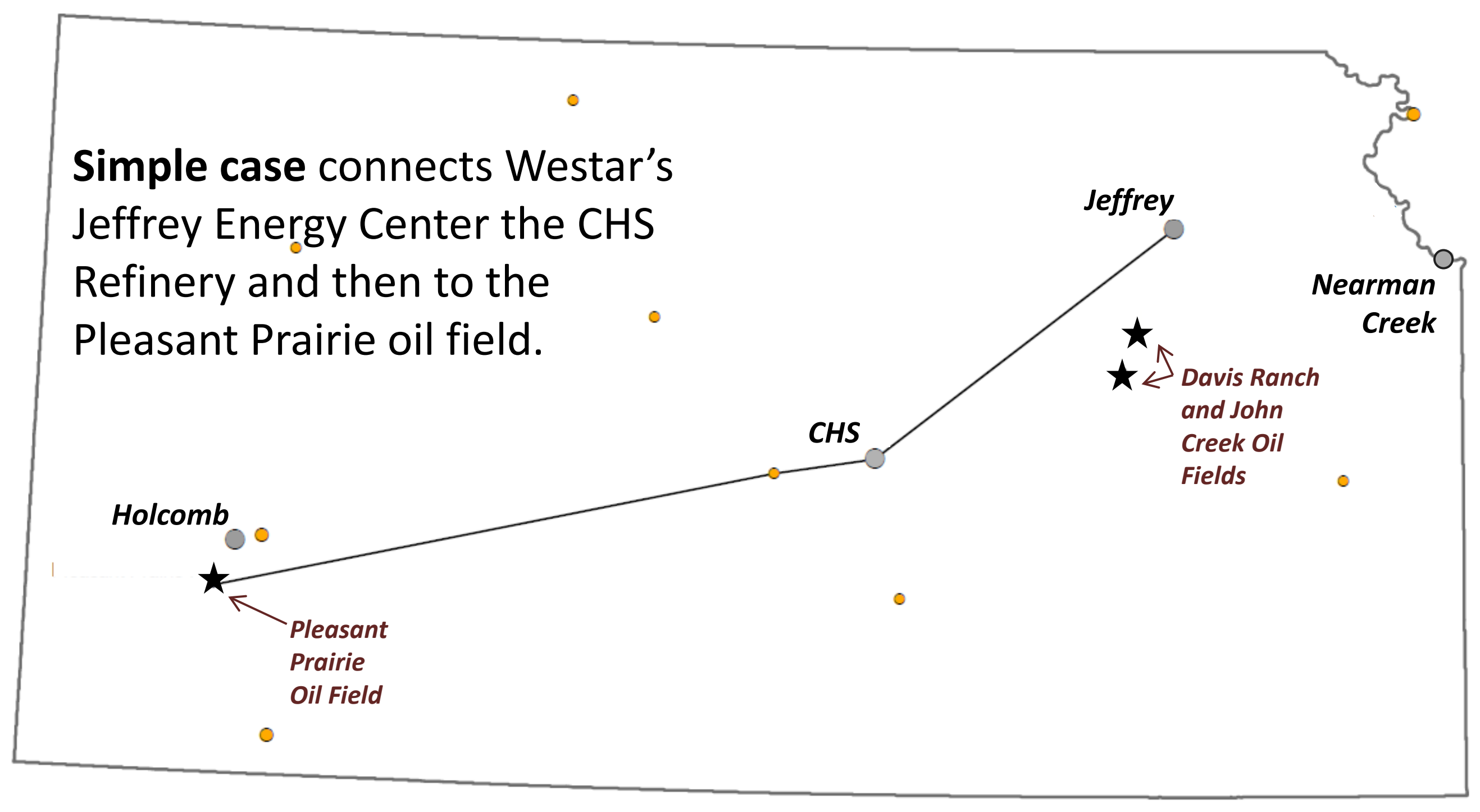
Model input and output data by pipeline segment for case 1, connecting 32 ethanol plants and Jeffrey Energy Center in a large scale pipeline system. Abbreviations include mi – mile, MT/yr – million tonnes/year, dec – decimal, psig – pounds per square inch gauge, ft -feet, in – inch. Costs are in thousands of dollars.

CAPITAL COSTS	
Material	$487.6
Labor	$1,171.8
ROW-Damages	$389.9
Miscellaneous	$352.1
CO2 Surge Tanks	$39.8
Pipeline Control System	$3.6
Booster Pumps	$107.3
Total Capital Costs	$2,552.0



OPERATING EXPENSE	
Pipeline	$15.8
Equipment & pumps	$6.0
Electric costs - pumps	$77.9
Total annual operating expenses	$99.8





Simple case connects Westar's Jeffrey Energy Center the CHS Refinery and then to the Pleasant Prairie oil field.

Results and Discussion

Summary Data for Multiple Pipeline System Cases

(20 years of operations)

	Distance (mi)	CO2 Volume (MT/yr)	Pipeline Size (inches)	CapX ($Million)	Annual OpX ($Million)	CapX $/tonne	OpX $/tonne	Total $/tonne	Total $/mcf
Ethanol gathering + Jeffrey EC	1867	13.44	4"-24"	$2,598	$99.8	$9.67	$7.43	**$17.09**	$0.90
Ethanol gathering only	1686	10.97	4"-20"	$2,127	$86.5	$9.70	$7.89	**$17.58**	$0.93
Jeffrey EC to MidCon Trunk line	181	2.5	12"	$183	$4.3	$3.66	$1.70	**$5.36**	$0.28
Jeffrey EC + CHS to Pleasant Prairie	353	3.25	12"	$365	$12.7	$5.62	$3.90	**$9.51**	$0.50
Jeffrey EC to Pleasant Prairie	353	2.5	12"	$353	$7.1	$7.06	$2.83	**$9.89**	$0.52
Generic large source point-to-point	500	13.44	24"	$1,280	$40.5	$4.76	$3.01	**$7.77**	$0.41
Generic small source point-to-point	300	1.25	8"	$226	$4.9	$9.02	$3.90	**$12.92**	$0.68
CVR to Thrall-Aagard (DEFE-0001942)	80	0.73	8"	$61	$1.0	$4.18	$1.37	**$5.55**	$0.29

Mileage is 1.2X straight-line distance
Costs do not include finance costs and profit margin

Multiple Cases:

1. Ethanol gathering system + Jeffrey Energy Center - large-scale system depicted in the Midcontinent map
2. Ethanol gathering only – same as above but without Jeffrey EC
3. Jeffrey EC to Midcontinent Trunk line – feed to the Ethanol gathering system
4. Jeffrey EC + CHS to Pleasant Prairie storage site – illustrated in Kansas map
5. Generic large source point-to-point – mimic a very large natural CO2 source to market
6. Generic small source point-to-point – mimic a very large ethanol plant to oil field
7. CVR to Thrall-Aagard oil field – proposed pipeline in Integrated Mid-Continent CCS and EOR project, DEFE-0001942 (McPherson et al., 2010)

Discussion:

1. Sensitivity to distance and pipeline size is very evident
2. Jeffrey EC to the trunk line costs are about half what the direct route to the Pleasant Prairie storage site
3. The generic large source, mimics a large natural source, illustrating tough price competition with a disparate small source gathering system
4. Cost for the 80-mile CVR to Thrall-Aagard were estimated by Rooney Engineering at $82.6M in 2010, 35% higher than the cost-model estimate.

More comparisons with actual cost data, especially for small volume, short pipeline segments is needed

- ✓ FE/NETL model cost results compare favorably with two Denbury pipelines carrying 11.2 and 12.6 Mt/yr CO2, 232 and 314 miles respectively. (Morgan and Grant, 2014)
- ✓ FE/NETL model are similar to a 2008 proprietary engineering study for a similar but smaller project than Ethanol CO2 system in this poster.
- ✓ FE/NETL model cost are 35% lower than 2010 engineering study for 80-mile pipeline in Kansas reported in FE0001942 final report.