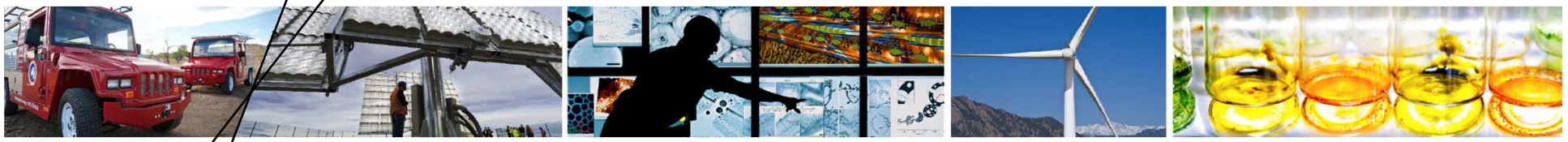
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Techno-economic and Market Analysis of Pathways from Syngas to Fuels and Chemicals



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November 20, 2013

Objective

Assess the economics of producing fuels and chemicals from biomass-derived synthesis gas.

- Process economics based on literature (consistent TEA assumptions)
- Perform more rigorous TEA on promising pathways
  - Biochemical conversion of syngas to ethanol and higher alcohols
  - Ethanol and higher alcohols to infrastructure-compatible hydrocarbons
- Simple product market analyses

What can we do with syngas?

Analysis Approach

- **Simplified TEA model**
- **Inputs from literature sources**
  - Feedstock rate and properties (heating value)
  - Product yields
  - Operating costs (variable & fixed)
  - Capital costs
- **Common scaling assumptions**
  - Capital scaling exponents
  - Economies of scale for fixed operating costs
- **Operating and financing assumptions for n^{th} plant and pioneer plant**
- **Minimum Product Selling Price**

  literature values ➔ average, standard deviation & 90% confidence intervals

n^{th} Plant Assumptions

Parameter	Value
Basis year for analysis	2011
Feedstock processing capacity	2,000 Dry Tonnes / SD
Feedstock cost (woody biomass)	$75 / Dry Ton (€21.60 / MWh)
Debt / equity for plant financing	60% / 40%
Internal rate of return (after-tax) for equity financing	10%
Annual interest rate and term for debt financing	8% / 10 years
Total income tax rate	35%
Plant life	30 years
Plant depreciation schedule	7-year IRS MACRS MACRS = Modified Accelerated Cost Recovery System
Reliability of operations / on-stream factor	0.90
Site development costs	4% of ISBL Installed Capital
Working capital	5% of Fixed Capital Investment
Indirect costs for capital project	60% of Total Direct Costs
Capital equipment capacity scaling exponent	0.70

n^{th} Plant Assumptions

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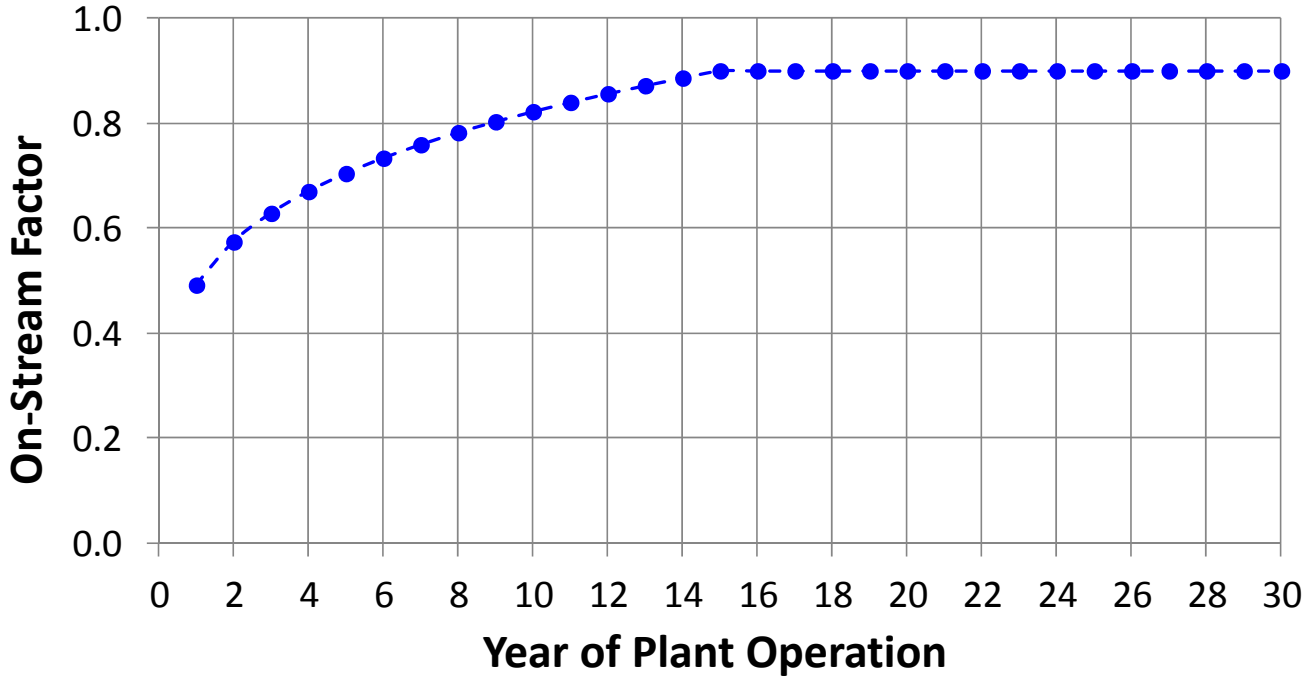
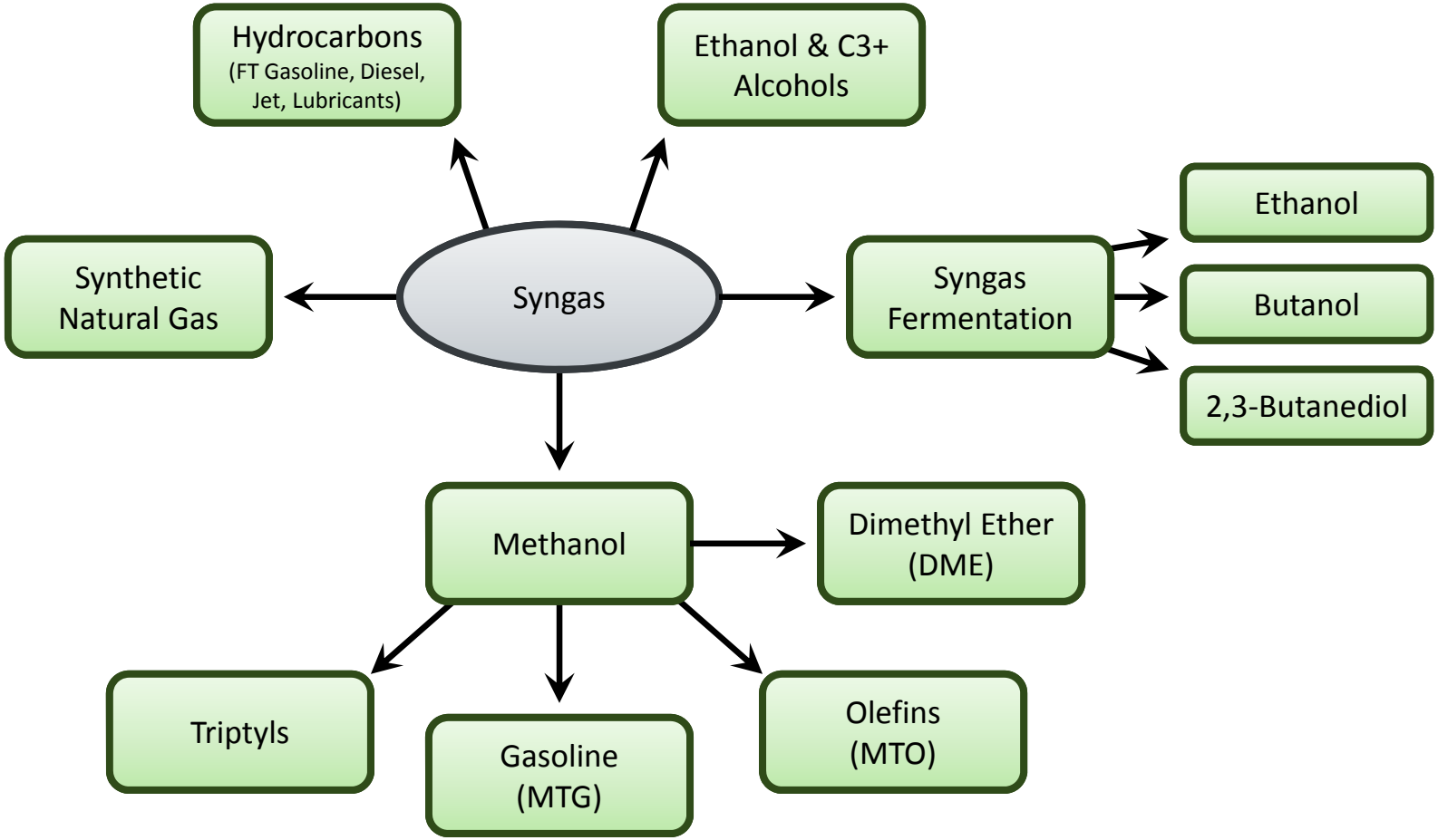
Pioneer Plant Assumptions

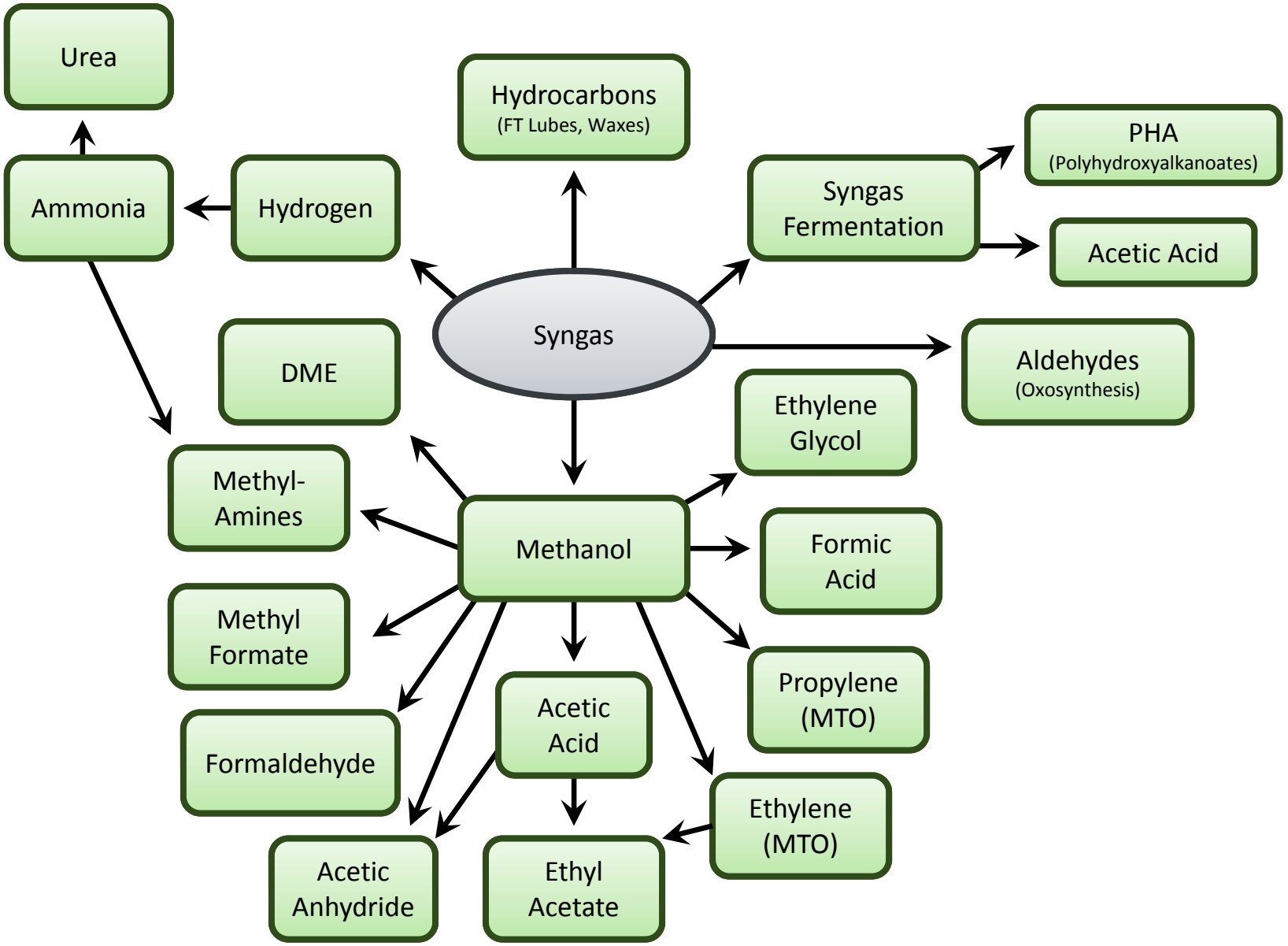
- **Internal Rate of Return (IRR):** 10% – 25%
- **Capital Costs:**
  Pioneer Plant Escalation ~ 210% of n^{th} Plant Estimates *(Merrow et al, Rand, 1981)*
- **Reliability of Operations / On-Stream Factor:**
  Initial value of 0.5 *(Merrow et al, Rand, 1981)*
  Increasing to 0.9 per experience curve *(Heinen, SRI Consulting, 2001)*



Fuel Pathways Explored



Chemical Pathways Explored



Major Pathway Categories Explored

- **Synthetic Natural Gas** via Methanation of Syngas
- **Ethanol**
  - Catalytic Mixed Alcohol Synthesis
  - Syngas Fermentation *
- **Hydrocarbons**
  - Fischer-Tropsch
  - Methanol to Naphtha Hydrocarbons
  - Ethanol & Higher Alcohols to Hydrocarbons *
- **Hydrogen** via Steam Reforming, WGS & Purification
- **Methanol** via Catalytic Methanol Synthesis

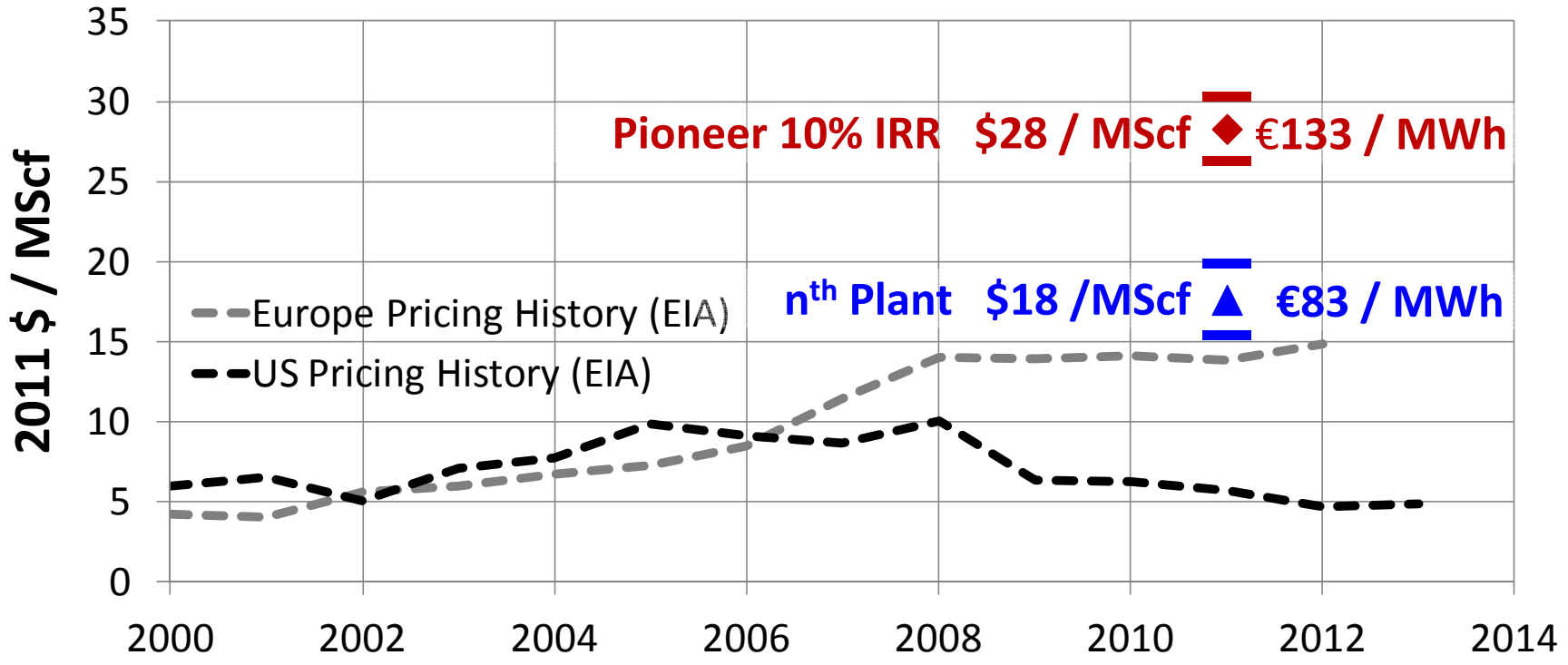
* *Pathways explored by NREL through Aspen modeling and rigorous TEA.*

Synthetic Natural Gas

- Methanation of Syngas

Synthetic Natural Gas

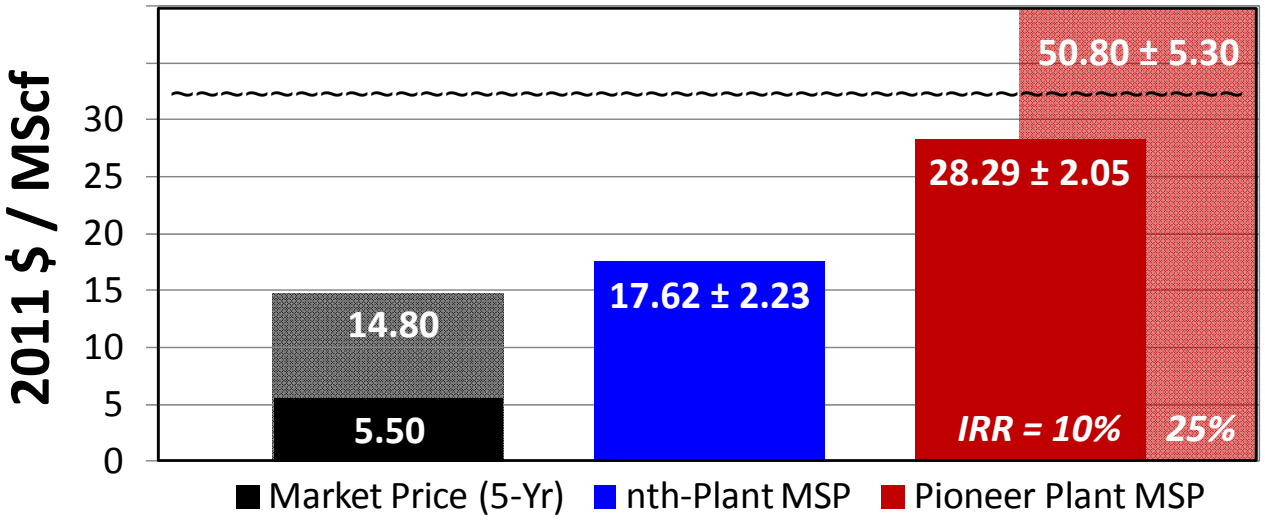
Process	Sources	Min. Selling Price Range ($ / MScf)	
Syngas to SNG via methanation	McKeough & Kurkela, 2007 Mozaffarian et al, 2004 van der Drift et al, 2005	n^{th} Plant	16.52 – 19.13
		Pioneer 10% IRR	27.07 – 29.52
		Pioneer 25% IRR	47.50 – 53.97



Historical Pricing Data Source: U.S. Energy Information Administration.

Synthetic Natural Gas

Techno-economic Analysis



Market Analysis

		U.S.	Europe
Average Product Yield	Scf / Ton	11,440	11,440
Consumption (EIA, 2012)	Scf / Year	25.5T	19.0T
10% of Natural Gas Market	Scf / Year	2.55T	1.90T
Equivalent Biomass Consumption	MMTon / Year	223	165
Equivalent Biorefineries (2,000 Tonne / Day)		**310**	**230**

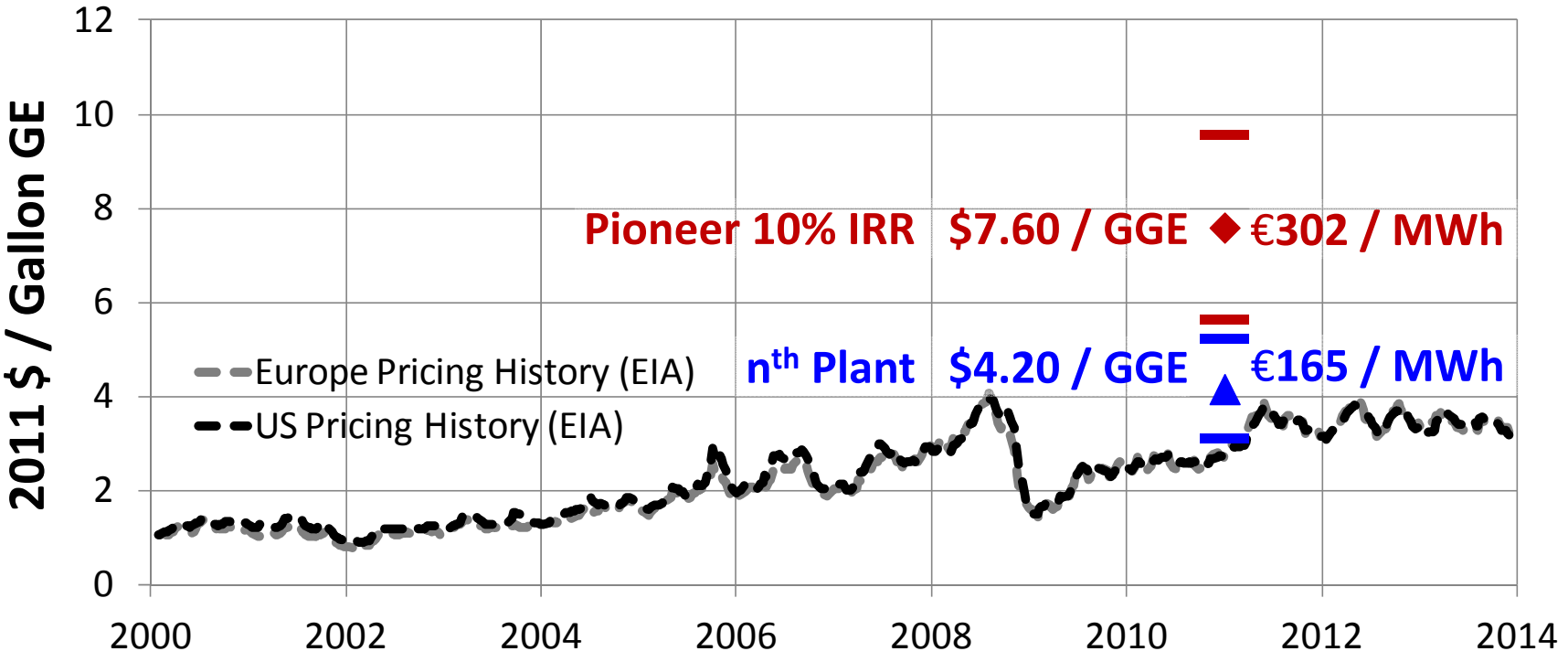
Ethanol

- Catalytic Mixed Alcohol Synthesis
- Syngas Fermentation *

* *Pathways explored by NREL through Aspen modeling and rigorous TEA.*

Ethanol via Mixed Alcohol Synthesis

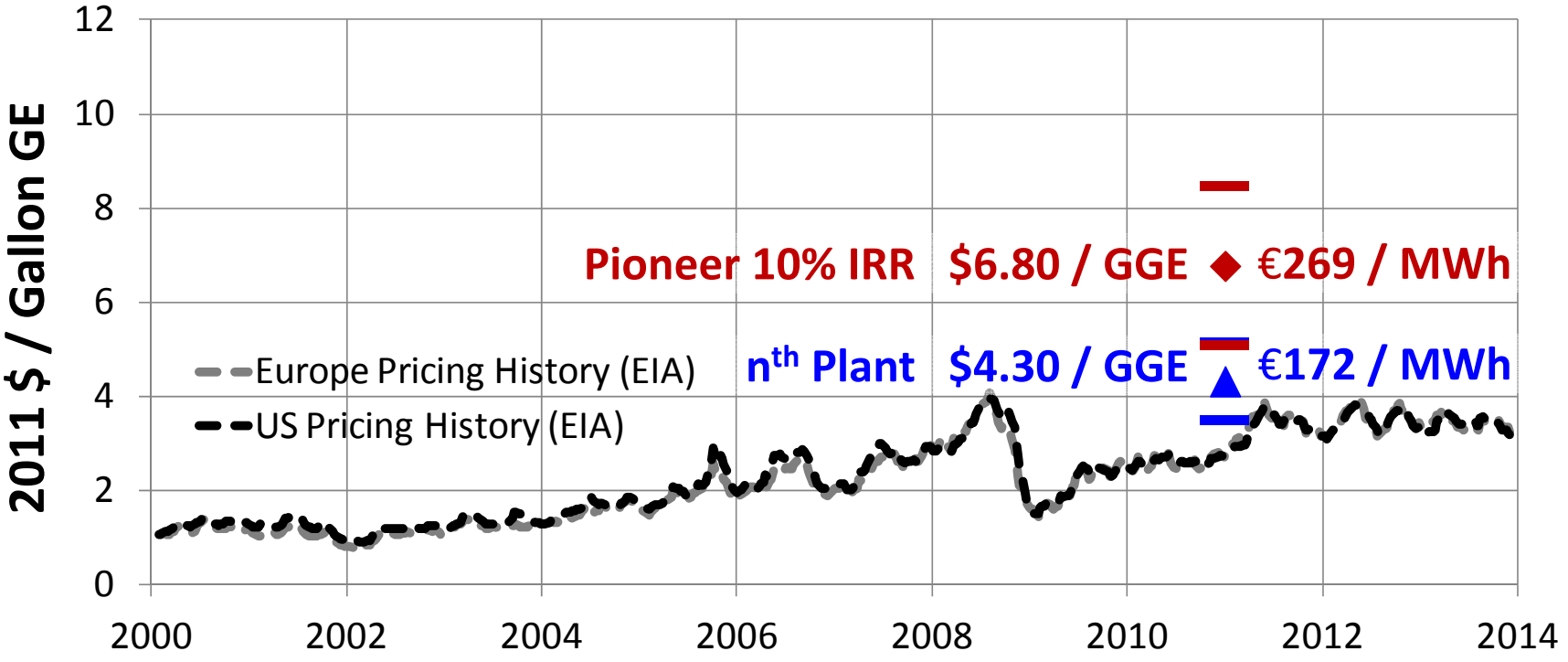
Process	Sources	Min. Selling Price Range ($ / Gal GE)	
Syngas to ethanol via catalytic mixed alcohol synthesis	Dutta et al, 2011 Dutta & Phillips, 2009 Dutta et al, 2010 He & Zhang, 2011 Villanueva Perales et al, 2011	n^{th} Plant	2.87 – 4.83
		Pioneer 10% IRR	5.34 – 9.08
		Pioneer 25% IRR	10.66 – 18.15



Historical Pricing Data Source: U.S. Energy Information Administration.

Ethanol via Syngas Fermentation

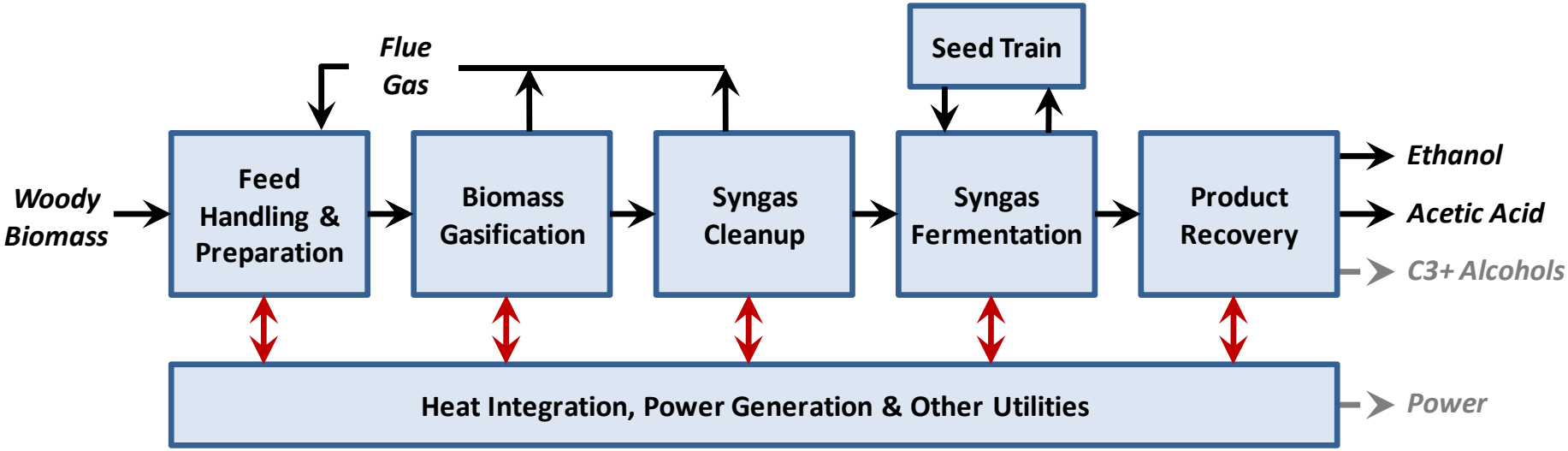
Process	Sources	Min. Selling Price Range ($ / Gal GE)	
Ethanol via syngas fermentation	Putsche,1999 van Kasteren & Verbene, 2005 Piccolo & Bezzo, 2007	n^{th} Plant	3.67 – 5.08
		Pioneer 10% IRR	5.77 – 8.50
		Pioneer 25% IRR	8.92 – 16.12



Historical Pricing Data Source: U.S. Energy Information Administration.

Ethanol via Syngas Fermentation

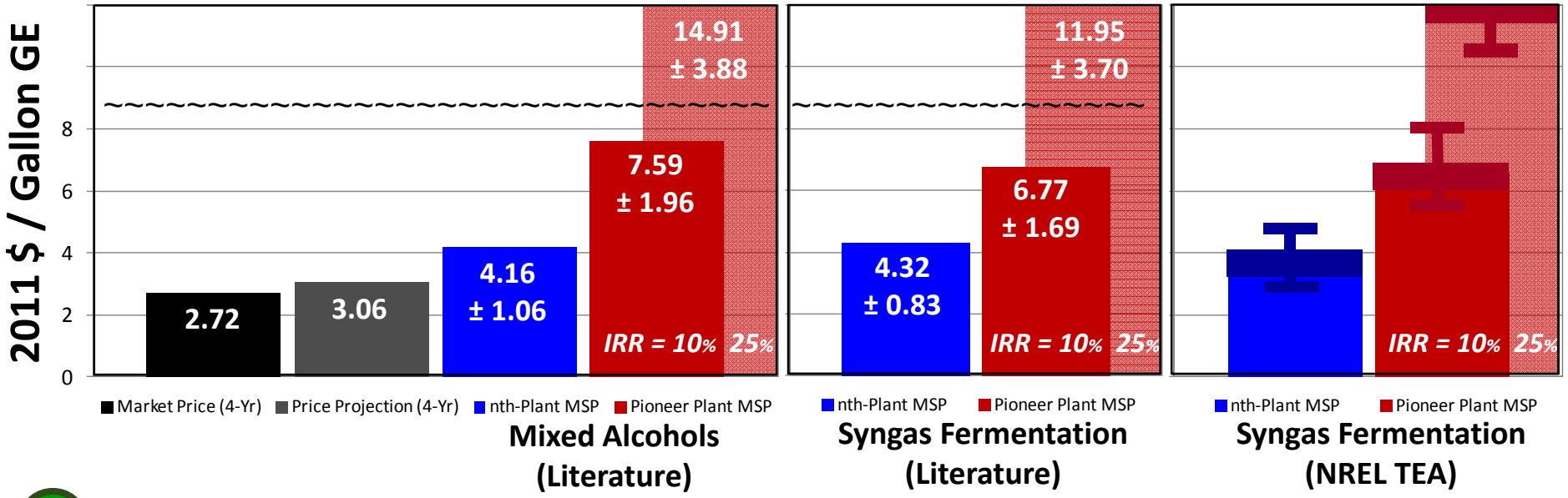
NREL TEA Model



- Design Report NREL/TP-5100-51400 utilized as basis through clean compressed syngas from biomass.
- Yield structures based on publications from LanzaTech & INEOS Bio.
- Capital costs for fermenters, seed train and cell recovery developed by Harris Group Inc.

Ethanol

Techno-economic Analysis



Market Analysis

		U.S.	Europe
Average Product Yield	Gallons / Ton	85	85
Consumption (EIA, 2013)	Gallons / Year	13.0B	10.0T
50% of Fuel Ethanol Market	Gallons / Year	6.5B	5.0T
Equivalent Biomass Consumption	MMTon / Year	76	60
Equivalent Biorefineries (2,000 Tonne / Day)		**100**	**80**

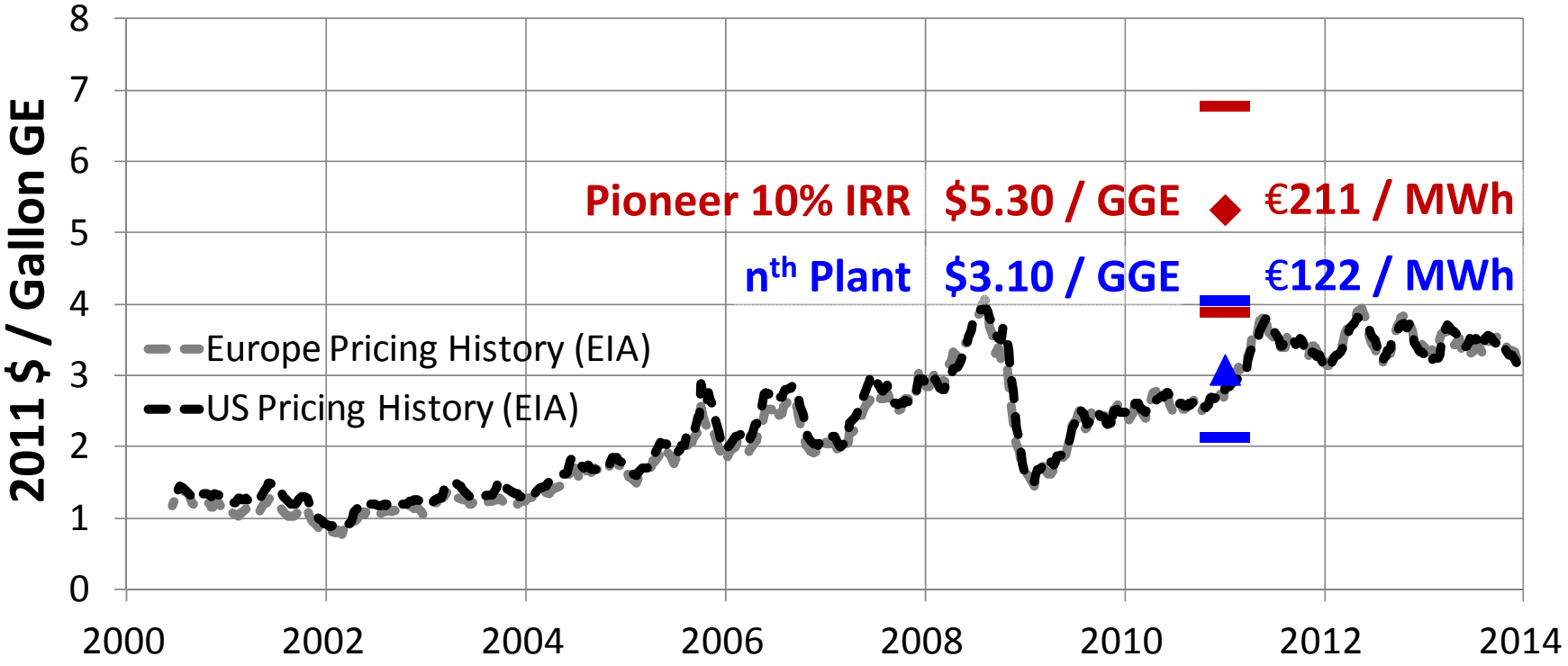
Hydrocarbons

- Fischer-Tropsch
- Methanol to Naphtha Hydrocarbons
- Ethanol & Higher Alcohols to Hydrocarbons *

* *Pathways explored by NREL through Aspen modeling and rigorous TEA.*

Fischer-Tropsch Hydrocarbons

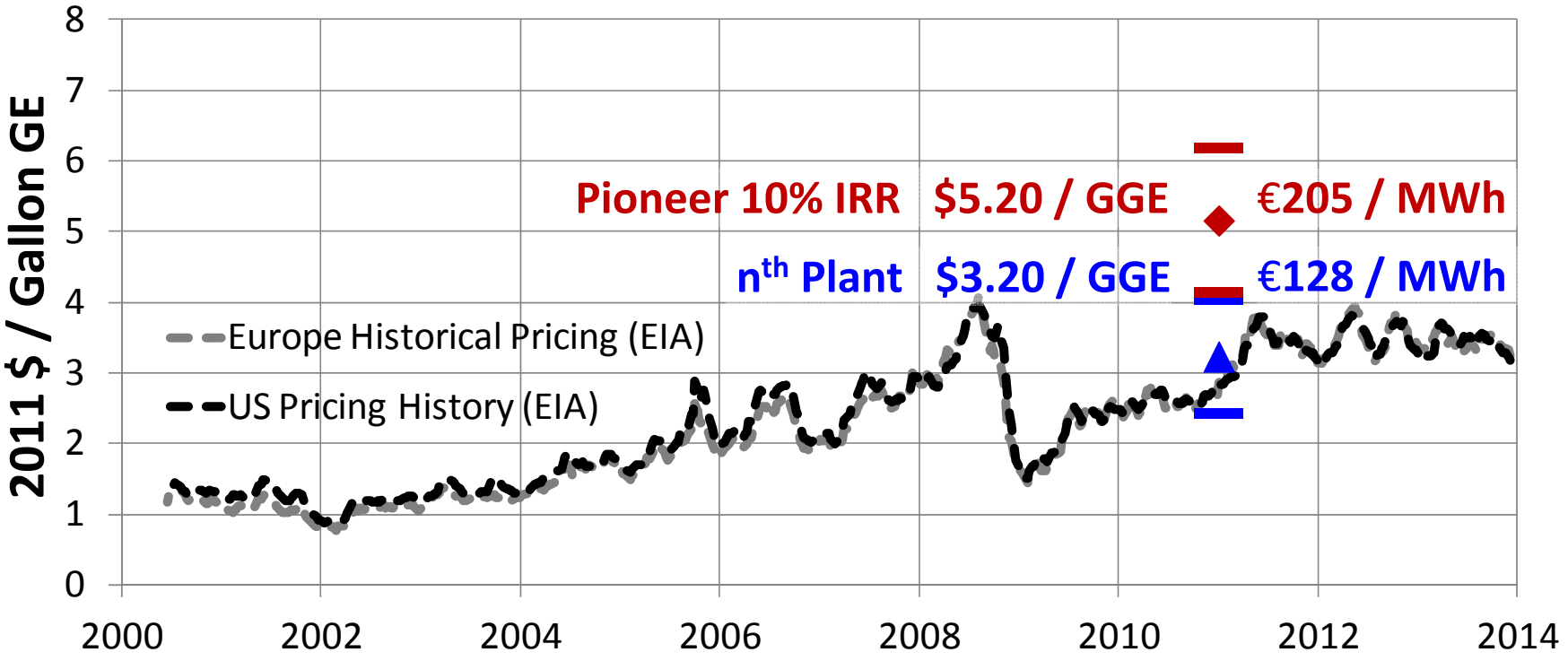
Process	Sources	Min. Selling Price Range ($ / Gal GE)	
Hydrocarbons via Fischer-Tropsch synthesis	Hamelinck et al, 2003 Larson et al, 2009 McKeough & Kurkela, 2007 SRI PEP Yearbook, 2009 Udengaard, 2011 Byrne, 2011 Freeman, 2011	n^{th} Plant	2.52 – 4.19
		Pioneer 10% IRR	4.50 – 7.00
		Pioneer 25% IRR	9.04 – 12.80



Historical Pricing Data Source: U.S. Energy Information Administration.

Methanol to Hydrocarbons

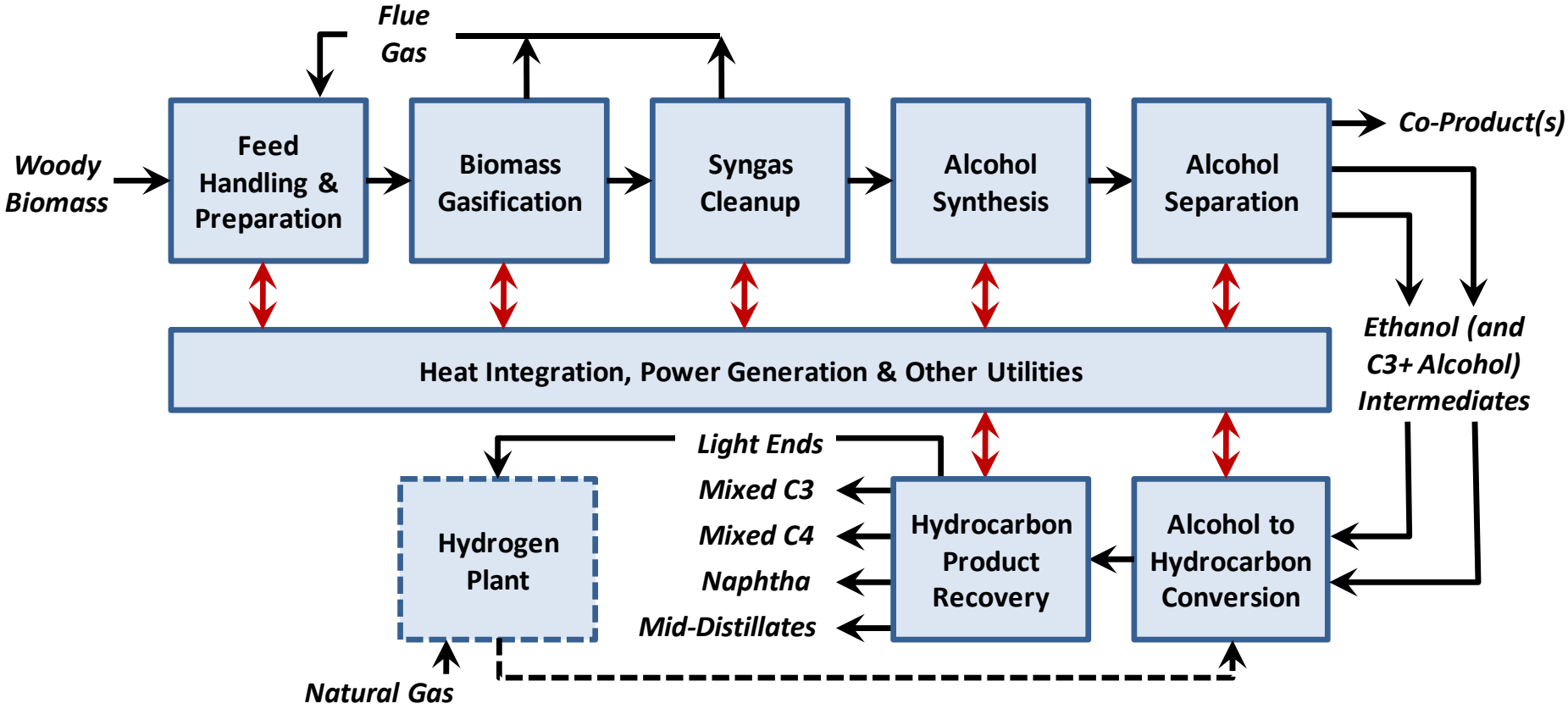
Process	Sources	Min. Selling Price Range ($ / Gal GE)	
Hydrocarbons via methanol synthesis and methanol conversion	Phillips et al, 2011 Hindman, 2010 SRI PEP Report 191A, 1999 Udengaard, 2011 Jones & Zhu, 2009 Ahn et al, 2009	n^{th} Plant	2.61 – 3.84
		Pioneer 10% IRR	4.42 – 6.12
		Pioneer 25% IRR	8.22 – 10.79



Historical Pricing Data Source: U.S. Energy Information Administration.

Ethanol & Higher Alcohols to Hydrocarbons

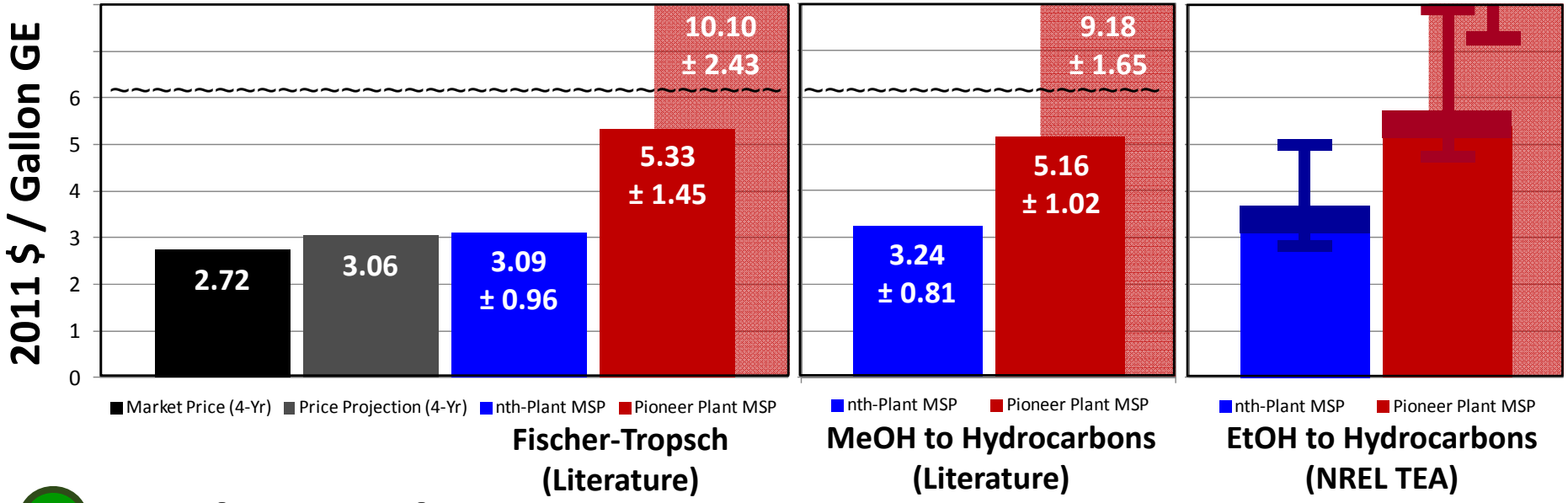
NREL TEA Model



- Ethanol (and higher alcohol) intermediates for hydrocarbon fuel production.
- Eliminates constraints of renewable ethanol blend limits.
- Technology development taking place in academia, national labs and industry.

Hydrocarbon Fuels

Techno-economic Analysis



Fischer-Tropsch (Literature)

MeOH to Hydrocarbons (Literature)

EtOH to Hydrocarbons (NREL TEA)

Market Analysis

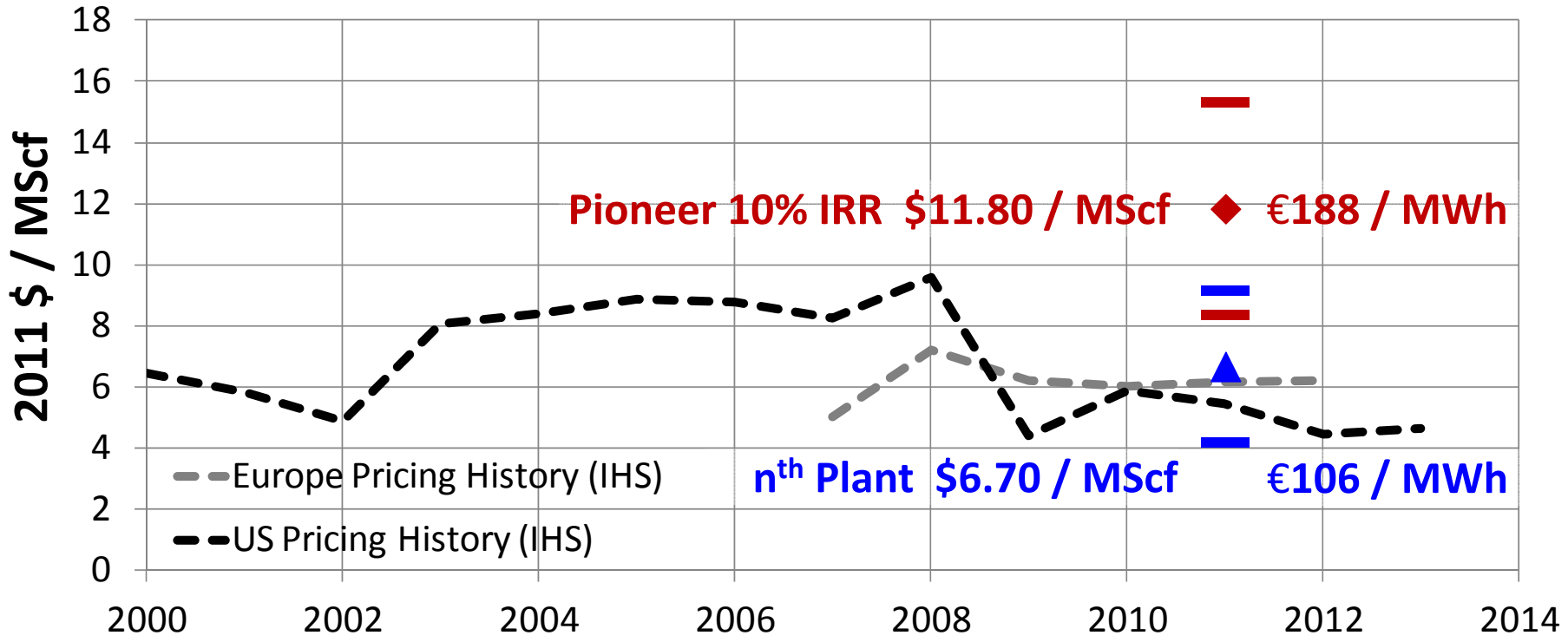
		U.S.	Europe
Average Product Yield	Gallons / Ton	65	65
Consumption (EIA, 2013)	Gallons / Year	220B	160B
10% of Hydrocarbon Fuels Market	Gallons / Year	22B	16B
Equivalent Biomass Consumption	MMTon / Year	338	242
Equivalent Biorefineries (2,000 Tonne / Day)		**440**	**310**

Hydrogen

- Steam reforming, water-gas shift & purification

Hydrogen

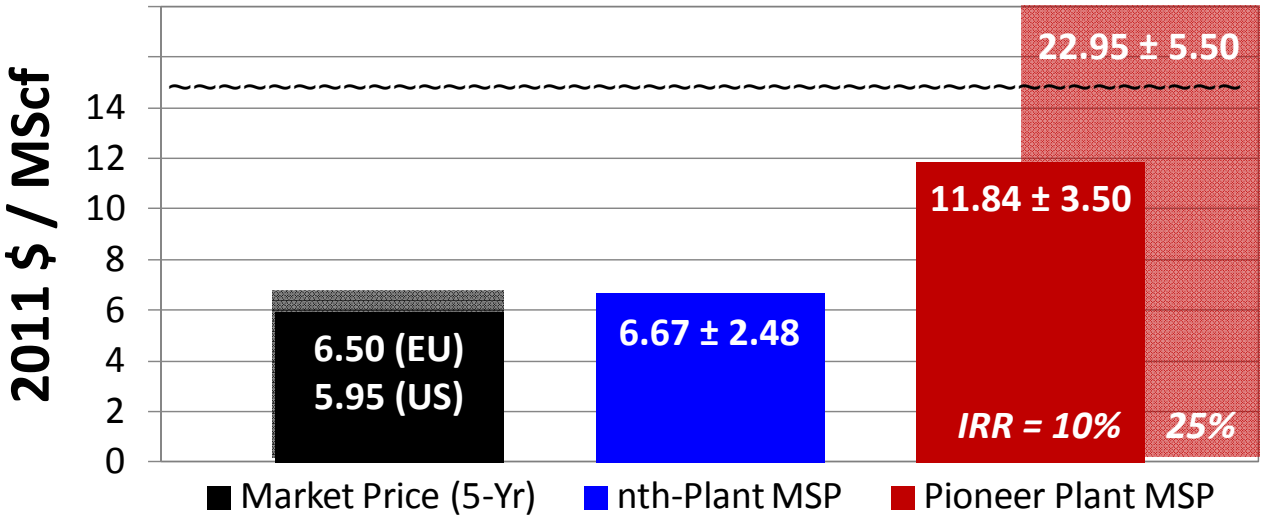
Process	Sources	Min. Selling Price Range ($ / MScf)	
Syngas to H_2 via steam reforming, water-gas shift & purification	Spath et al, 2005 McKeough & Kurkela, 2003 Williams et al, 1995 Hamelinck & Faaij, 2001	n^{th} Plant	5.33 – 8.84
		Pioneer 10% IRR	9.87 – 14.82
		Pioneer 25% IRR	19.80 – 27.60



Historical Pricing Data Source: SRI / IHS CEH Marketing Research Reports. Projected values based on ratios to EIA natural gas projections.

Hydrogen

Techno-economic Analysis



Market Analysis

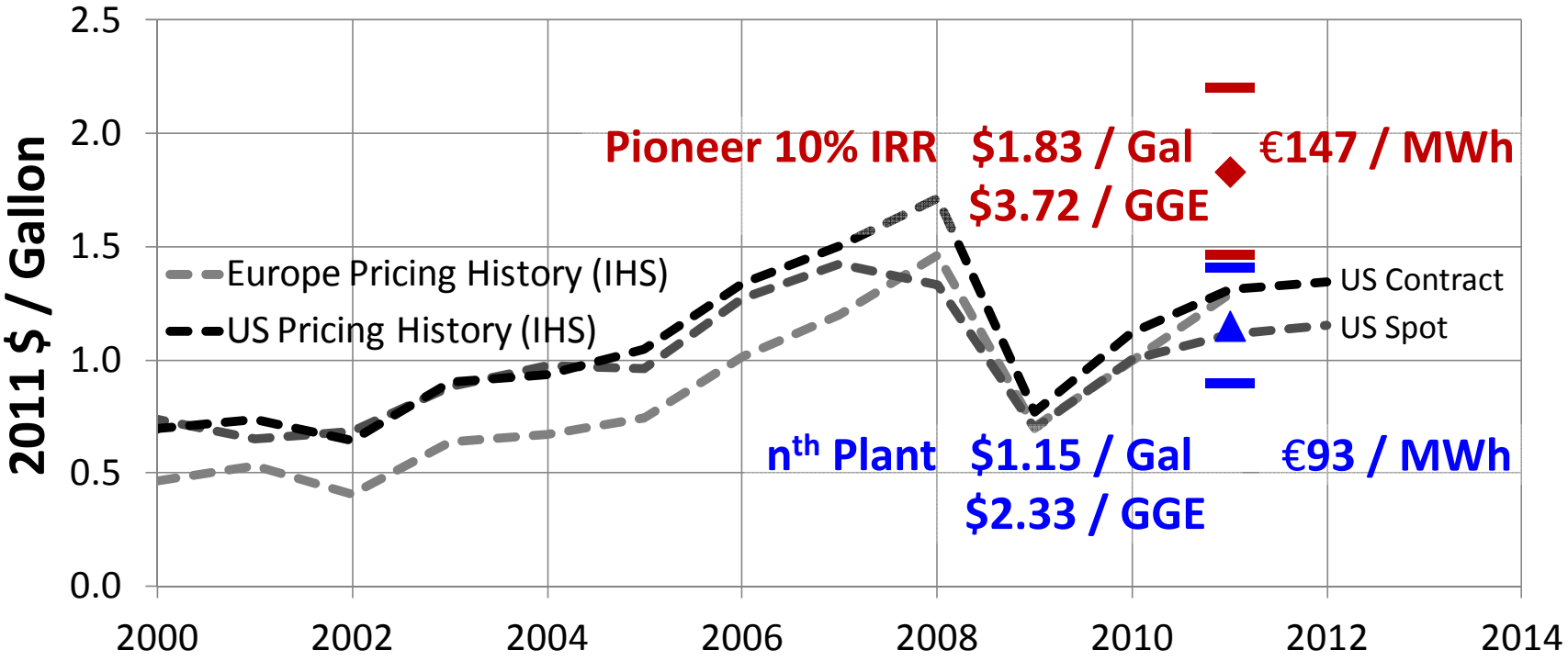
		U.S.	Europe
Average Product Yield	SCF / Ton	37,500	37,500
Consumption (EIA, 2013)	SCF / Year	4.1T	3.2T
10% of HydrogenMarket	SCF / Year	0.41T	0.32T
Equivalent Biomass Consumption	MMTon / Year	11	8.5
Equivalent Biorefineries (2,000 Tonne / Day)		**14**	**11**

Methanol

- Catalytic Methanol Synthesis

Methanol

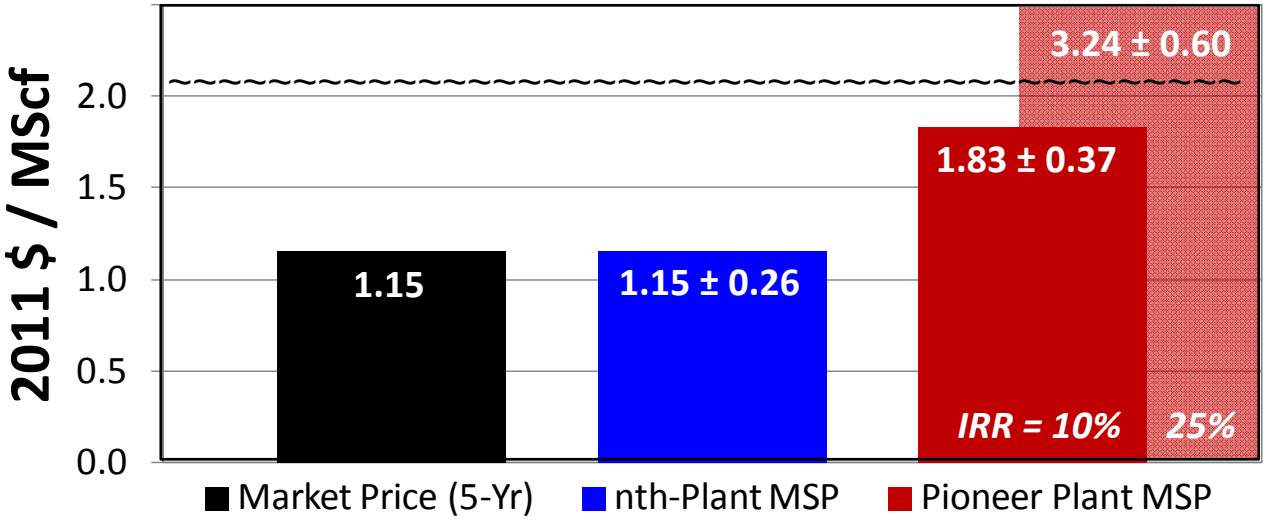
Process	Sources	Min. Selling Price Range ($ / Gal)	
Syngas to methanol via catalytic synthesis	Tarud & Phillips, 2011 McKeough & Kurkela, 2007 SRI PEP Yearbook, 2009 Williams et al, 1995 Hamelinck & Faaij, 2001	n^{th} Plant	0.96 – 1.32
		Pioneer 10% IRR	1.54 – 2.03
		Pioneer 25% IRR	2.82 – 3.71



Historical Pricing Data Source: IHS CEH Marketing Research Report, 2013.

Methanol as Chemical Intermediate

Techno-economic Analysis

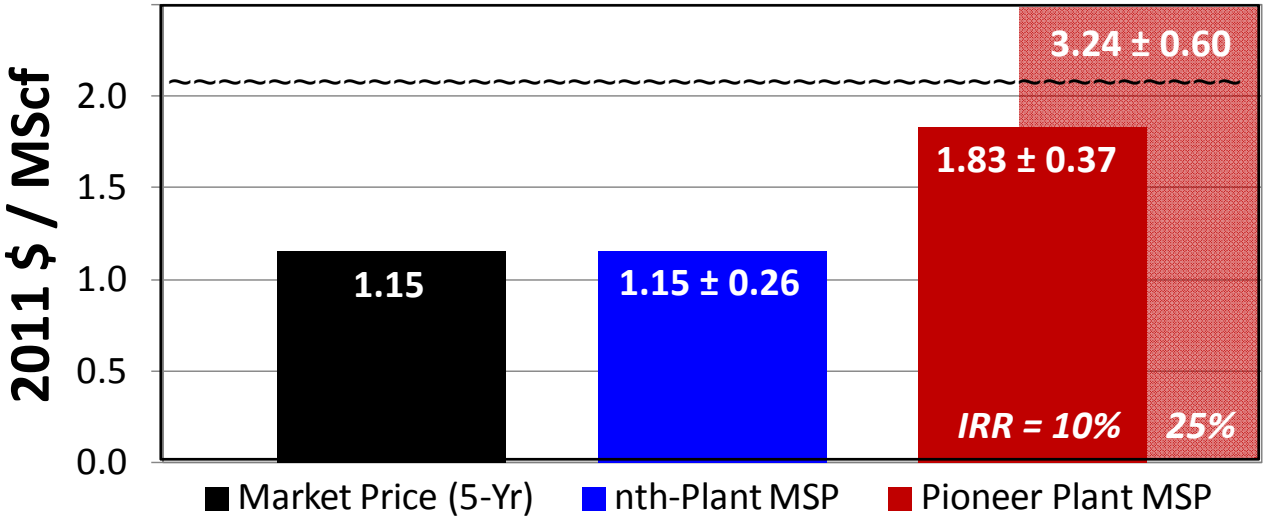


Market Analysis

		U.S.	Europe
Average Product Yield	Gallons / Ton	170	170
Consumption (IHS)	Gallons / Year	1.9B	2.2B
10% of Methanol Market	Gallons / Year	0.19B	0.22B
Equivalent Biomass Consumption	MMTon / Year	1.1	1.3
Equivalent Biorefineries (2,000 Tonne / Day)		**1.4**	**1.6**

Methanol as Fuel Intermediate

Techno-economic Analysis



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Equivalent Biorefineries (2,000 Tonne / Day)		**440**	**310**

Conclusions

- Hydrocarbon, ethanol and methanol economics can be competitive for n^{th}-plant.
- Pioneer plant economics are challenged overall.
- Market capacities do not constrain bio-product pathways in major hydrocarbon fuel markets (natural gas, petroleum fuels).
- With fixed ethanol blend limit, cellulosic pathways and grain-derived product will compete for limited market.
- Market capacities for methanol-derived chemicals are constraining.
- Syngas fermentation is potentially competitive, depending on CO / H_2 conversion to product(s).
- Methanol and ethanol are attractive intermediates for production of infrastructure-compatible hydrocarbons.

Future Work

- Apply simplified TEA and market analysis on emerging pathways to identify economic feasibility in early stages of development.
- Explore opportunities to improve Pioneer Plant economics
  - Biomass co-feeding opportunities (NG-Biomass to Liquids)
  - Utilizing inexpensive feedstocks
  - High-value co-products
  - RIN credits
- Evaluate infrastructure hurdle for methanol economy

Acknowledgements

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- Bioenergy Technology Office (BETO) of the United States Department of Energy
- NREL Biorefinery Analysis and Thermochemical Platform Teams

References

For a complete list of references utilized in this analysis, please contact Mike Talmadge (michael.talmadge@nrel.gov / 303-275-4632)