Conversion of CO_2 to Alkyl Carbonates Using Ethylene Oxide as Feedstock

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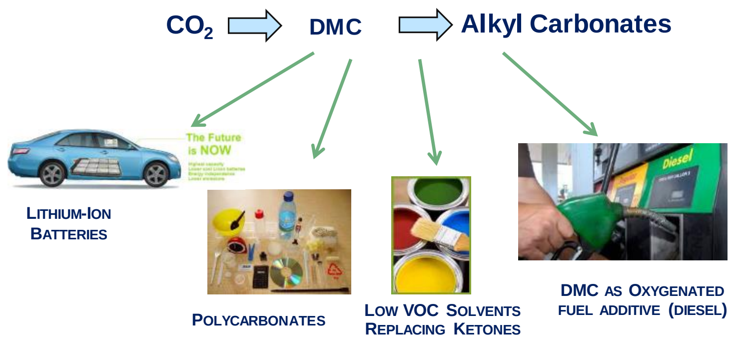
SBIR Phase II Project Status

- **Technical**: Developed validated ASPEN Plus® design based on pilot-scale tests at Michigan State University
- **Economic Analysis**: CAPEX for a 50 kTA DMC plant, competitive selling price of DMC compared to syngas-based DMC production, *ProForma* based NPV & IRR
- **Intellectual Property**: Two patents on DMC process plus one patent on Differential Kinetic Test Unit (DKTU)
- **Industry Interactions**: Interactions with potential industrial organizations for feedback on TRL status and economic analysis
- **Path Forward**: Commercial demonstration (build and operate) to validate techno-economic merits

Alkyl Carbonates - Ideal Candidates for Conversion of CO_2 to Value-Added Products

Expanding Market Demands

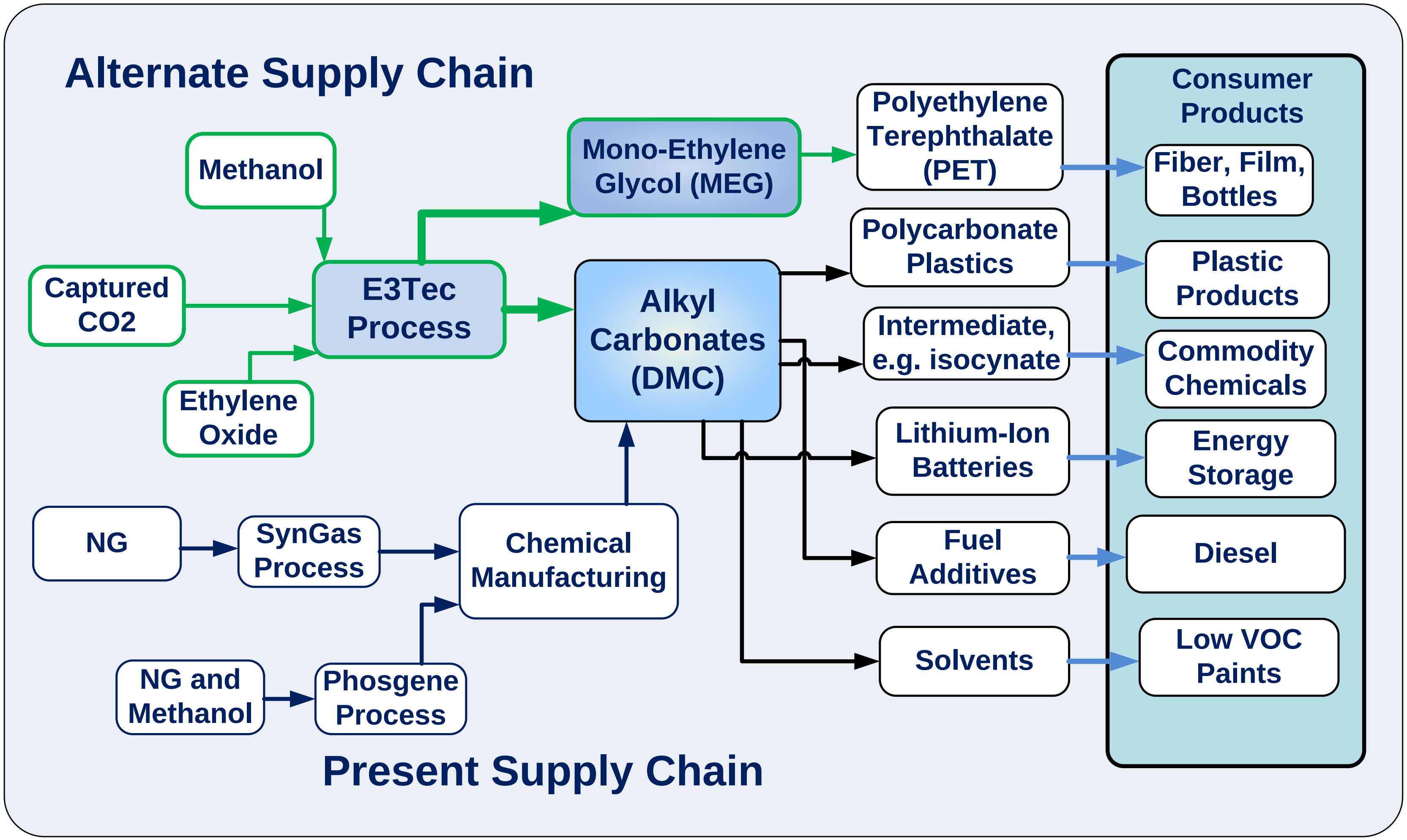
- High market growth considering replacement of phosgene based process and to meet expanding demands for polycarbonates and surging demand for Li-ion batteries
- E3Tec focus on high-purity 99.9%+ CO_2 based DMC
- MEG is one of the top 50 chemicals



Application	Global DMC Market Potential - kTA*	
	2017	2030
DMC in Polycarbonate Production	2,440	4,910
Li-Ion Battery Electrolyte	45	350
Solvents (replacing ketones)	1,430	1,820
Chemical Intermediate, e.g. Polyurethane	11,350	18,470
Potential diesel oxygenate additive**		1,580,000

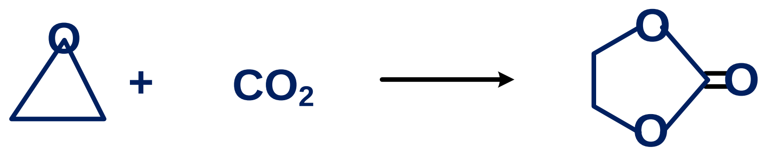
*kTA - Thousand Tonnes Per Year ** Based on government approval for pollution control

Alkyl Carbonate Supply Chain

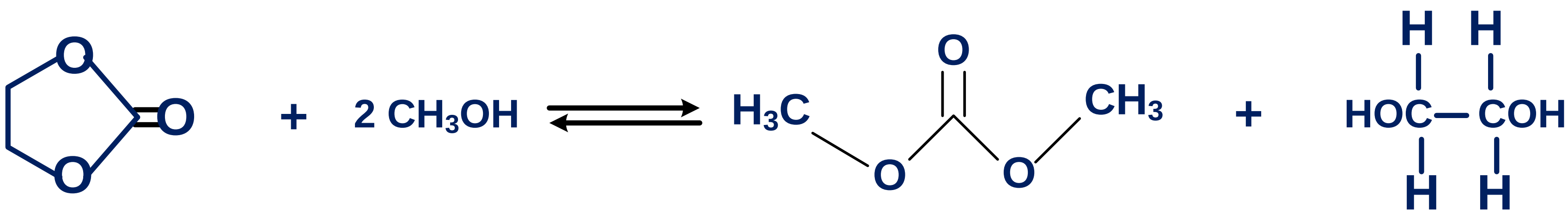


E3Tec's Process Based on Two Chemical Pathways

Ethylene-Oxide-Based Process with Selective Co-Production of Mono-Ethylene Glycol (MEG)



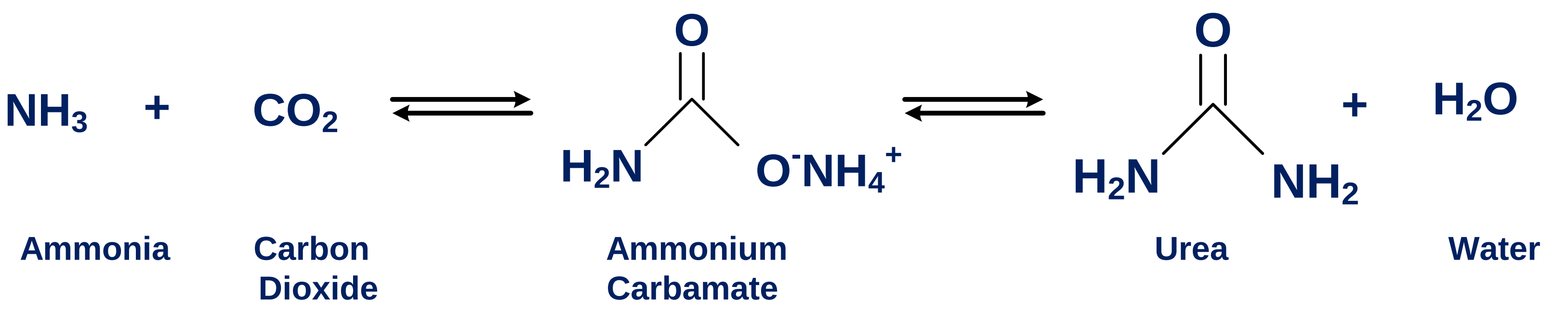
Ethylene Oxide | Carbon Dioxide | Ethylene Carbonate

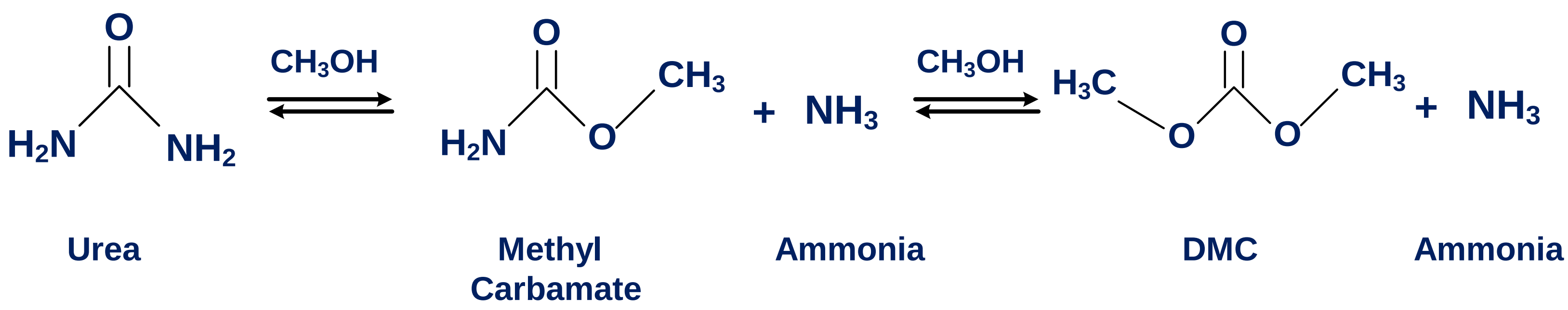


Ethylene Carbonate | Methanol | Di-Methyl Carbonate (DMC) | Mono-Ethylene Glycol

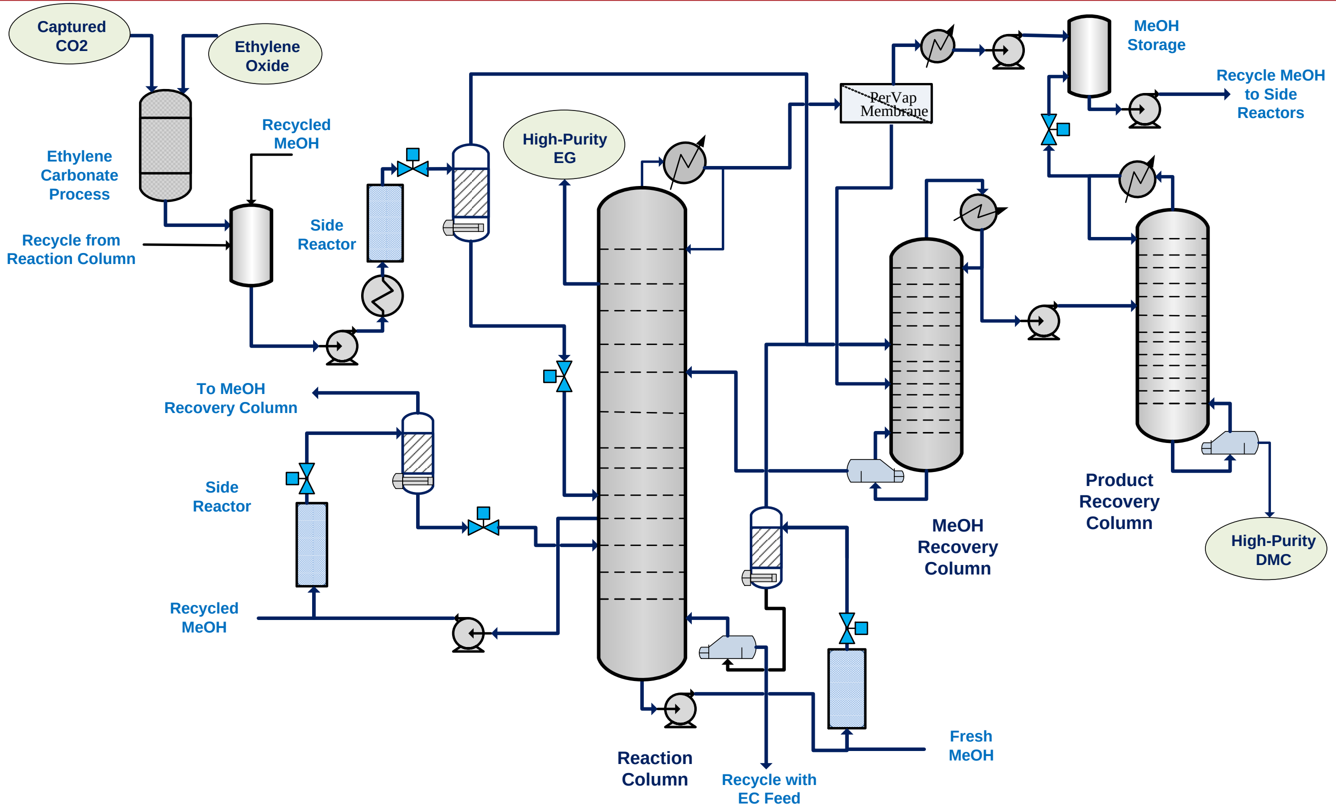
E3Tec's Process Based on Two Chemical Pathways

Urea-based Process with Ammonia Acting as a Chemical Carrier and for Breaking DMC/Methanol Azeotrope





Heat Integrated Reactive Distillation (HIRD) Process Equipped with Side Reactors & PerVap Membrane

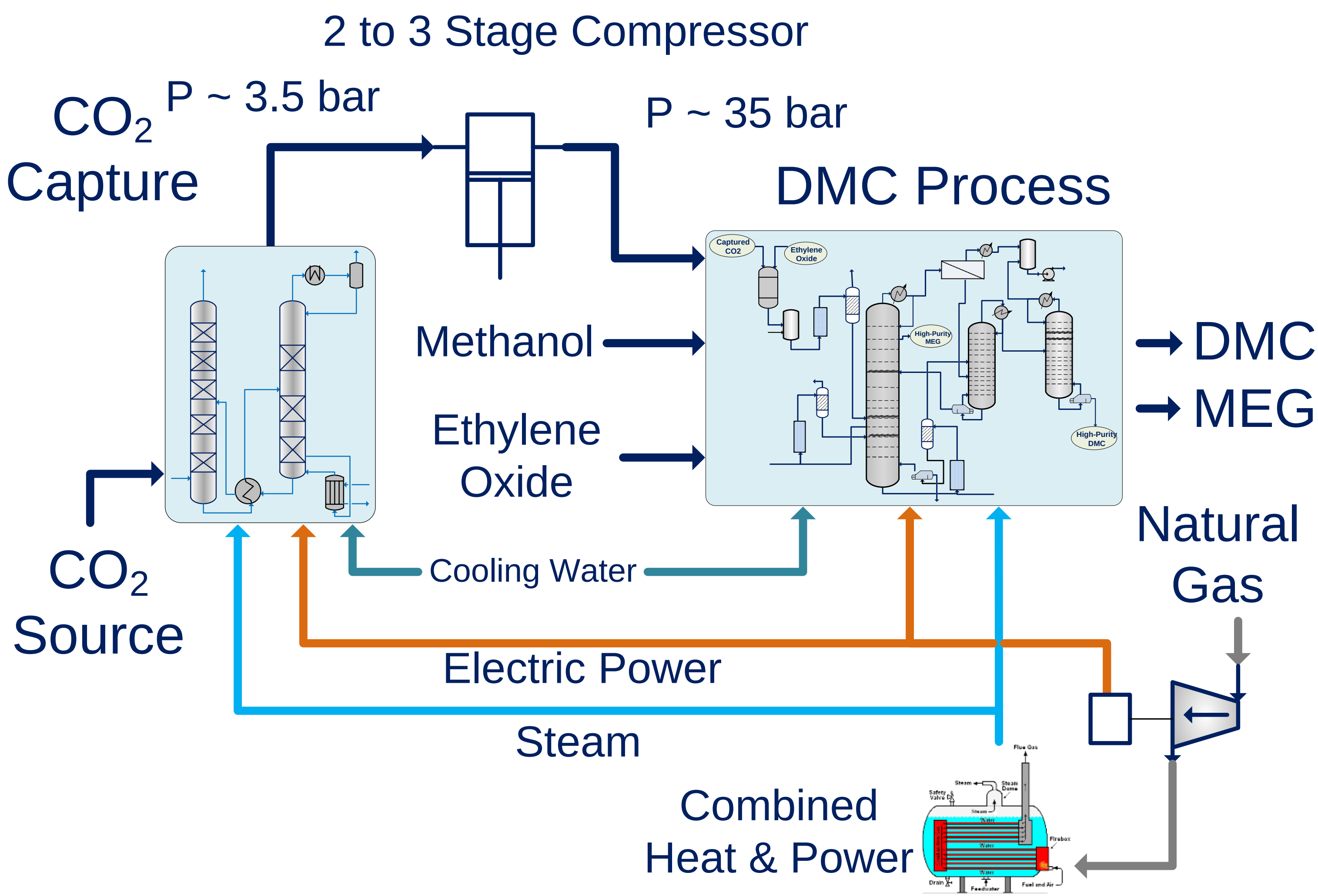


DMC 51.7 kTA MEG 35.8 kTA CO_2 Consumption 25.6 kTA

Purity of Products: DMC 99.99% wt MEG 98.9% wt

US Patent 9,518,003 B1 December 2016 and 9,796,656 B1 October 2017

Integrated CO_2 Source DMC Process



Economic Analysis of Integrated Process

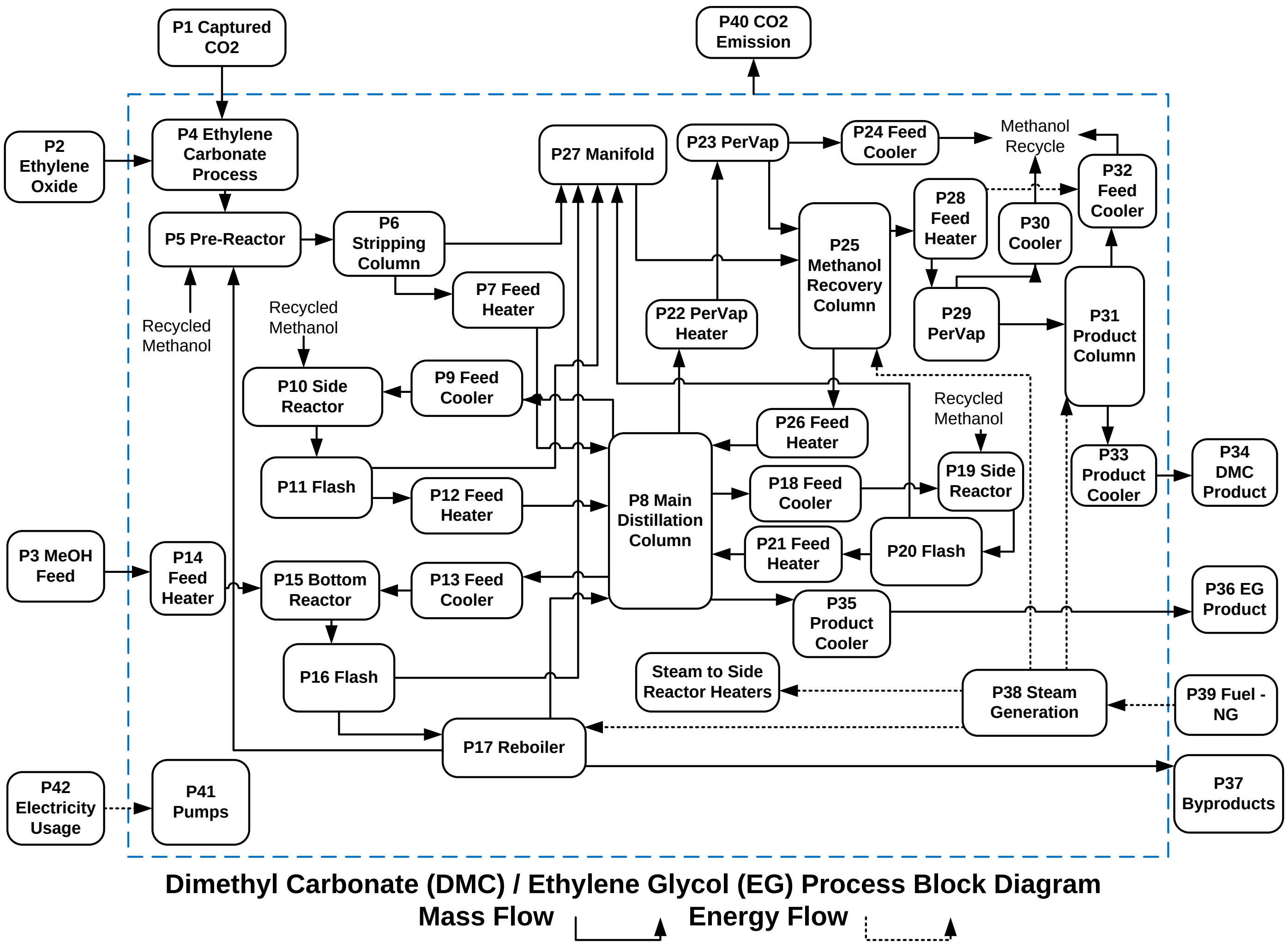
E3Tec

Case Study: 15 MWe Coal Plant

Baseline Case	UIUC 15 MW Coal Plant	
Power Generation	15	MWe
CO_2 Emission	300	Tonnes / day
CO2 Capture & Sequestration Costs		
CO_2 Capture Costs	$56.2	$ / Tonne CO_2
	$16,860	$ / day
Sequestration Costs	$44.8	$ / Tonne CO_2
	$10,080	$ / day
COE Impact (assuming 90% availability)		
CO_2 Capture	$52	$/MWe
CO_2 Sequestration	$31	
Total	$83	
DMC/MEG Production		
Fraction of CO_2 Emission Consumed in DMC	25%	
CO_2 Consumption	75	Tonnes / day
DMC Production	150	
MEG Production	105	
Annual DMC Produciton	50.0	kTA
Annual MEG Production	35.0	
Product Margin Required for Offsetting CO_2 Costs		
CO_2 Capture & Sequestraiton	$180	$ / Tonne DMC
Commercial Price of 99.99 wt % Purity DMC	$1,789	
Production Costs of CO_2-Based DMC	$1,285	
Product Margin	$504	

C-footprint Analysis

ASPEN Plus® based process block diagram



Dimethyl Carbonate (DMC) / Ethylene Glycol (EG) Process Block Diagram

C-footprint Analysis

Offsetting CO_2 Emissions

	CO_2-Based Process	Syngas-Based Process
CO_2 Consumption, tonne CO_2/tonne DMC	-0.51	0
CO_2 Emission Inside Battery Limits (ISBL)	0.58	1.29
Energy Consumption		
Thermal, MWh/Tonne DMC	2.87	4.41
Electric, MWh/tonne DMC	0.01	0.02
Cooling water, tonnes/tonne DMC	108.0	206.5
CO2 emission Outside Battery Limits (OSBL)		
Methanol, tonne CO_2/tonne DMC	0.39	0.47
Ethylne oxide, tonne CO_2/tonne DMC	0.31	
Total CO_2 Emission, tonnes CO_2/tonne DMC	1.28	1.76
Offsetting CO_2 Emission of MEG Produciton	-0.58	0
Net Emission tonne CO_2/tonne DMC	0.19	1.76

Potential Abatement of CO_2 Emissions

Application	Global CO_2 Abatement Potentials* kTA	
	2018	2030
DMC in Polycarbonate Production	3,831	7,708
Li-Ion Battery Electrolyte	71	550
Solvents (replacing ketones)	2,245	2,857
Chemical Intermediate, e.g. Polyurethane	17,820	28,998
Potential diesel oxygenate additive**		2,480,600

*Based on offsetting CO_2 emissions by commerial production of DMC by syngas and MEG by hydration of ethylene oxide processes

** Based on government approval for pollution control

Economic Analysis

Competitive Product Margin

	E3Tec Process	Syngas Based Process
Plant Capacity, kTA		
DMC	**51.7**	**50.0**
MEG	**35.0**	**0.0**
Capital Costs (CAPEX), $ Million	**$ 164**	**$ 223**
Costs $/tonne DMC		
Total Variable	**$ 291**	**$ 431**
Total Fixed	**$ 196**	**$ 254**
Cash Cost of Production	**$ 487**	**$ 685**
Capital Charge	**$ 798**	**$ 1,104**
Selling Price	**$ 1,285 ***	**$ 1,789**
Product Margin	**$ 504**	

*** Taking into credit for MEG as co-product**

Economic Analysis

Proforma Based NPV and IRR

Economic Parameters

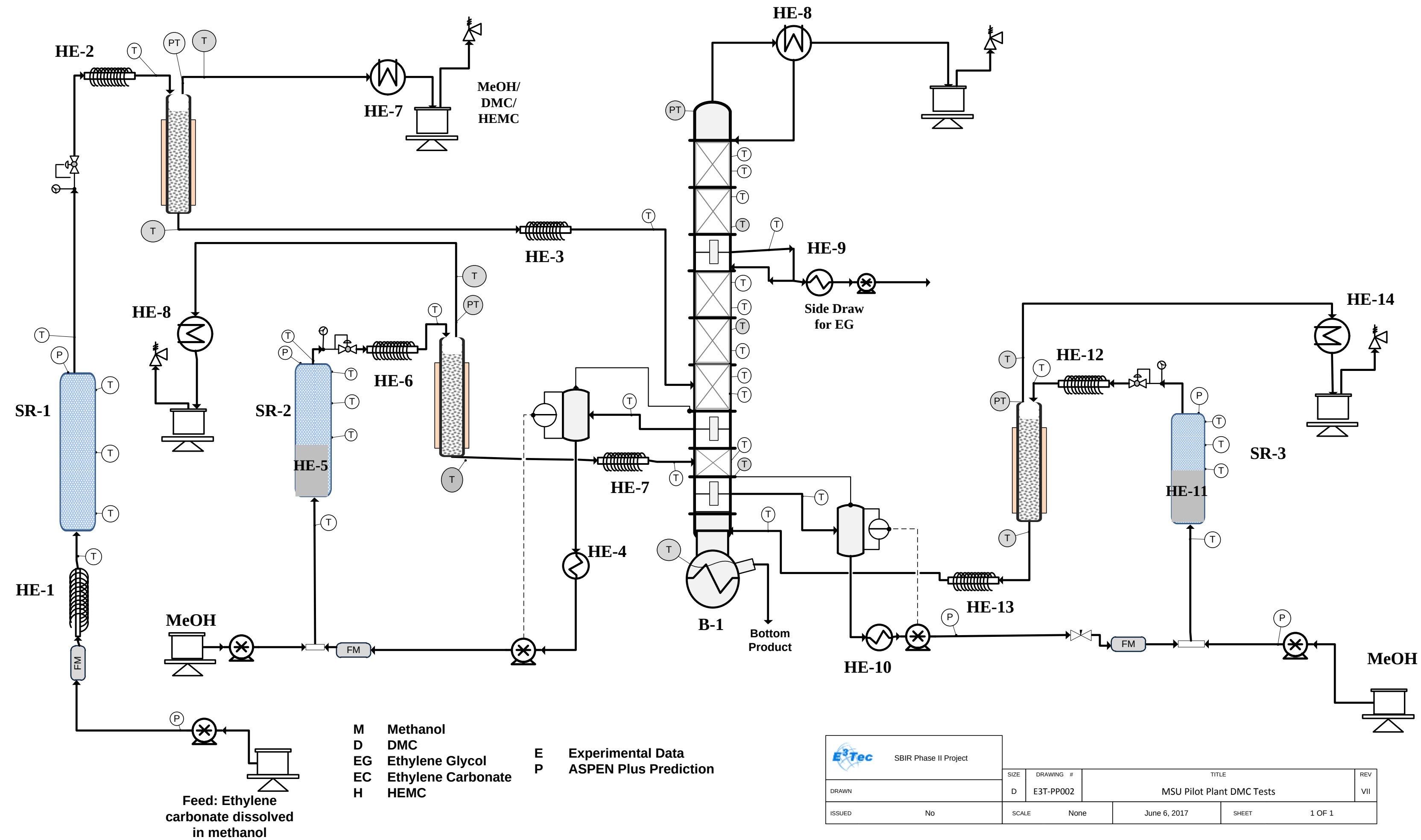
Plant Service Life	**30 Years**
Normal Discount Rate	**9 %**
Corporate Income Tax	**34 %**
Inflation Rate	**Between 2.2 % & 3.0 %**
Net Present Value (NPV)	**$ 249 million**
Internal Rate of Return (IRR)	**21%**

Technology Demo Unit as Next Step

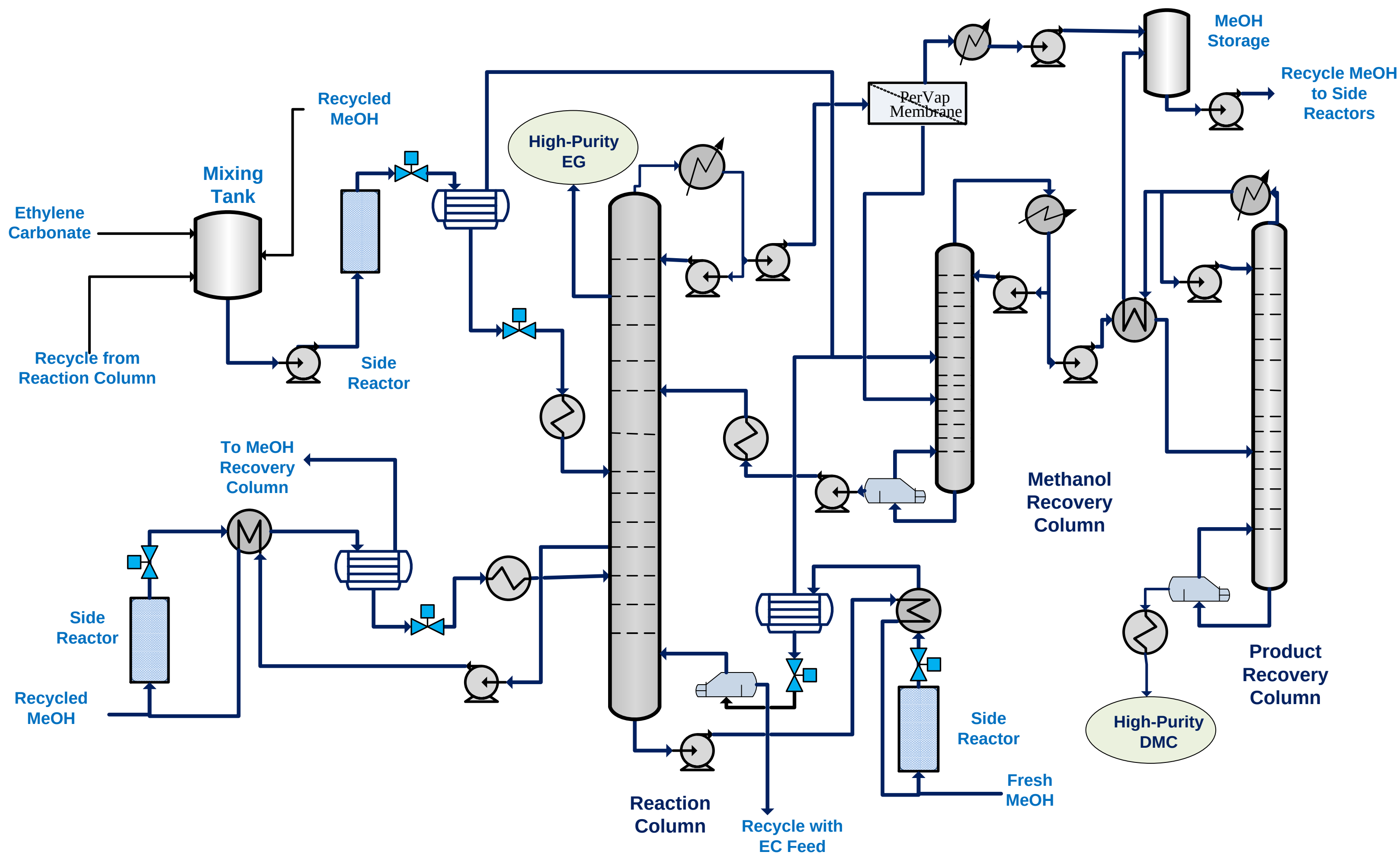
Design Criteria

- Skid-mounted unit with DMC capacity of one tonne per day
- Total Installed Cost (TIC) within $10 million
- Continuous operation of fully integrated process, including recycle streams
- Catalyst activities for an extended period (12 months or more)
- Demonstrate product yield and purity – DMC and MEG
- Scale-up from MSU test unit ➔ Demo Unit ➔ Commercial plant
- Validation of the ASPEN Plus® design model as well as reactor models

MSU Test Unit



Technology Demo Unit Scaled up from MSU Test Unit



Path Forward

Partnership Opportunities

- **Funding and Investment**: Pilot plant demonstration of the technology at a cost of $10 million with a possibility of SBIR Phase III CRADA funding
- **Licensing Partners**: Licensing the patented technologies and/or strategic alliances for advancing TRL to commercialization stage
- **Facilities**: Industrial site for pilot plant demonstration
- **Collaboration for Marketing**: DMC Offtakes
- **Path Forward**: Commercial demonstration (build and operate) to validate techno-economic merits