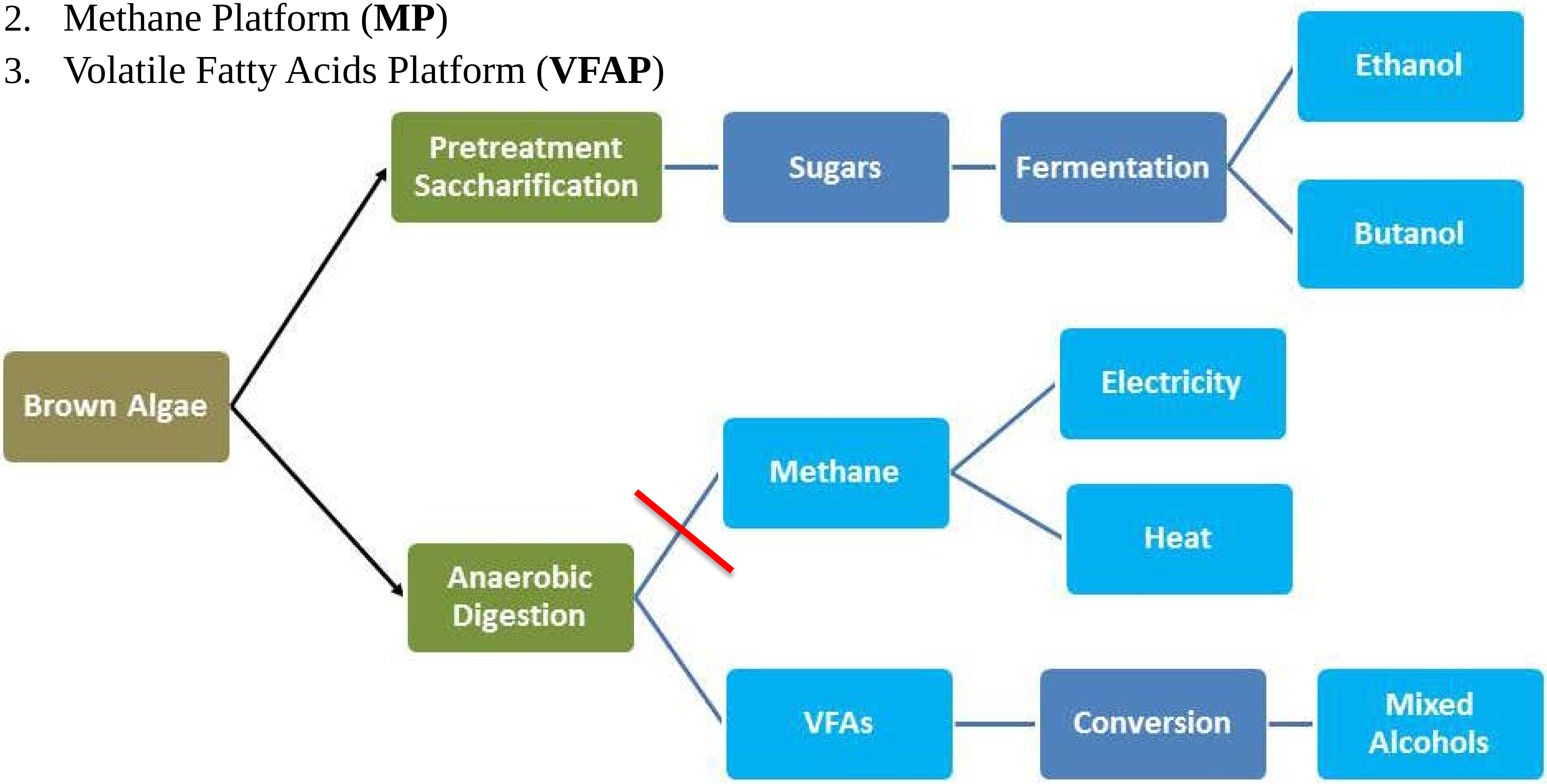
해조류 바이오연료 생산공정 설계 동향

- 모든 생화학적 전환경로의 비교 -

부경대학교 화학공학과
유준

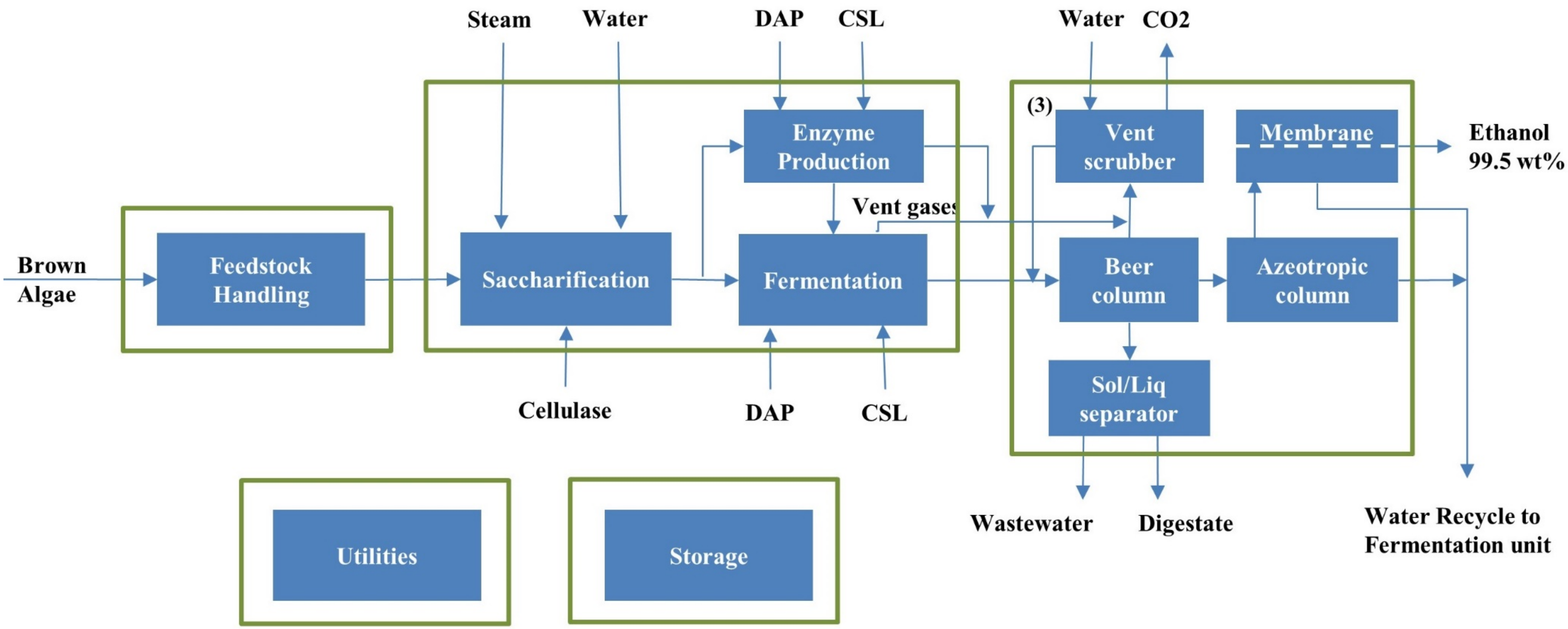
Biochemical Conversion of Biomass

1. Sugar Platform (**SP**)
2. Methane Platform (**MP**)
3. Volatile Fatty Acids Platform (**VFAP**)



Process Description: SP

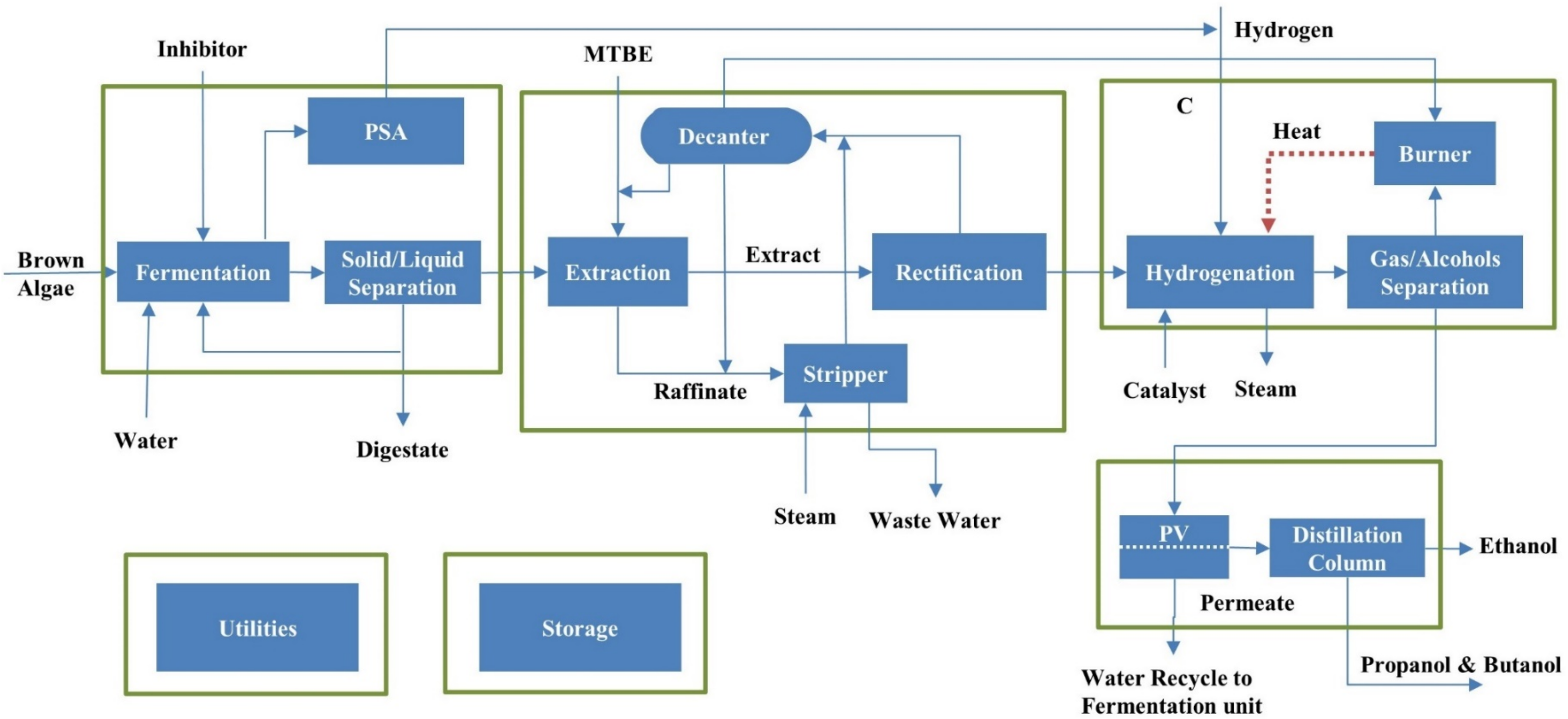
- Saccharification Temperature: **48°C**
- Fermentation Temperature: **30°C**
- Solid Loading: **20 wt%**
- Reported Yield Range: $\mathbf{0.22 - 0.28\ \frac{kg\ Eth}{kg\ dry}}$
- Saccharification: **2.67 days**
- Fermentation: **2.67 days**
- PV membrane permeate flux: **8.5 kg/m² h** at **75°C**, **Selectivity>10,000** (Sato et al., 2011)



Fasahati, Woo, & Liu, *Applied Energy* (2015)

Process Description: VFAP

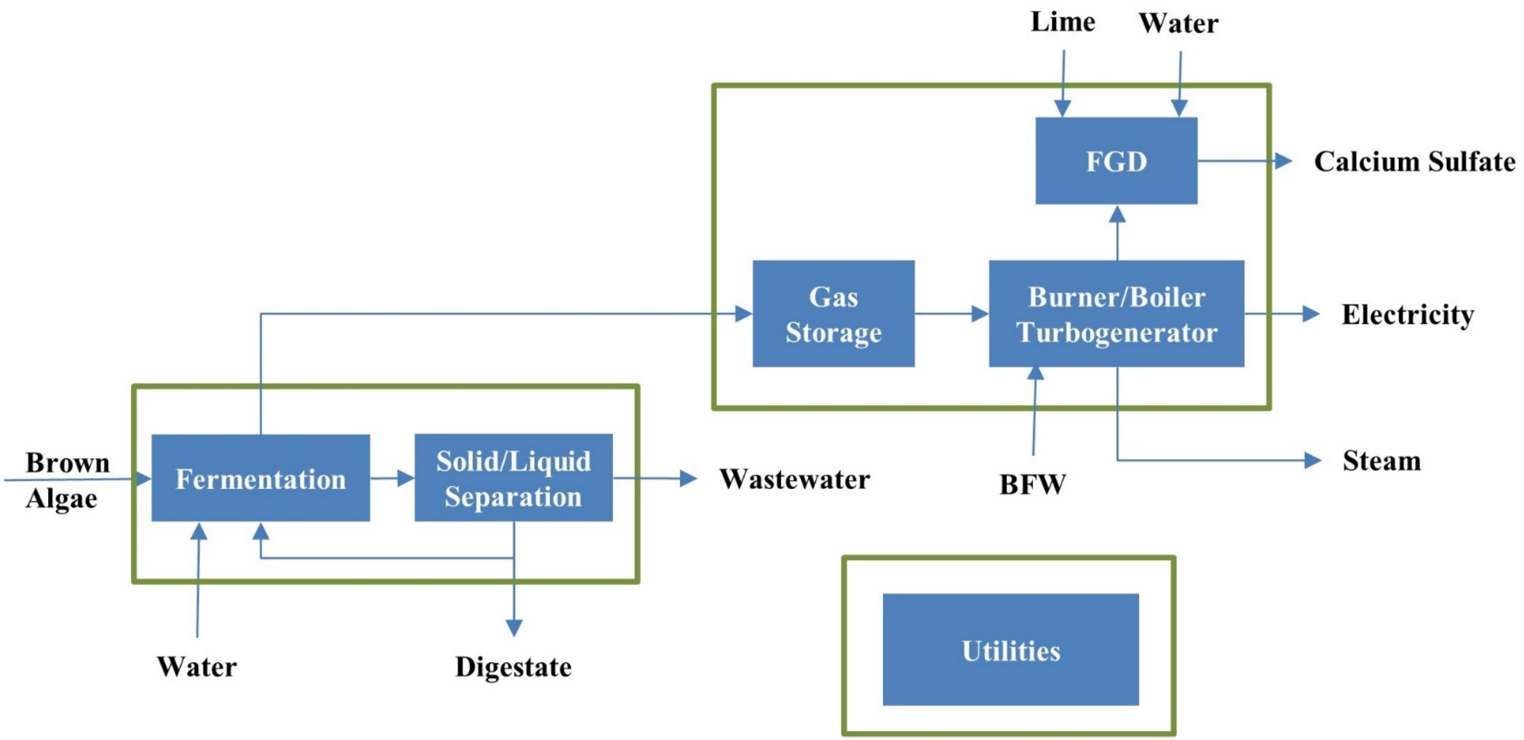
- Fermentation Temperature: **35°C (5 days)**
- Solid Loading: **13 wt% (5% VFA conc.)**
- Reported Yield Range $\mathbf{0.3 - 0.4} \frac{\text{kg}\, VFA}{\text{kg}\, dry}$
- VFA mol%: 67% AcAc, 22% PrAc, 11% BuAc
- VFA Rec.: **95%**
- Hydrogenation conv.: **97%** (290°C and 60 bar)
- PV membrane permeate flux: **8.5 kg/m² h** at **75°C, Selectivity>10,000**



Fasahati & Liu, *Energy* (2015)
Fasahati & Liu, *Chem. Eng. Res. & Des.* (2015)

Process description: MP

- ❖Fermentation Temperature: **35°C (10 days)**
- ❖Solid Loading: **10 wt%**
- ❖Reported Yield Range: $\mathbf{0.23 - 0.3\ \frac{m^3}{kg\ VS}}$
- ❖Net Electricity: **27,100 kW**



Fasahati & Liu, *Energy Conversion & Management*, accepted (2016)

Process Simulation

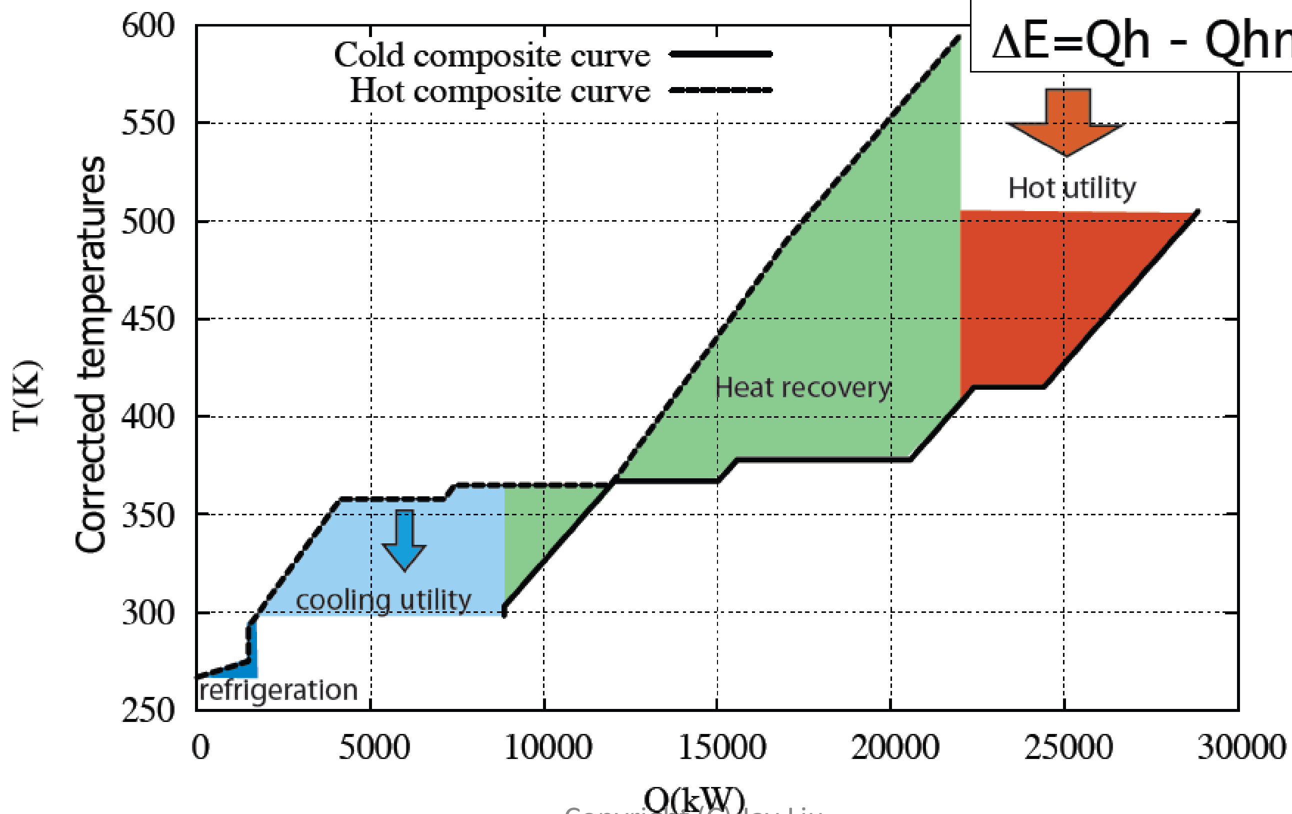
- With experimental data from literature, all processes are rigorously simulated in Aspen Plus.

	SP	VFAP	MP
Temperature (°C)	Saccharification: 48 Fermentation: 30	35	35
Solid Loading	20 wt%	13 wt%	10 wt%
Fermentation Time (days)	Saccharification: 2.67 Fermentation: 2.67	5	10
Fermentation Yield	$0.25\ \frac{\text{kg Eth}}{\text{kg dry}}$ Range: 0.24 ~ 0.28	$0.35\ \frac{\text{kg VFA}}{\text{kg dry}}$ Range: 0.3 ~ 0.4	$0.265\ \frac{m^3}{kg\ VS} = 0.174\ \frac{kg}{kg\ VS}$ Range: $0.23 \sim 0.3\ \frac{m^3}{kg\ VS}$
Plant Scale	400, 000 ton dry/year		
Product	Ethanol: 12,400 kg/hr	Ethanol: 7,400 Prop. & But.: 6,100	Net Electricity: 27,100 kW

Heat Integration

❖ Heat integration analysis is performed separately for each process in order to minimize the utility requirements. An inventory of the heat demand and supply within the plant is made and ordered by temperature range.

Benefit :
ΔE=Qh - Qhmin



Heat Integration

- **LP steam** at **164°C**, **MP steam** at **186°C**, and **HP steam** at **254°C** are used as heating sources. Cooling demands at **above 40°C** are met by **cooling water**. Cooling below 40°C is required in the saccharification and fermentation reactors, as well as liquefaction of permeate and ketones, and production of ammonium bicarbonate, where **chilled water** (**4-15 °C**) and **liquid propane** (**-20 °C**) are used, respectively.
- Hot and cold streams are matched under the following criteria:
  - Matches between near streams (same plant section) are preferred;
  - A minimum temperature differences of **5°C, 10°C**, **20°C**, and **30°C** are imposed for condensation, **liquid-liquid**, **liquid-gas**, and **gas-gas** heat transfer matches.

Techno-economic analysis

A techno-economic model similar to the one developed in **NREL** for lignocellulosic biomass is used for economic assessments.

- **Start-up** period **three month** and **30 years** plant life.
- **Contingency 10%** of total project cost.
- **10%** internal rate of return (**IRR**).
- **Working capital 5%** of total capital expense per year.
- **Tax rate 35%** per year.
- Startup period
    - **Revenues** during **start-up**: **50%**
    - **Variable costs** incurred during **start-up** : **75%**
    - **Fixed costs** incurred during **start-up** : **100%**
- Membrane cost : 1000 $/m2 (US-DOE-NETL)
- Membrane replacement : every 5 year
- Ethanol price: **2.58 $/gal (EIA, 2012)**
- Butanol: **1.5 $/kg (Tecnon, 2013)**
- Electricity: **0.0984 $/kWh (EIA, 2012)**
- **Depreciation** method (recovery period) : **200%** declining balance (**7 years**)
- **Land**: **6%** of **installed cost**.
- **Salvage** value**: 0 M$**
- Construction period: **One year**
- Operating hours per period: **8000 h/year**

Techno-economic analysis

Fixed operating costs	
Labor cost	1.6% of total installed cost
Maintenance cost	3.0% of total installed cost
Property insurance and tax	0.7% of FCI
Variable operating cost	
Biomass	Laminaria japonica
Cost of macroalgae cultivation	54.4 $/ton (dry basis)
Transport cost	13.6 $/ton (dry basis)
Total macroalgae cost	68 $/ton (dry basis)
Hydrogenation catalyst	18.975 $/lb catalyst
LP steam at 164°C	12.68 $/ton
Waste water	0.041 $/m3
Hydrogen	1.5 $/kg
Disposal of Ash	32 $/ton
Boiler Chemicals	5092 $/ton
MTBE	1100 $/ton
Process water	0.27 $/ton

Direct costs	% of installed costs
Installed costs	100%
Warehouse	4%
Site development	9%
Additional piping	4.5%
Indirect costs	% of total direct costs (TDC)
Prorateable costs	10%
Field expenses	10%
Home office and construction	20%
Project contingency	10%
Other costs	10%

Cost estimation

- Base year: 2012
- Chemical engineering plant cost index (**CEPCI**).

Item	Scaling Exp.	Year of Quote	Cost US$	Inst. Fac.	Ref.
Hydrogenation reactor	0.56	2002	2,026,515	2.47	Phillips et al., 2007
Flash tank	0.7	2009	511,000	2.0	Humbird et al., 2011
Alcohols Separation Column	0.68	1996	525,800	2.1	Aden et al., 2002
Azeotropic Column	0.68	1996	525,800	2.1	Aden et al., 2002
Reboiler	0.68	1996	158,374	2.1	Aden et al., 2002
Condenser	0.68	1996	29,544	2.1	Aden et al., 2002
Pressure Filter	0.8	2010	3294700	1.7	Humbird et al., 2011
Fermentation Reactors	1.0	2009	844,000	1.5	Humbird et al., 2011
PSA unit	0.6	2002	4,855,471	2.47	Spath et al., 2005
Digesters	0.6	2012	6,450,000	1.1	Davis et al., 2013
Saccharification Tanks	0.7	2009	480,000	2	Humbird et al., 2011

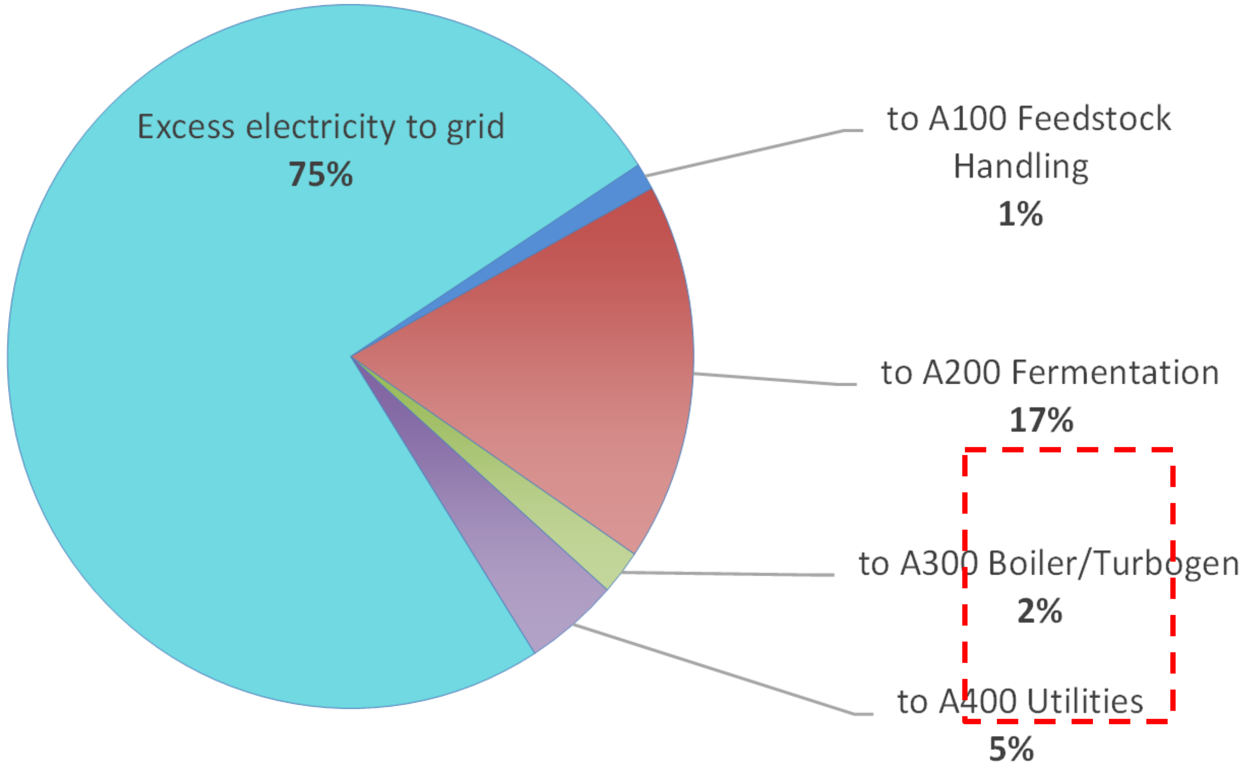
GHG Emissions calculation

- CO_2 emissions: calculated according to **US EPA (Environmental Protection Agency)**.
- **Natural gas** was considered as fuel for provision of heat and steam.
- CO_2 emissions due to **electricity** consumption were calculated based on US annual output emission rates for electricity production.
- **80% boiler efficiency** were considered for steam production.
- Compression refrigeration with **38˚C** condenser requires **1.31 kW/tonne** at **-18˚C**.
- Power requirement for **cooling water** and **chilled water** is obtained from Aspen Plus simulations.
- Emission factors were converted to **CO_2 equivalent** using **100 year global warming potential**:

Gas	100-year GWP
CH_4	25
N_2O	298

Utility Costs

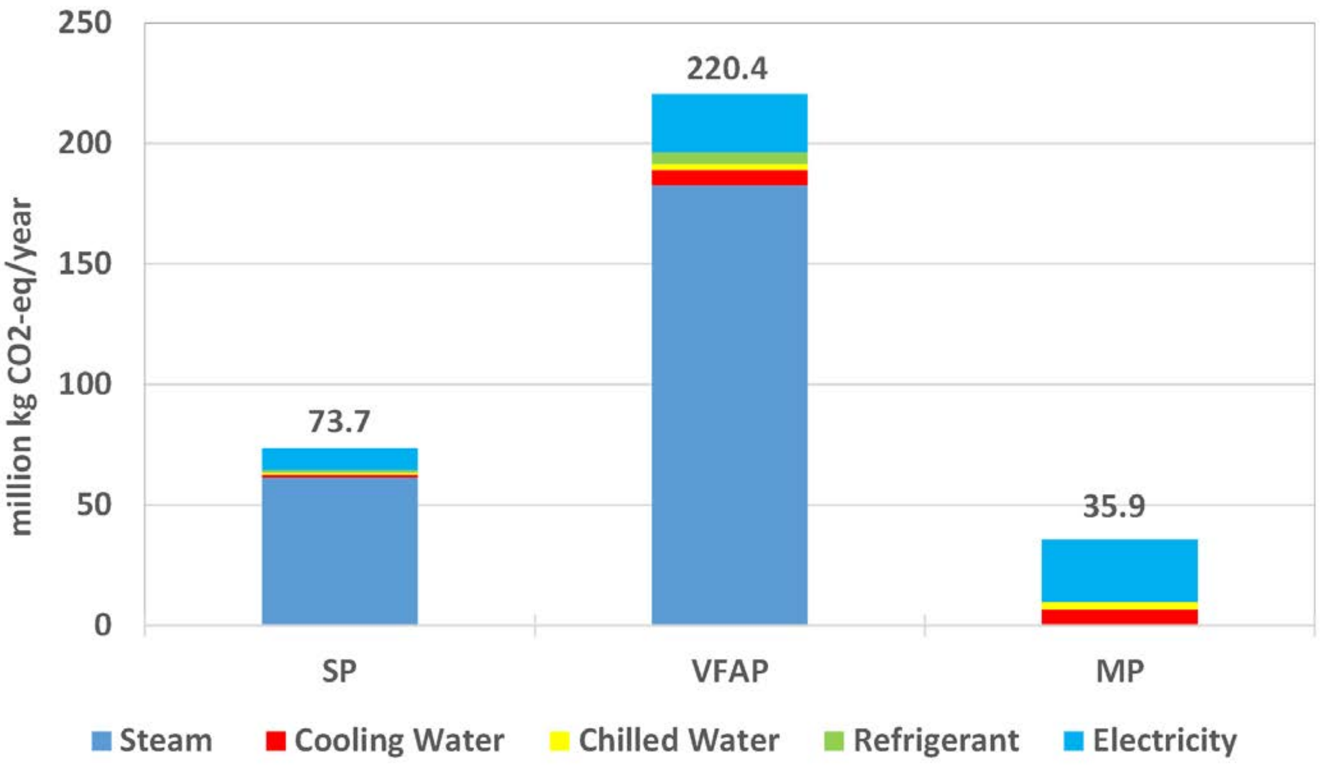
- Total utility costs: **11.6 (SP), 32.3 (VFAP)**, and **6.8 (MP) million$/year**
- The energy requirements of the MP is covered by part of electricity produced in the process.



Electricity consumption breakdown for MP.

GHG emissions

❖ CO_2 emissions: **73.7(SP)**, **220.4(VFAP)**, and **35.9(MP) million kg CO_2-eq/year**.



Total Capital Investment

- **TCI:**, **84.7 (SP), 106.4 (VFAP)**, and **105.9** (**MP)** million$

	SP (Million$)	VFAP (Million$)	MP (Million$)
Feedstock Handling	17.0	17.0	17.0
Fermentation	21.2	23.1	18.5
Extraction/Distillation	-	16.4	-
Hydrogenation	-	4.1	-
Boiler/Turbogenerator	-	-	30.0
Distillation/Recovery	16.7	2.6	-
Storage	3.1	3.5	-
Utilities	1.4	3.9	4.1
Total Installed Costs	**42.4**	**53.6**	**52.6**
Total Direct Costs (TDC)	49.1	61.7	61.1
Total Indirect Costs	29.4	37.0	36.7
Fixed Capital Investment (FCI)	78.5	98.7	97.8
Total Capital Investment (TCI)	**84.7**	**106.4**	**105.9**

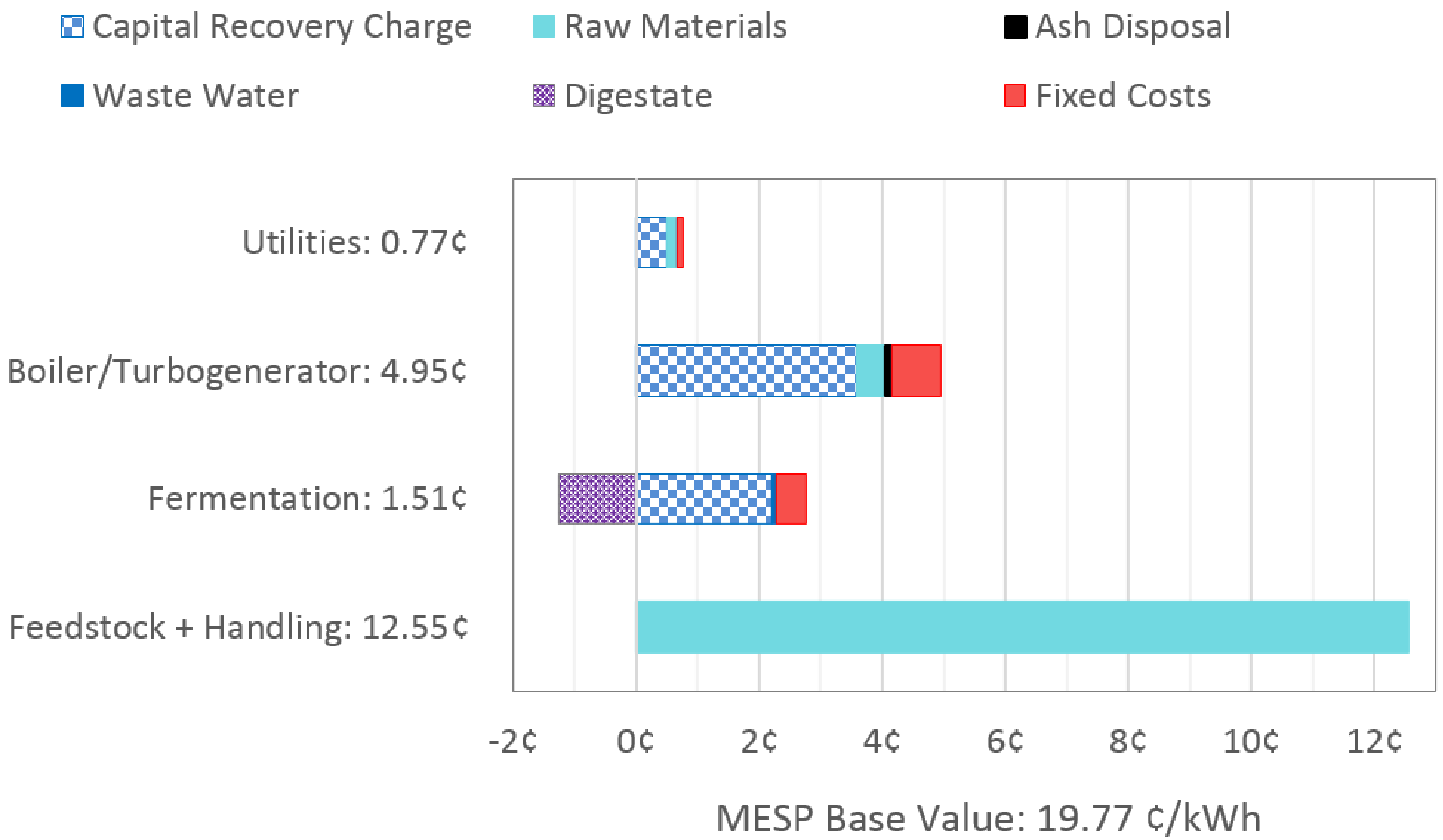
NPV

	SP	VFAP	MP
TCI (mm$)	**84.7**	**106.4**	**105.9**
Feedstock (mm$/y)	27,2	27,2	27,2
Utility (mm$/y)	11.6	32.2	0
Other Variable Cost (mm$/y)	1.4	11.3	1.8
Fixed Operating Cost (mm$/y)	2.3	2.9	3.0
Annual Manufacturing Cost	**42.5**	**73.6**	**31.9**
Ethanol (mm$/y)	85.7	51.1	-
Propanol & Butanol (mm$/y)	-	55.9	-
Electricity (mm$/y)	-	-	21.3
Digestate (mm$/y)	3.4	3.4	2.7
Total Annual Sales	**89.1**	**110.4**	**24.0**
NPV (mm$)	**216.7**	**140.0**	**-179.6**

Ethanol price: **2.58 $/gal**; Butanol: **1.5 $/kg**; Electricity: **0.0984 $/kWh**; Biomass: **68 $/ton**

Minimum Electricity Selling Price for MP

- MESP: **19.77 ¢/kWh** to reach a breakeven point after 30 years of plant life.



Cost contribution details from each process area to total MESP for MP

Minimum Electricity Selling Price for MP

- MESP: **19.77 ¢/kWh** to reach a breakeven point after 30 years of plant life.

Period	California	Arizona	Michigan	New York	Connecticut	Hawaii	Washington
2015	18.24	10.09	15.43	18.44	19.20	29.87	9.36

Average selling Price (¢/kWh) of Electricity for residential sector at 2015 (http://www.eia.gov/)

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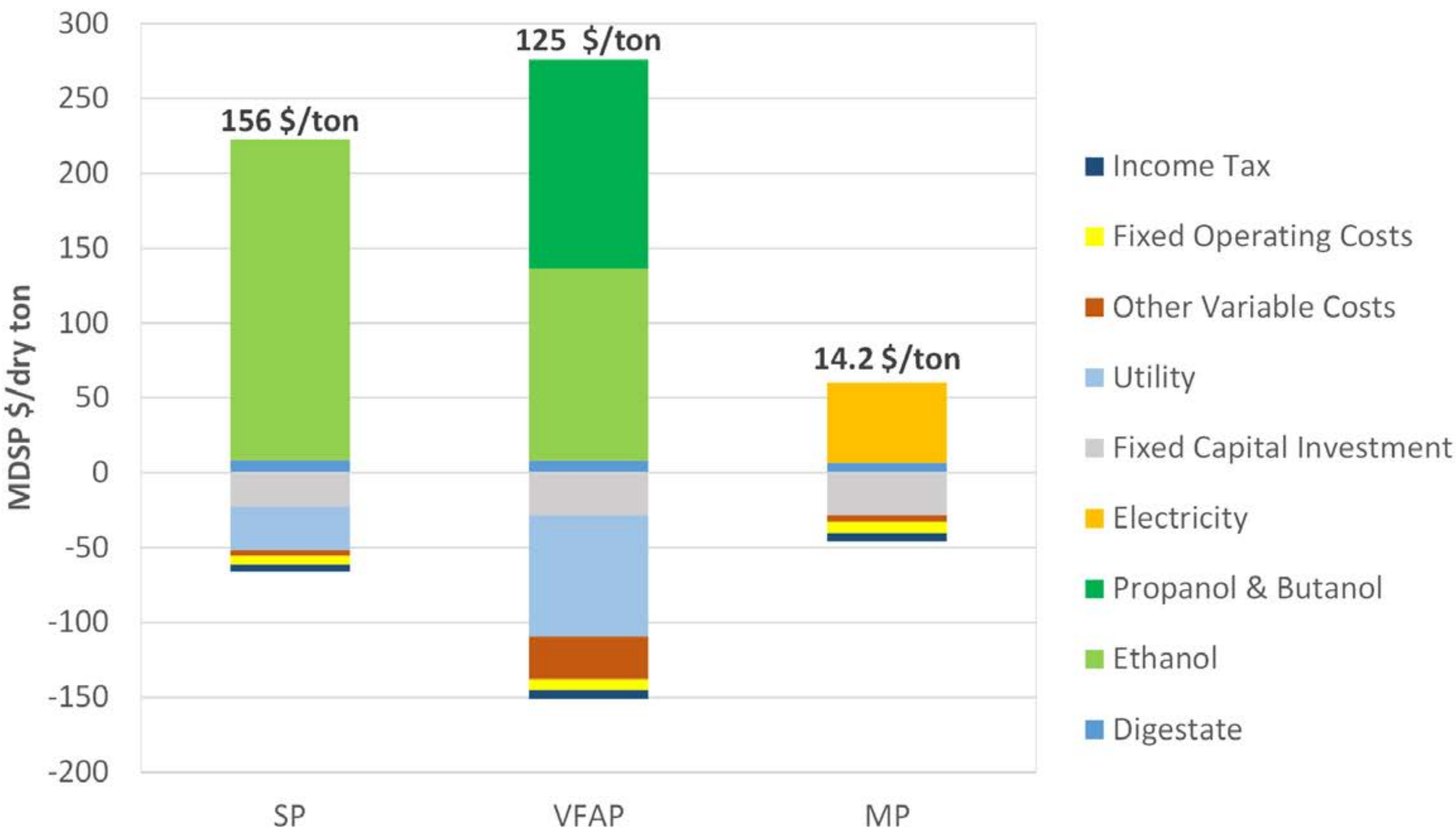
Maximum Seaweed Price (MSP)

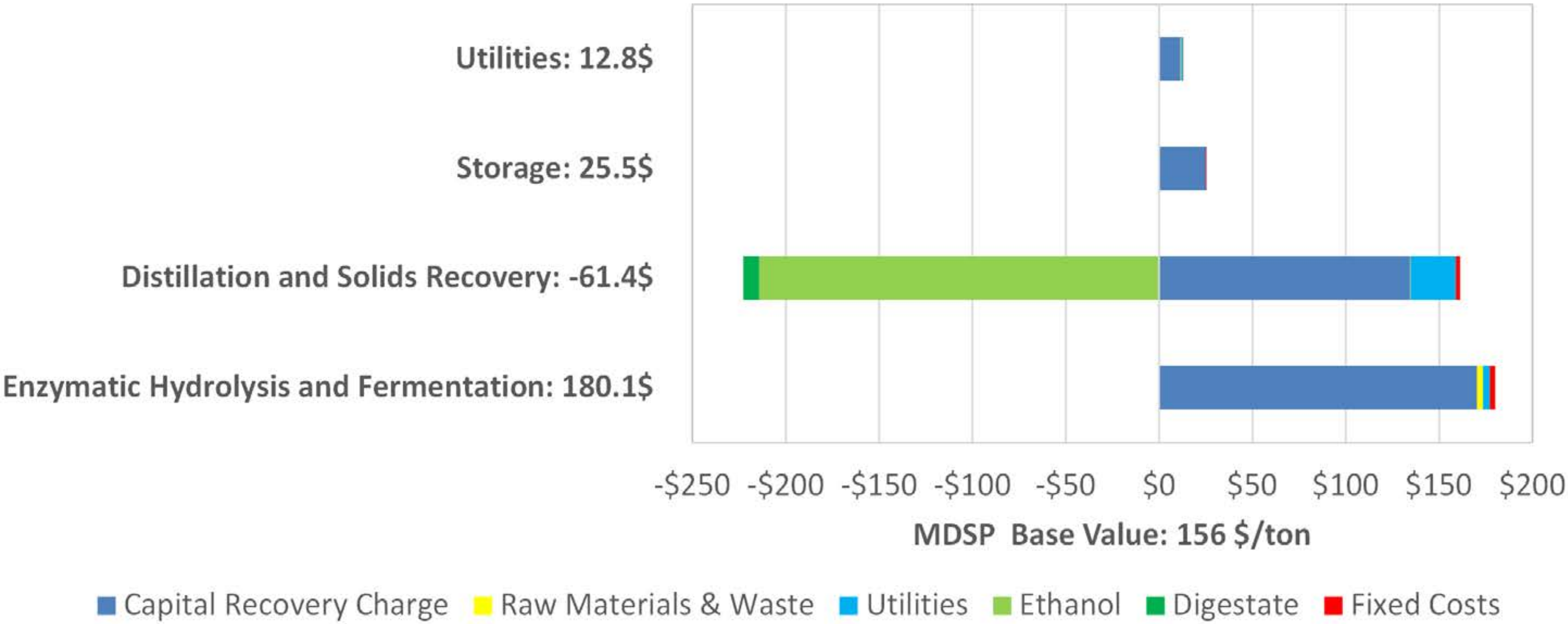
❖ The MSP: **156 (SP), 125 (VFAP)**, and **14.2 (MP) $/dry ton**



the price of the feedstock at the plant gates (costs of cultivation, storage, and transportation)

MSP of SP

❖ Fermentation and distillation units have highest contribution.



Cost contribution details from each process area to total MDSP for SP.

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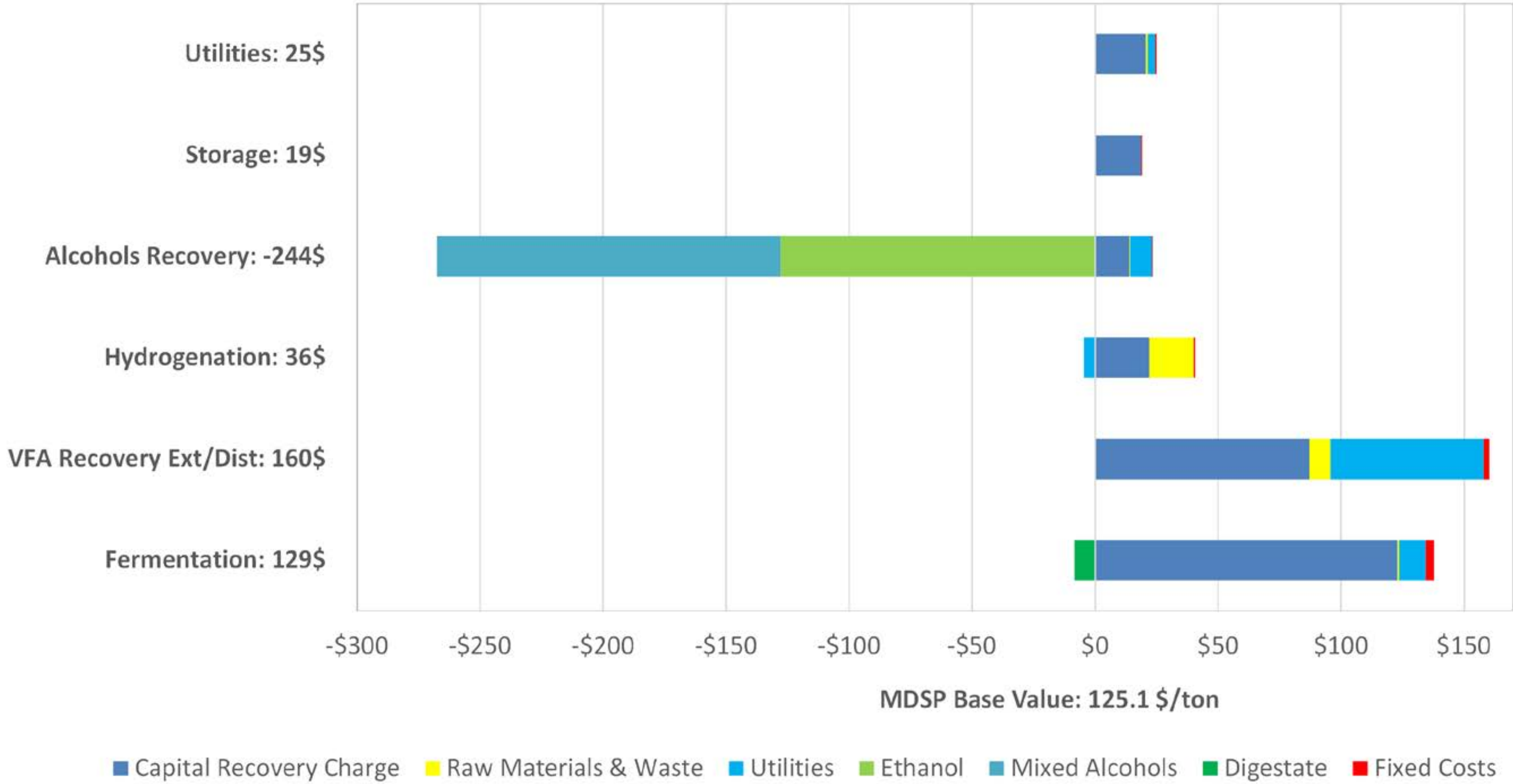
MSP of VFAP

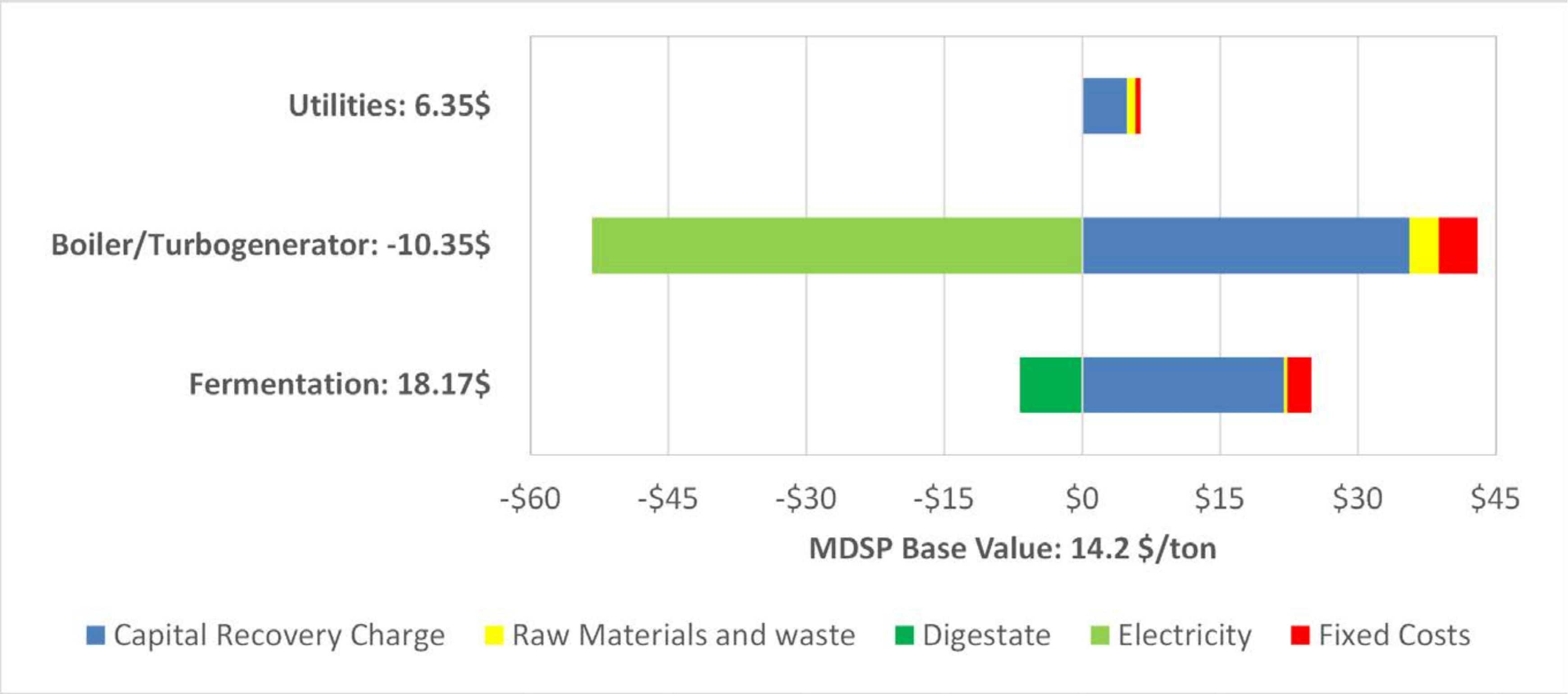
❖ Fermentation and VFA recovery units and utility demands of VFA recovery have highest contribution.



Cost contribution details from each process area to total MDSP for VFAP

MSP of MP

- ❖ Boiler/turbogenerator and fermentation unit has the highest contribution.
- ❖ Low MDSP comes from low electricity selling price (0.0984 $/kWh).



Cost contribution details from each process area to total MDSP for MP

Summary

- Brown algae are viable biomass resources for biofuel and bioenergy production.
- **SP** is economically **superior** over VFAP and MP in NPV and MDSP.
- In VFAP, **high utility demands for VFA recovery** and hydrogen purchase makes the production process very costly.
- In MP, low electricity selling prices does not allow the process to recover the capital and operating costs. However, **MP has the lowest energy demands** and is able to provide all of its energy requirements which results in **zero GHG emission**.
- Decreasing the biomass price by enhanced artificial seaweed mass cultivation can strongly improve the process economics.