해조류 바이오연료 생산공정 설계 동향

- BIOCHEMICAL CONVESION 2 -

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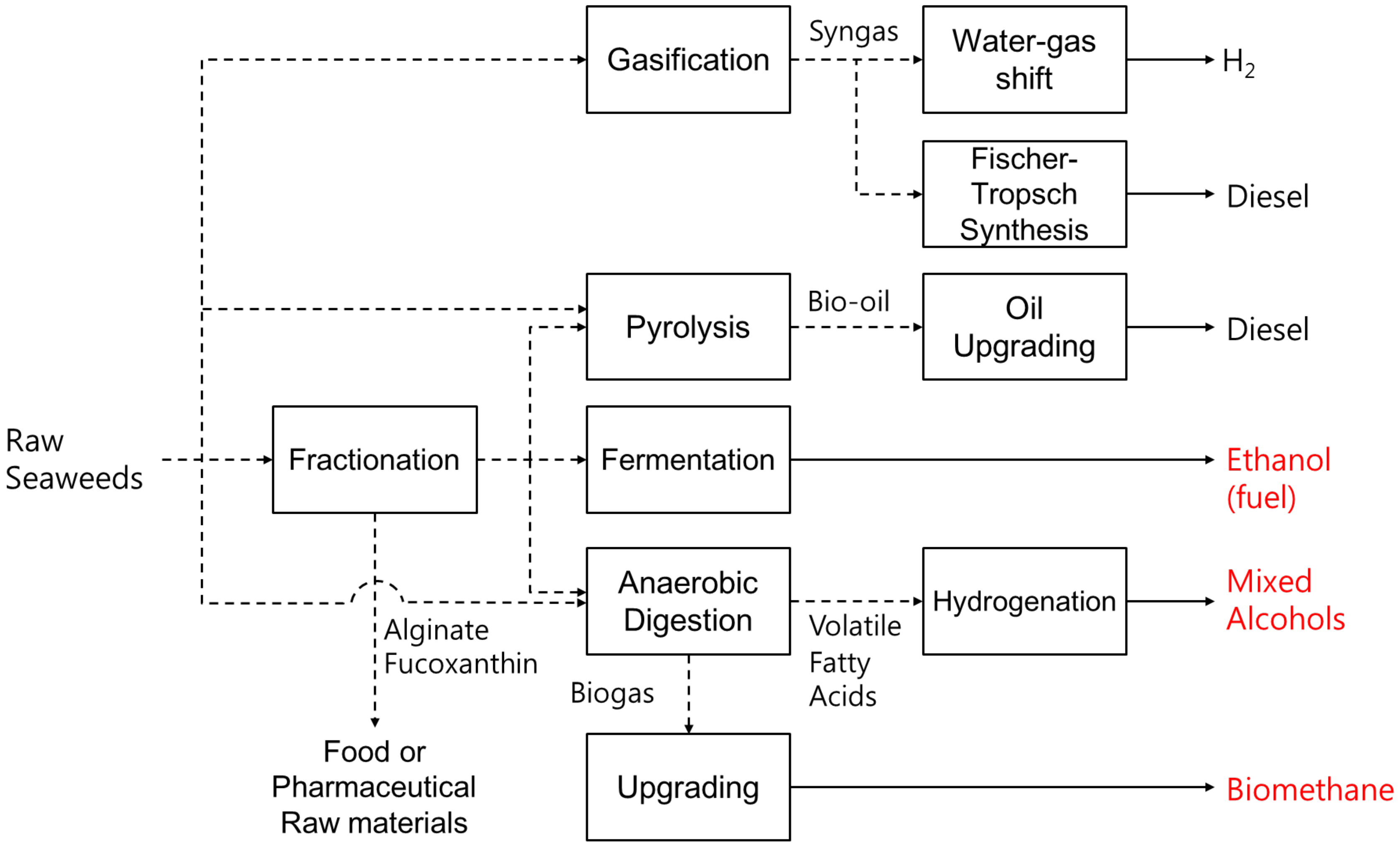
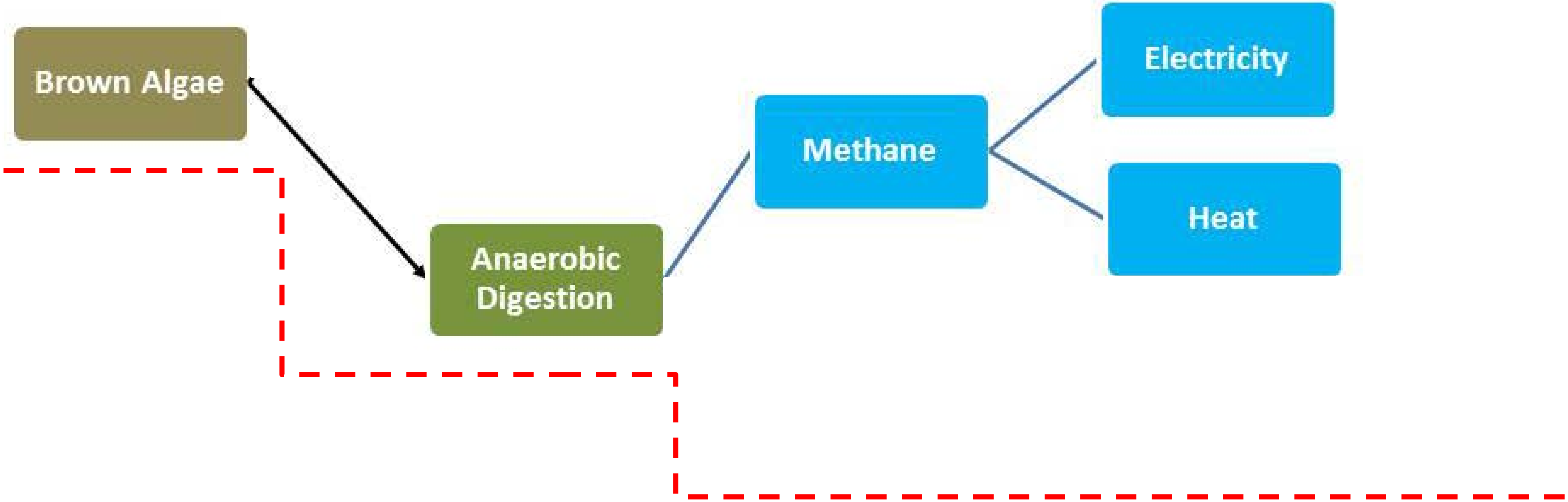
(Possible) Biorefinery network for seaweed biomass



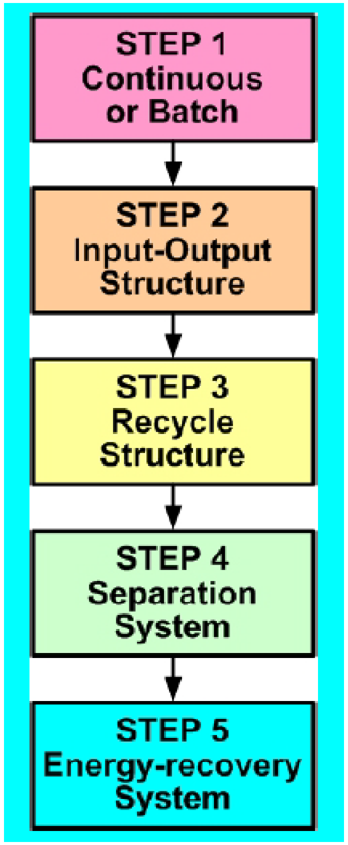
Biochemical Conversion of Biomass

2. Methane Production

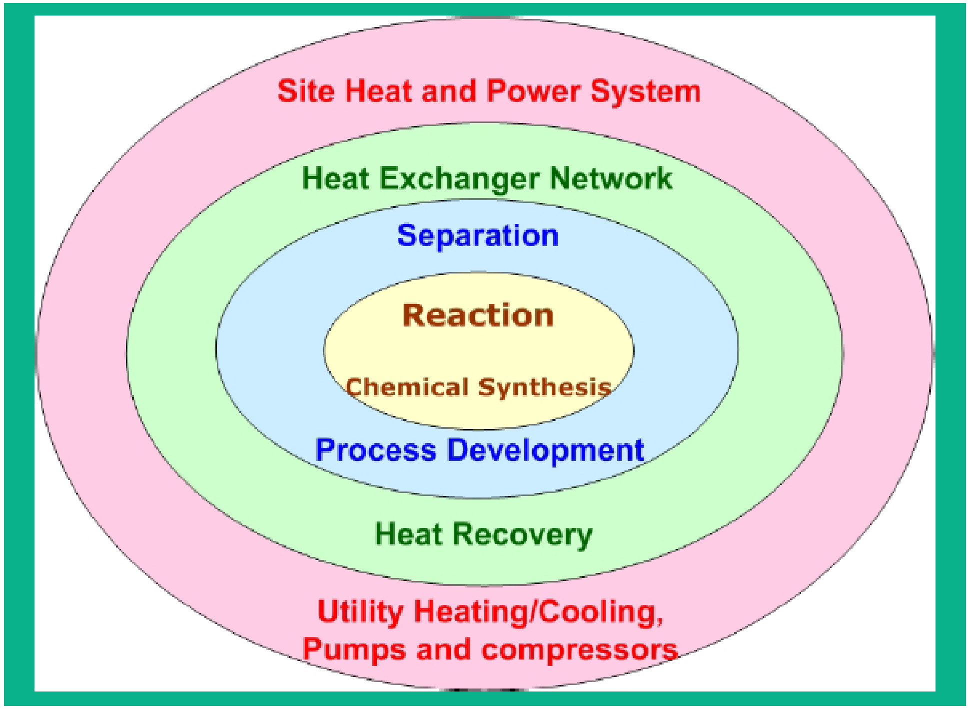


Conceptual process design

Hierarchical design



Onion model



Conceptual design of methane production

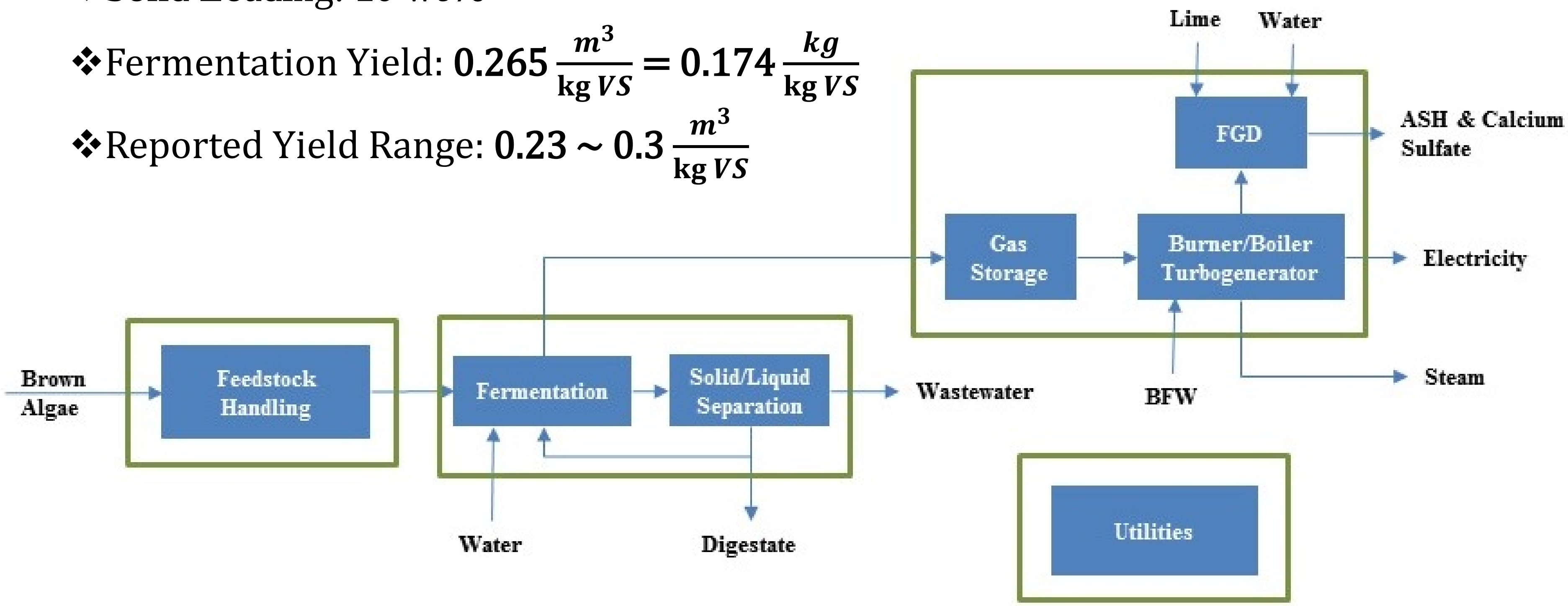
Base case

❖Fermentation Temperature: **35°C (10 days)**

❖Solid Loading: **10 wt%**

❖Fermentation Yield: $\mathbf{0.265\,\frac{m^3}{kg\,VS} = 0.174\,\frac{kg}{kg\,VS}}$

❖Reported Yield Range: $\mathbf{0.23 \sim 0.3\,\frac{m^3}{kg\,VS}}$



Conversions

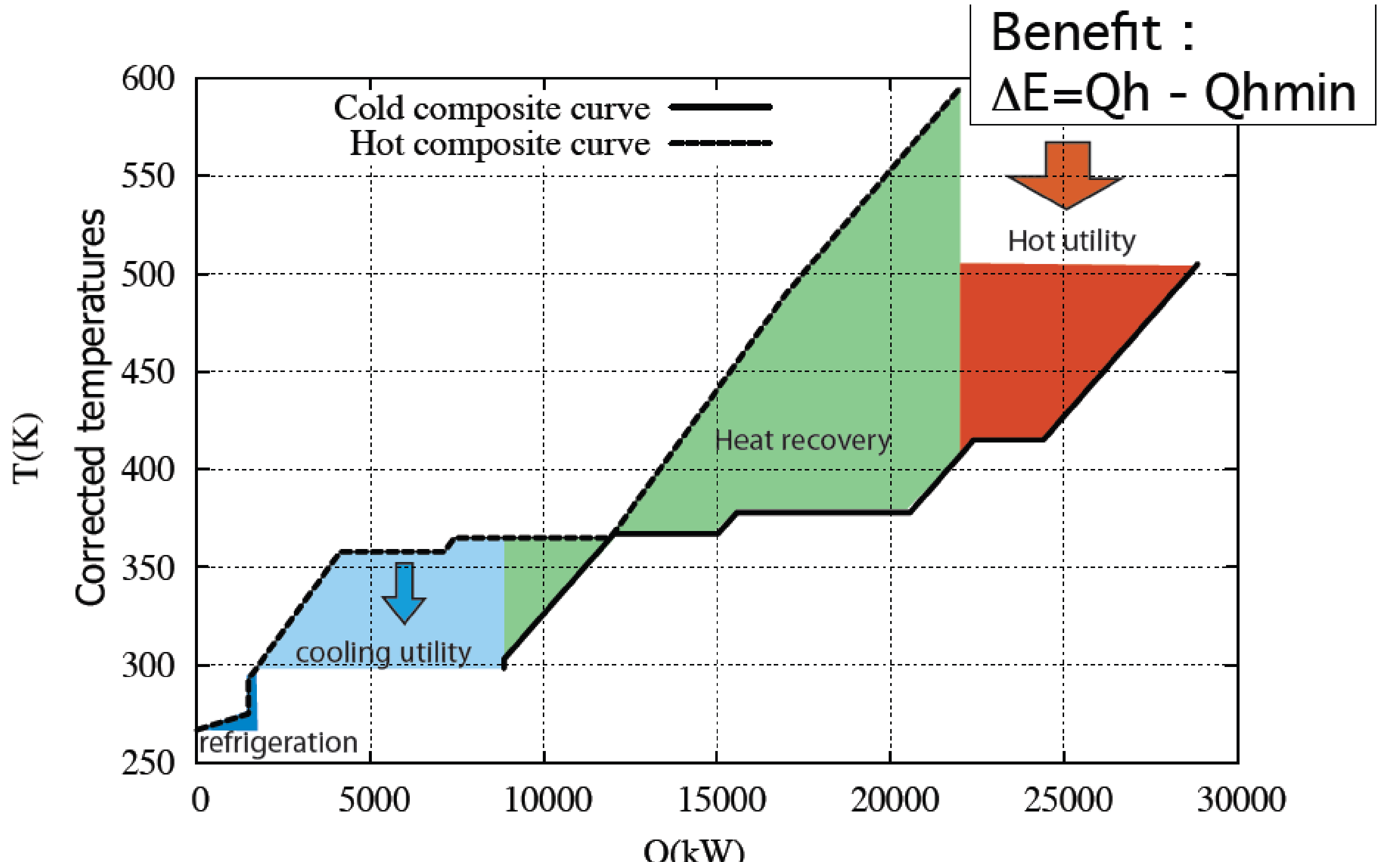
Brown algae type	CH_4 yield (m^3/kg VS)	Temperature (°C)	Time (days)
L. japonica	0.18	35	6~20
L. Digitata	0.14~0.17	37	21
L. japonica	0.297	55	17~28
L. japonica	0.25~0.28	35	14~46
L. japonica	0.24~0.30	35	9~30
L. Saccharina	0.205~0.220	37	25
L. saccharina	0.230	35	24
Ascophyllum nodosum	0.110	35	24
L. hyperborea	0.280	35	24
Macrocystis pyrifera (giant kelp)	0.277-0.310	38	18

Process Simulation

- A plant scale of **400,000** ton dry seaweed/year is considered.
- It was assumed that brown algal biomass contained **20% moisture** at the plant gates.
- The fermentation and reactors are modeled as conversion reactors (**RSTOIC**).
- Burner/Turbogenerator, FGD, cooling tower, and chilled water processes simulated according to NREL's Aspen Plus simulation for Ethanol from corn stover (Humbird et al., 2012).

Heat exchanger network design

- Heat integration analysis is performed for the 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.



Heat exchanger network design

- Cooling demands at **above 40°C** are met by **cooling water**. Cooling below 40°C is required in the fermentation reactors where **chilled water** (**4-15 °C**) is used.
- 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 model

- **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%**
- **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 model

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)
Waste water	0.041 $/m3
FGD Lime	203 $/ton
Disposal of Ash	32 $/ton
Boiler Chemicals	5092 $/ton
Cooling Tower Chemicals	3051 $/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%

Capital costs

- Using **NREL's equipment cost reports** quoted by vendors, the equipment costs were updated based on the **2012 dollar value**, by using the chemical engineering plant cost index (**CEPCI**).

Item	Scaling Exp.	Year of Quote	Cost US$	Inst. Fac.	Ref.
Digesters	0.6	2012	6,450,000	1.1	Davis et al., 2013
Flash tank	0.7	2009	511,000	2.0	Humbird et al., 2011
Boiler	0.6	2010	28,550,000	1.8	Humbird et al., 2011
Turbine/Generator	0.6	2010	9,500,000	1.8	Humbird et al., 2011
Amine Addition Pkg.	0.6	2010	40,000	1.8	Humbird et al., 2011
Deaerator	0.6	2010	305,000	3	Humbird et al., 2011
Pressure Filter	0.8	2010	3294700	1.7	Humbird et al., 2011
Cooling Tower System	0.6	2010	$1,375,000	1.5	Humbird et al., 2011
PSA unit	0.6	2002	4,855,471	2.47	Spath et al., 2005

Sensitivity Analyses

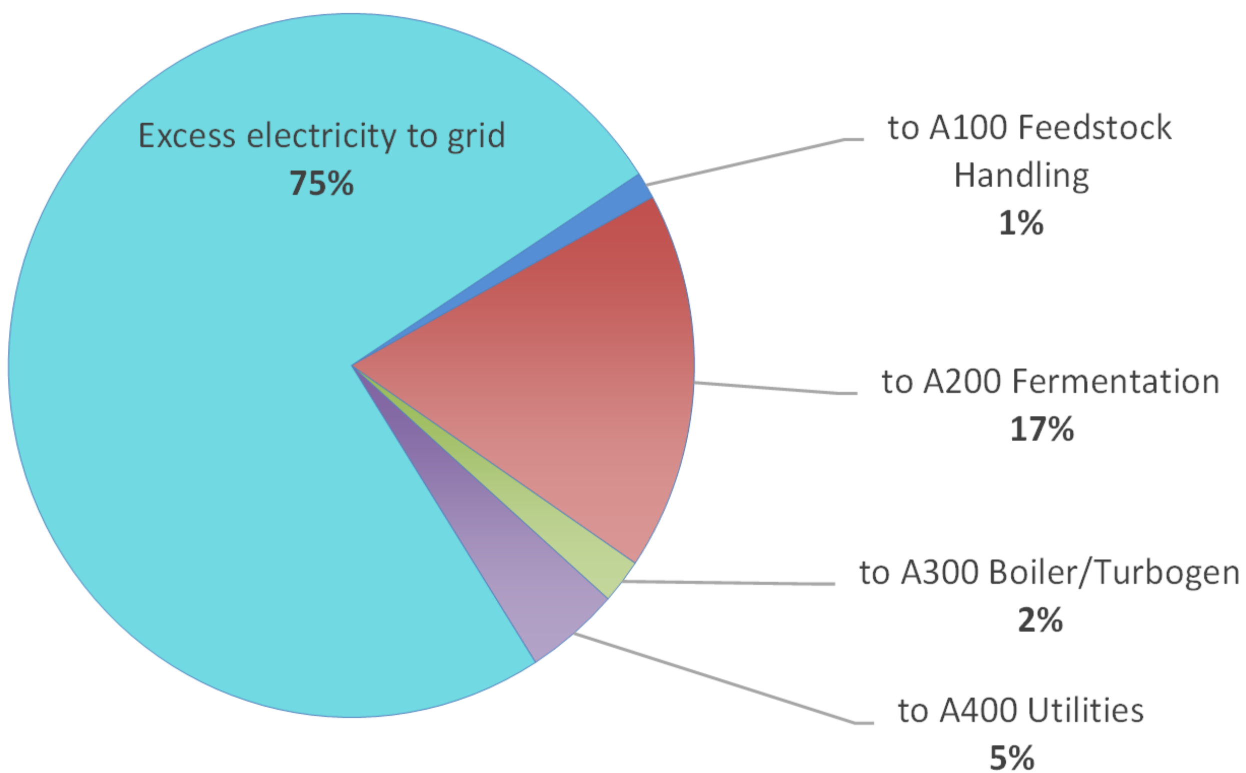
- Sensitivity analysis were performed on economic and process parameters to cover for process uncertainties and find the bottle necks of the process.
  1) Techno-economic model parameters (FCI, IRR, biomass price,…)
  2) Fermentation temperature
  3) Hydrogen recovery
  4) Solid loading
  5) Yield

Results: Main stream MB & EB

Stream	Mass flow (kg/hr)
Brown algae	62,500
Net electricity to the grid (kW)	28,450
Digestate	33,148
Fresh water	609,250
Waste water	489,860
Solid waste	1,030
FGD Lime	614
Boiler chemicals	0.0323
Cooling tower chemicals	1.52

Results: Energy Requirements

- Total electricity produced in the process is **35,760 kW** from which **25%** is consumed by the process and **27,100 KW** is delivered **to the grid**.



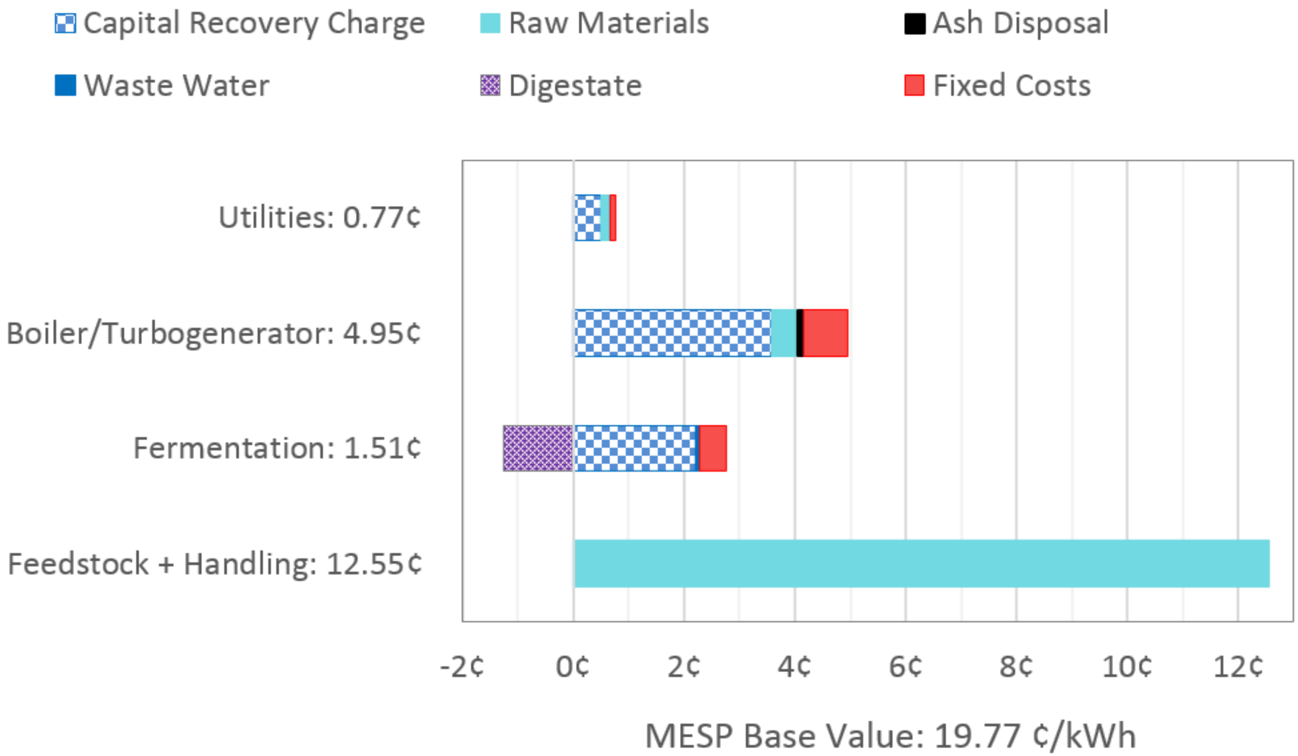
Results: TCI & manufacturing costs

	MP (Million$)
Feedstock Handling	17.0
Fermentation	18.5
Boiler/Turbogenerator	30.0
Utilities	4.1
Total Installed Costs	**52.6**
Total Direct Costs (TDC)	61.1
Total Indirect Costs	36.7
Fixed Capital Investment (FCI)	97.8
Total Capital Investment (TCI)	**105.9**

	MP
Feedstock (mm$/y)	27,2
Utility (mm$/y)	0
Other Variable Cost (mm$/y)	1.8
Fixed Operating Cost (mm$/y)	3.0
Annual Manufacturing Cost	**31.9**
Digestate (mm$/y)	2.7

Results: Minimum Electricity Selling Price (MESP)

- The MESP was calculated as **19.77 ¢/kWh** to reach a breakeven point after 30 years of plant life.



Cost contribution details from each process area to total MESP.

Results: Minimum Electricity Selling Price (MESP)

Period	Residential	Commercial	Industrial	Transportation	All Sectors
2012	11.88	10.09	6.67	10.21	9.84
2013	12.13	10.26	6.89	10.55	10.07
2014	12.50	10.75	7.01	10.27	10.45

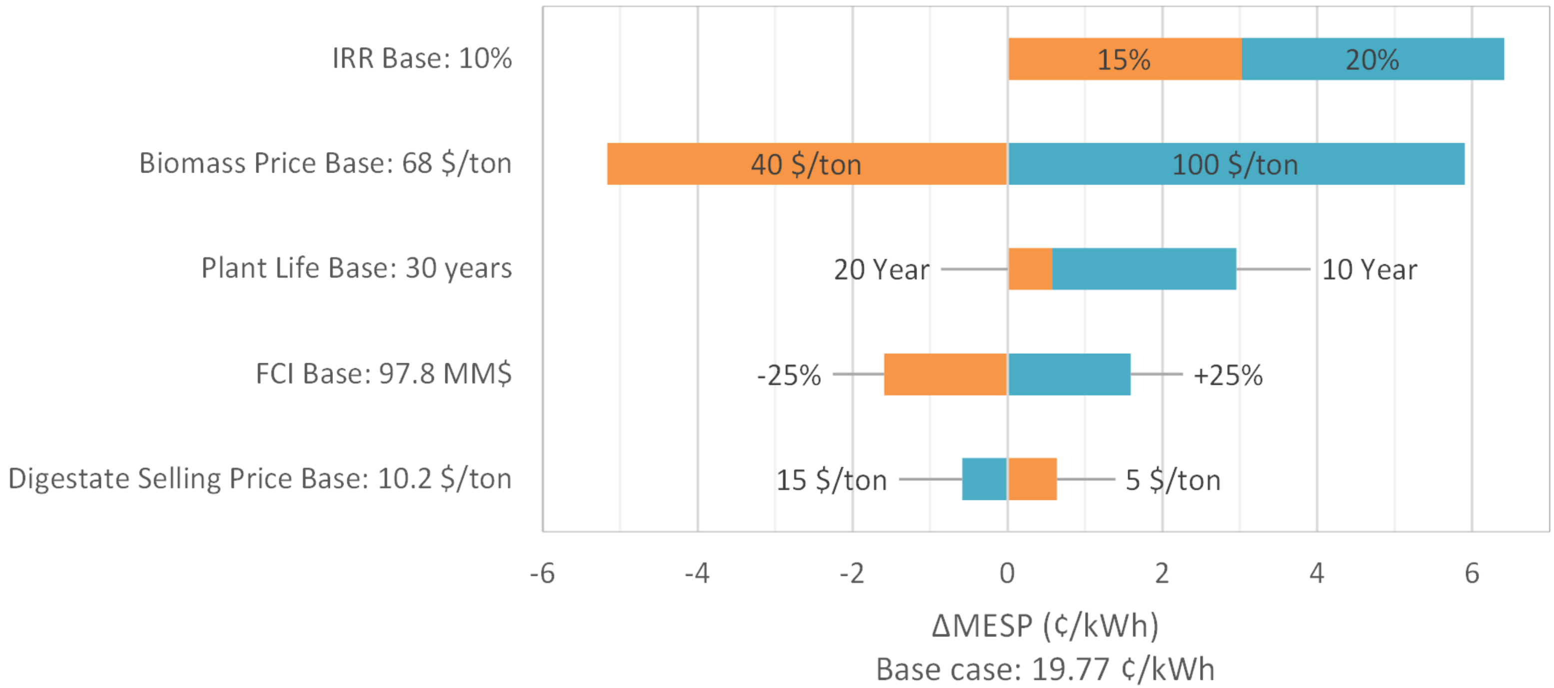
Average Price (¢/kWh) of Electricity to Ultimate Customers (http://www.eia.gov/)

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

Sensitivity Analyses: Economic parameters

- MESP showed the highest sensitivity to IRR and biomass price and minimum sensitivity to byproduct selling price.

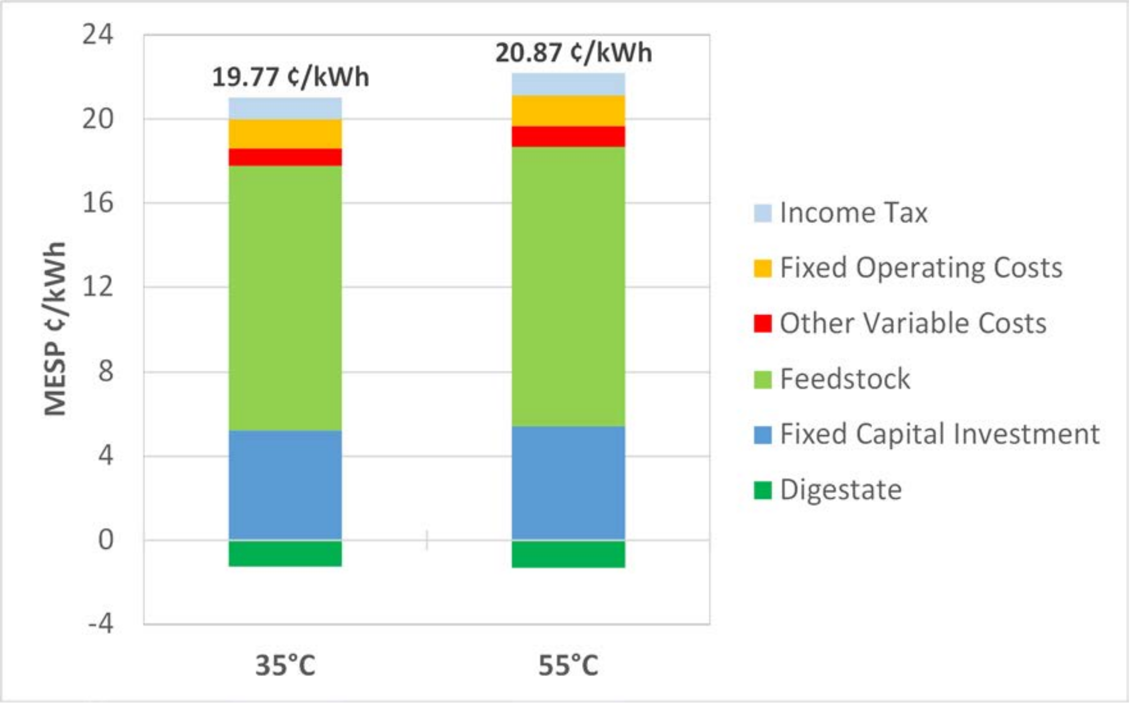


Results of sensitivity analysis on economic parameters.

Sensitivity Analyses: Fermentation temperature

- The capital cost and net electricity to grid:

  105.9 MM$/year & **27,100 kW (**35°C) ➔ **102.9 MM$/year & 25,700 kW (**55°C)
- MESP: **19.77** ¢/kWh (35°C) ➔ **20.87** ¢/kWh (55°C)



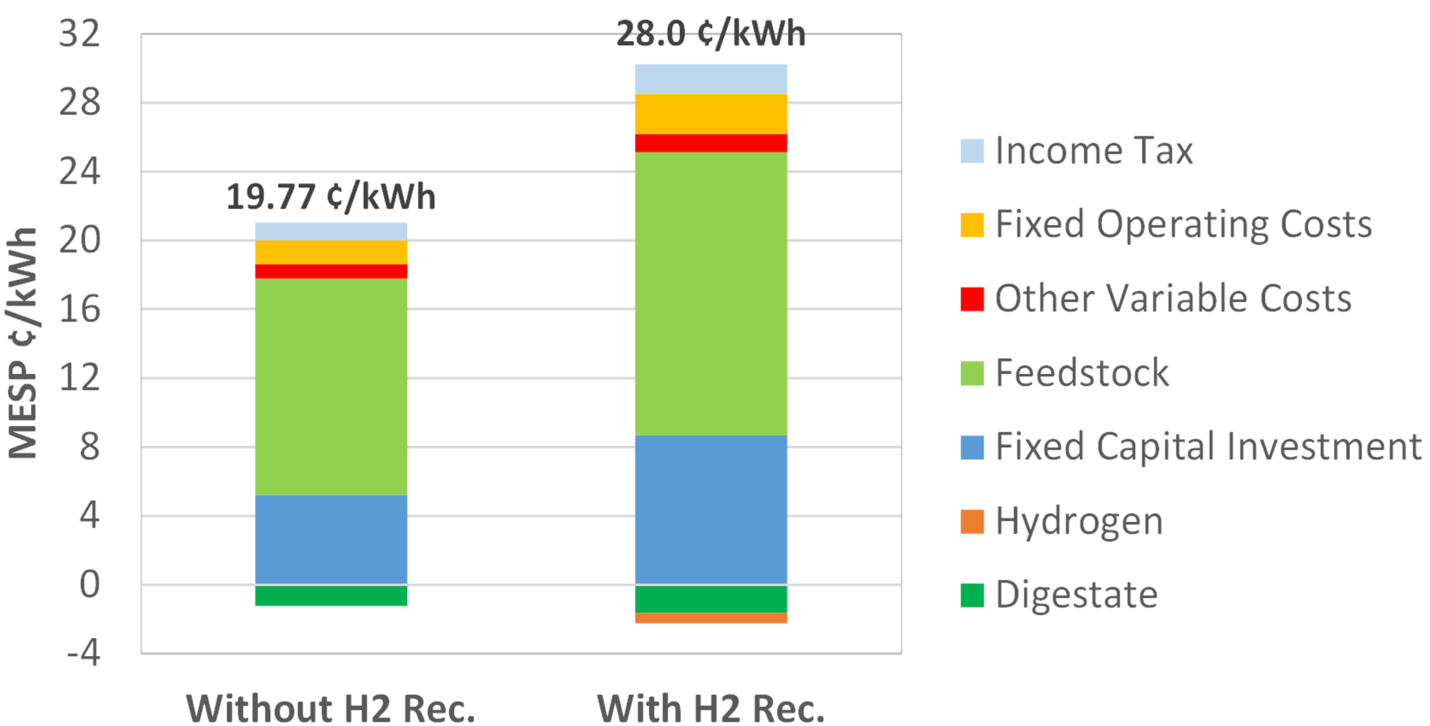
Sensitivity Analyses: Hydrogen Recovery

- Adding a PSA assuming hydrogen selling price of **1.5 $/kg** (NETL, 2009).
- The vapors from the fermenters are compressed in a two-stage isentropic compressor to **25** atm with an interstage cooling to 60°C. The compressed gases are further cooled to 40°C by cooling water and entrained liquids are removed in a knock out drum.
- For a **70 mol% hydrogen feed** to PSA, a hydrogen **recovery rate** of **85%** with a product **purity** of **99.9 vol%** is possible (Spath et al.,2005).

	No H2 Recovery	With H2 Recovery
TCI (mm$)	105.9	134.6
Electricity to grid (KW)	27,100	20,686
Hydrogen selling ($/year)	0	998,400

Sensitivity Analyses: Hydrogen Recovery

➢As a result, the MESP was changed from its base value of **19.77 to 20.87** ¢/kWh .



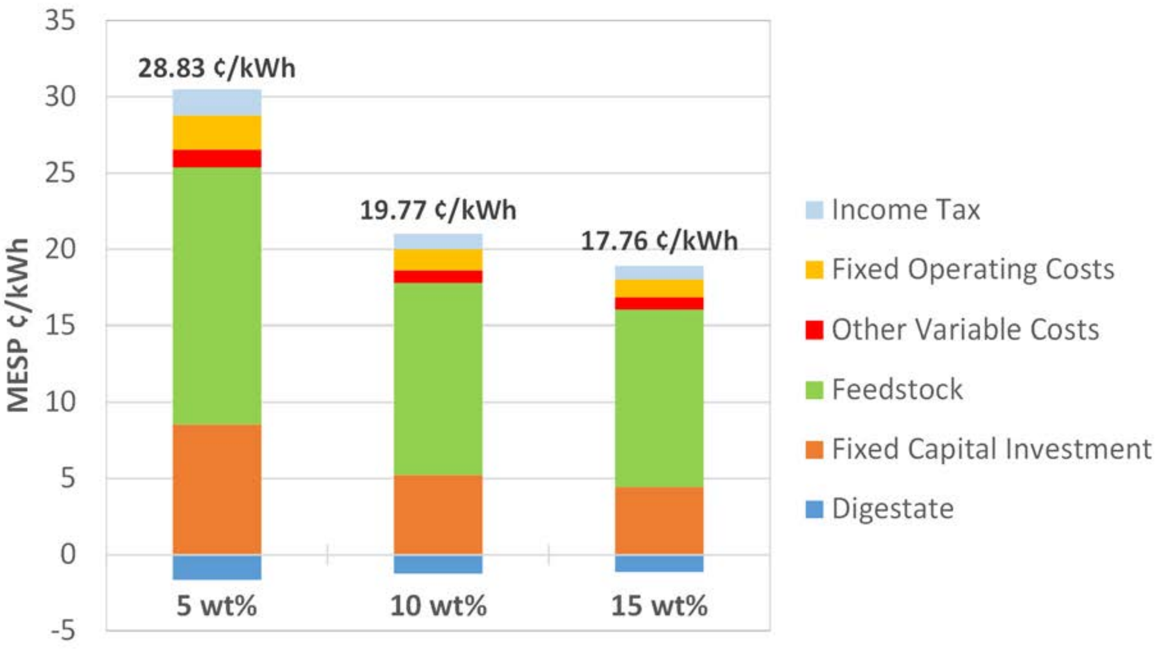
Sensitivity Analyses: Solid Loading

- The impact of solid loading was assessed by changing it from base value of **10 wt%** to **5** and **15 wt%.**
- At lower solid loadings, the process power consumption increases because of power requirements for agitation and cooling demands.

	5 wt%	10 wt%	15 wt%
TCI (mm$)	129.4	105.9	97.7
Electricity to grid (KW)	20,200	27,100	29,341

Sensitivity Analyses: Solid Loading

➢The MESP was changed from its base value of **19.77** to **28.83** and **17.76** ¢/kWh for **5** and **15 wt%** solids loading, respectively. .



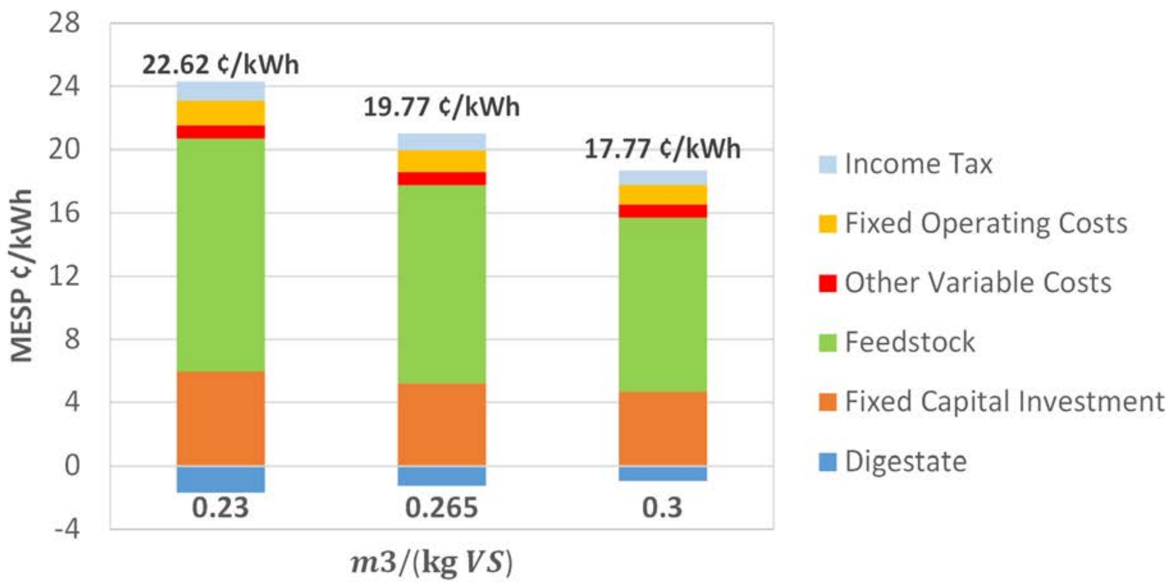
Sensitivity Analyses: Methane Yield

- The impact of methane yield was assessed by changing it from base value of **0.265** $\frac{m^3}{\text{kg } VS}$ to **0.23** and **0.3** $\frac{m^3}{\text{kg } VS}$.
- The MESP was changed from its base value of 19.77 to 22.62 and 17.77 ¢/kWh for 0.23 and **0.3** $\frac{m^3}{\text{kg } VS}$ methane yield, respectively.

	0.23 $\frac{m^3}{\text{kg } VS}$	0.265 $\frac{m^3}{\text{kg } VS}$	0.3 $\frac{m^3}{\text{kg } VS}$
TCI (mm$)	103.2	105.9	107.9
Electricity to grid (KW)	23,100	27,100	30,800
Digestate (mm$/yr)	3.1	2.7	2.3

Sensitivity Analyses: Methane Yield

- The impact of methane yield was assessed by changing it from base value of **0.265** $\frac{m^3}{\text{kg } VS}$ to **0.23** and **0.3** $\frac{m^3}{\text{kg } VS}$.
- The MESP was changed from its base value of 19.77 to 22.62 and 17.77 ¢/kWh for 0.23 and **0.3** $\frac{m^3}{\text{kg } VS}$ methane yield, respectively.



Conclusions

- ❖ Brown algae: viable biomass resources for electricity production.
- ❖ The calculated MESP for the process is comparable with current electricity selling price for residential sector.
- ❖ Solid loading, IRR, and biomass price have the highest impact on MESP.
- ❖ Hydrogen recovery does not improve the process economics.