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Offshore Wind Production of Ammonia: A Technical and Economic Analysis

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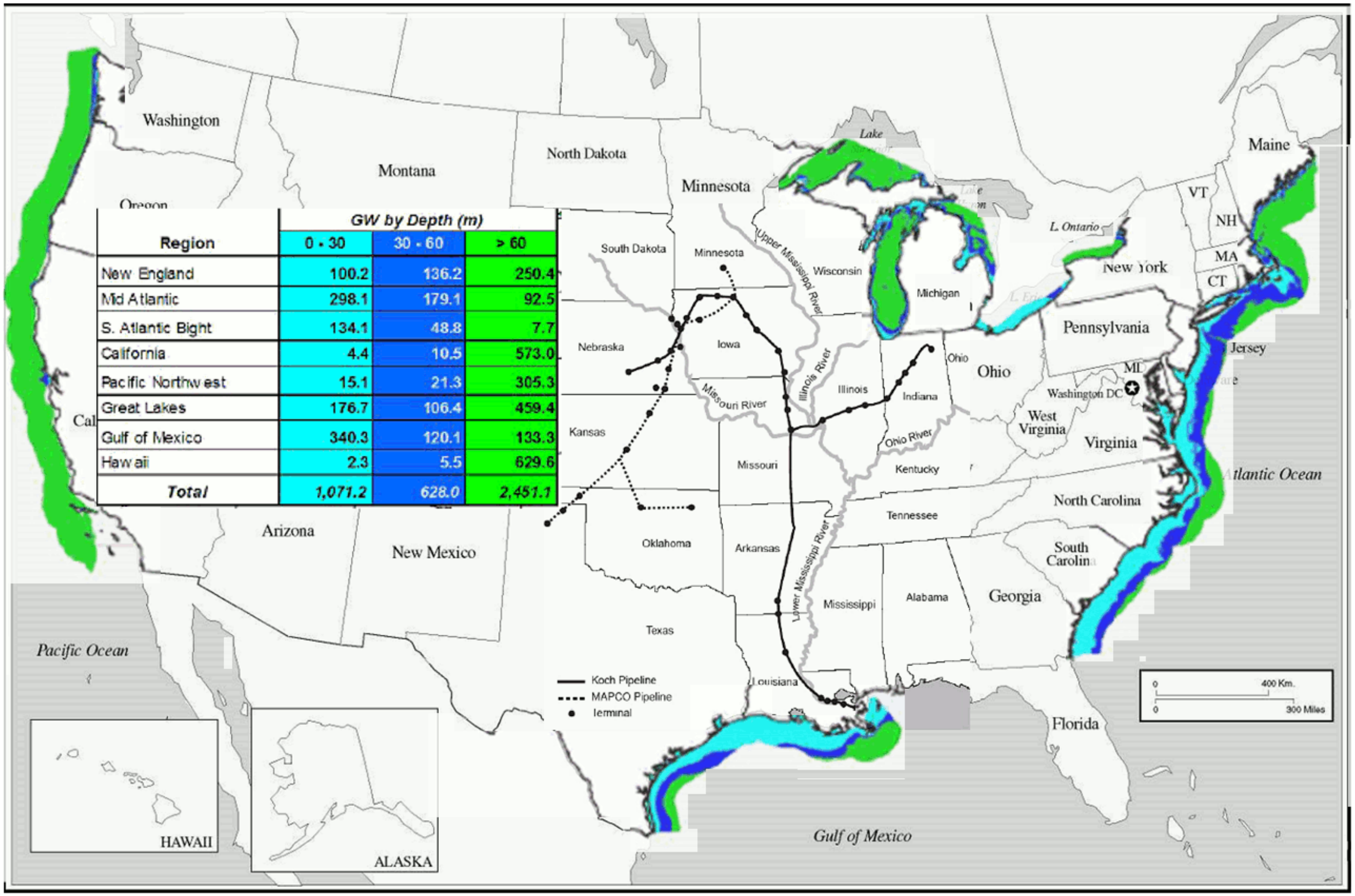
Outline

- Why wind and NH_3?
  - Energy storage for high penetrations of wind
- Offshore basics
- Baseline NH_3 plant considerations
- Economics
  - NH_3 subsystems
  - Offshore wind
- Case study in Gulf of Maine

Why Offshore Wind + Ammonia?

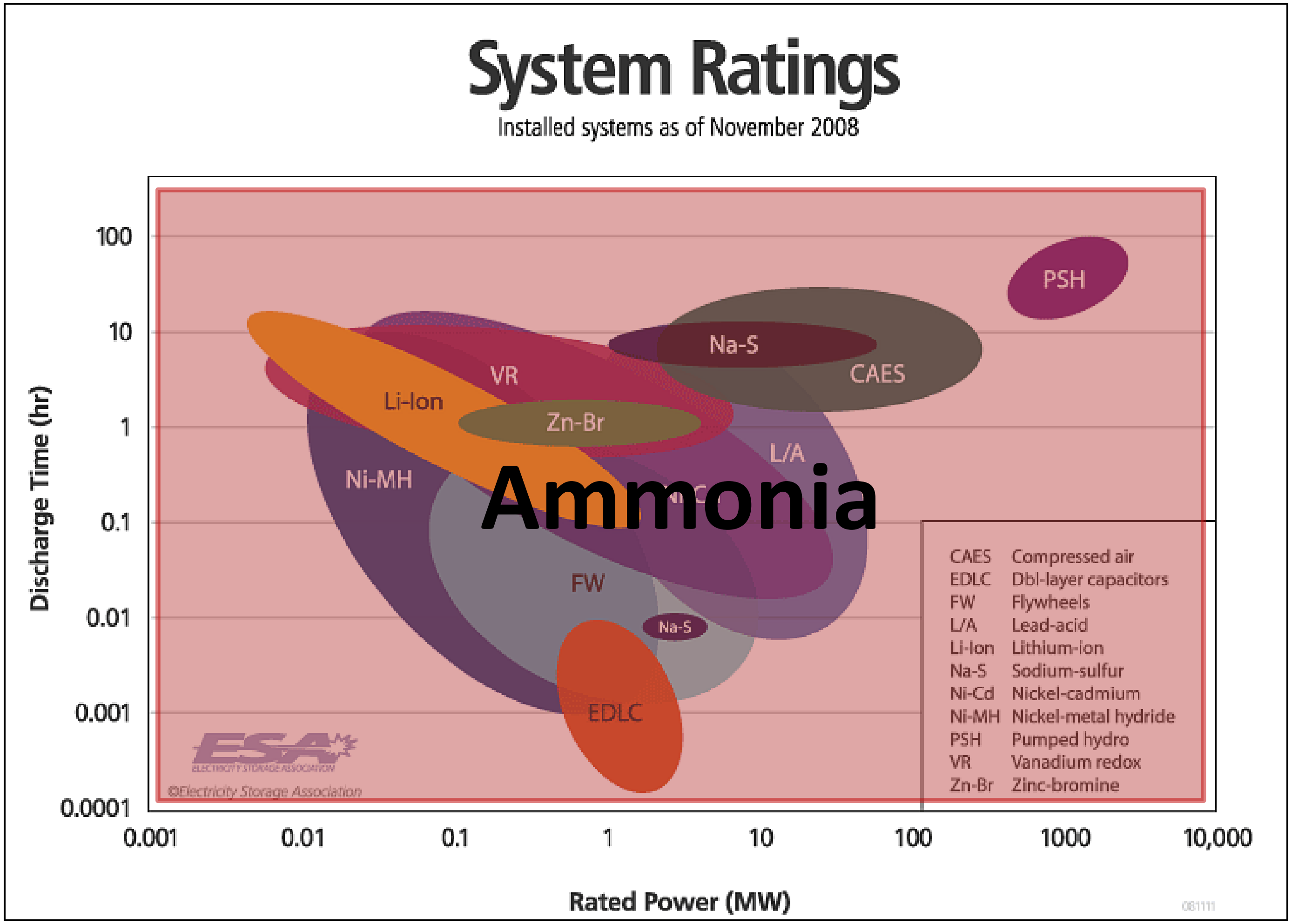


Region	GW by Depth (m) 0 - 30	30 - 60	> 60
New England	100.2	136.2	250.4
Mid Atlantic	298.1	179.1	92.5
S. Atlantic Bight	134.1	48.8	7.7
California	4.4	10.5	573.0
Pacific Northwest	15.1	21.3	305.3
Great Lakes	176.7	106.4	459.4
Gulf of Mexico	340.3	120.1	133.3
Hawaii	2.3	5.5	629.6
Total	*1,071.2*	*628.0*	*2,451.1*

Pipeline Source: Scheinberg, P. F. (1998). SURFACE TRANSPORTATION: Issues Associated With Pipeline Regulation by the Surface Transportation Board. Transportation Issues - Resources, and Economic Development Division. Washington, D.C., Government Accounting Office**: 6.**

Wind Map: Musial, W. and B. Ram (2010). Large-Scale Offshore Wind Power in the United States. Golden, CO, National Renewable Energy Laboratory.

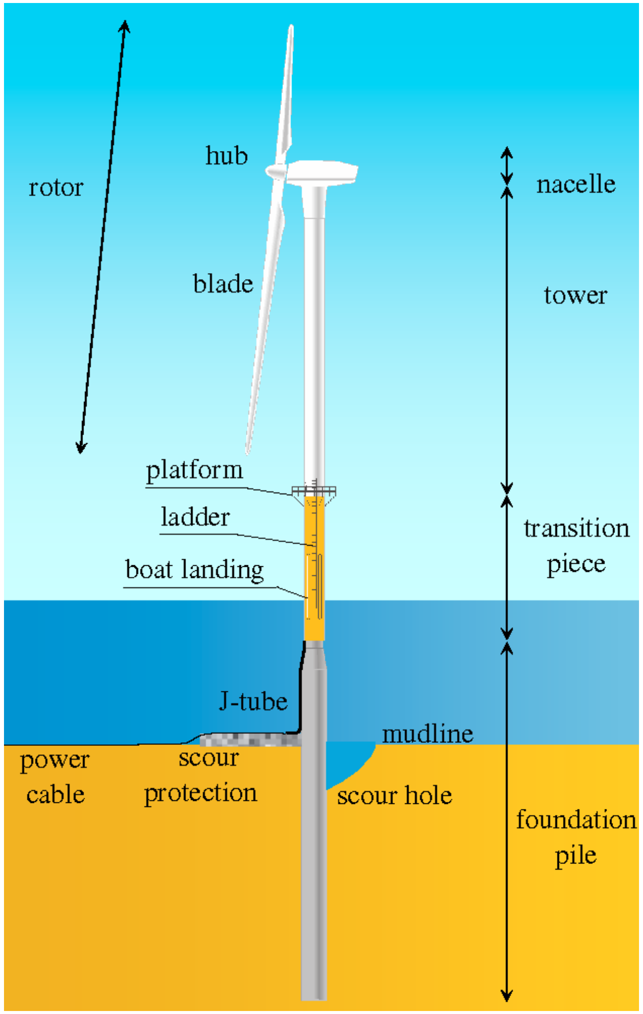
Conventional Energy Storage Options



Source: Electricity Storage Association (2009). "Power Quality, Power Supply." Retrieved February 9, 2011, from http://www.electricitystorage.org/ESA/technologies/.

Offshore Wind Turbines

- Turbine fundamentally the same as onshore
  - Foundations differ
- Wind turbines that are placed in oceans, seas, lakes, etc.
- Subjected to hydrodynamic loading
  - Waves
  - Currents



Source: Van Der Temple, J. (2006). Design of Support Structures for Offshore Wind Turbines. Delft, The Netherlands, Technical University of Delft. **PhD: 223.**

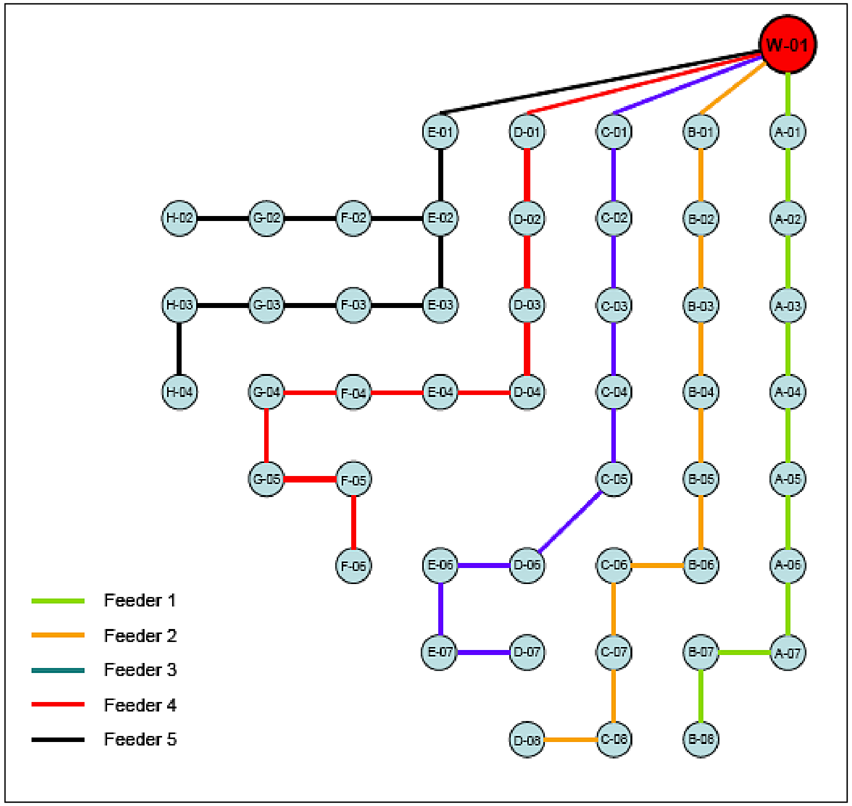
Offshore Wind Considerations

- Advantages
  - Large siting area
  - Load center proximity
  - High wind speeds
  - Low turbulence
  - Low wind shear
  - Low visual impact
- Disadvantages
  - Access restrictions
  - Higher costs
  - Lower availability
  - Corrosion prevention

Source: Barrow Offshore Wind Ltd. (2006). Barrow Offshore Wind Farm Construction Monitoring Report. Copenhagen, Denmark, DONG Energy**: 45.**

Offshore Wind Energy Production

- Turbine losses
  - Betz limit → *Cp* (16/27)
  - Mechanical efficiency
  - Generator efficiency
- Availability (> 95%)
- Electrical efficiency
- Array efficiency (90%+)

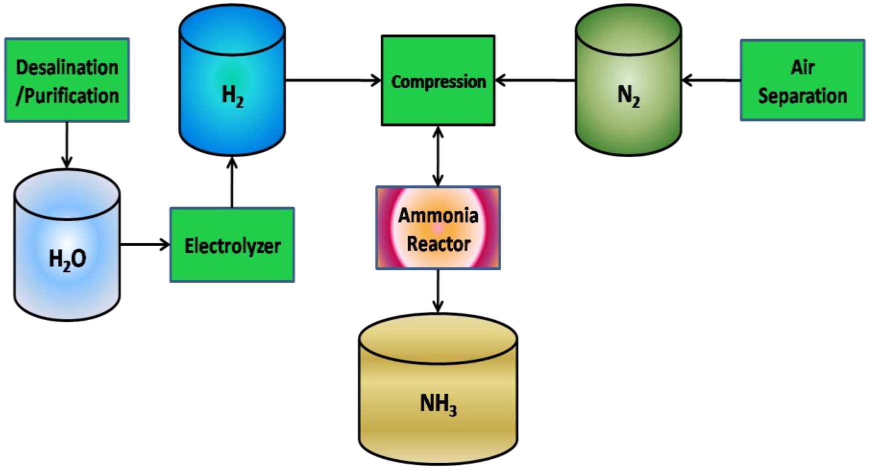


Sources: Jeppsson, J., P. E. Larsen, et al. (2008). Technical Description Lillgrund Wind Power Plant, Vattenfall**: 78.**

Producing Ammonia with Wind

$$N_2(g)+3H_2(g)\rightarrow 2NH_3(g)\ \Delta H=-92kJ$$

- All electric wind powered processes:
  - Air Separation (N_2)
  - Electrolysis of water (H_2)
    - Water purification
  - Haber-Bosch process
    - Extreme pressure and temperatures
    - Dissociation of N_2 and H_2
      - Iron Oxide Catalyst
    - Formation of NH_3



Sources:
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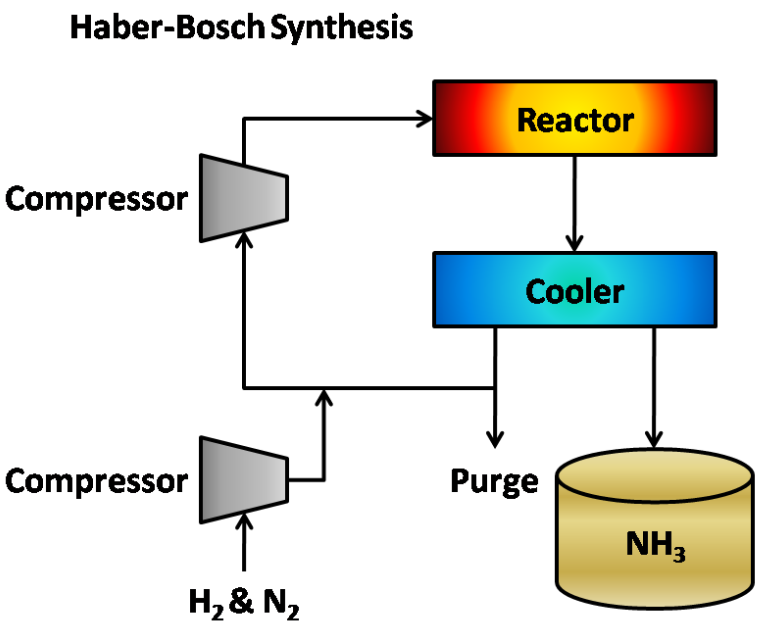
Dugger, G. L. and E. J. Francis (1977). "Design of an Ocean Thermal Energy Plant Ship to Produce Ammonia via Hydrogen." International Journal of Hydrogen Energy **2: 231-249.**

Ammonia Technical Requirements

- Syngas
  - H to N ratio 3:1 (NH_3)
  - Max Oxygen: 0.01 mol% in syngas
  - Pressure: 100-200 bar
  - Temperature: 350-550°C
- Reaction
  - 20-30% conversion rate
  - Exothermic reaction ≈ 8% of energy input (industrial)
- Availability > 90%
  - 5.7 shutdowns/year average
- Near constant reactor output
- Product: Anhydrous ammonia
- Plant sizes 300 t/d to 3000 t/d



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Appl, M. (1999). Ammonia: Principles and Industrial Practice. New York, Wiley-VCH.
Dybkjaer, I. (1995). Ammonia Production Processes. Ammonia Catalysis and Manufacture. A. Nielsen. New York, Springer-Verlag: **199-328.**
European Commission (2007). Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals - Ammonia, Acids and Fertilisers. Integrated Pollution Prevention and Control.
Bartels, J. R. and M. B. Pate (2008). A feasibility study of implementing an ammonia economy, Iowa State University.

Wind/NH_3 300 t/d Plant Characteristics

Process	Product	Amount	Flow Rate (kg/h)	Input Power (MW)
Air Separation	N_2	245 tonnes	10200	2
Electrolysis	H_2 O_2	55 tonnes 435 tonnes	2300 18125	135 (AC)
Desalination	H_2O	490 tonnes	20000	1.5
Synthesis loop/ Compression	NH_3	300 tonnes	12500	9
NH_3 Reaction	Heat	2.7 GJ/tonne	-	-9.4

Subsystem Selection

Process	Selection	Reason(s)
Air Separation	Cryogenic	High purity product; high volume output; mature technology
Electrolysis	Alkaline	High output; good load range; mature technology (Statoil Atmospheric Type 5040)
Water Desalination	Mechanical Vapor Compression	Thermal system with possibility of heat integration; flexible with good load range; little pretreating required; high purity product needed for electrolysis

Bottom-Up Cost of New Electric NH_3 Plant

- Based on Turton et al. (2001) and Ulrich (1984)
  - Major equipment list for bare module cost
    - Equipment sizes from flow rates, heat transfer rates, etc.
    - Pressure and material factors
  - Total “Grass Roots” cost calculated ($2010)

Sources: Turton, R., R. C. Bailie, et al. (2009). Analysis, Synthesis and Design of Chemical Processes. Boston, MA, Prentice Hall.
Ulrich, G. D. (1984). A Guide to Chemical Engineering Process Design and Economics. New York, NY, John Wiley and Sons.

Equipment Costs

- Equipment costs often not available
- Estimates based on
  - Other known equipment costs (C_1)
  - Scaling relationships $\left(\frac{A_2}{A_1}\right)^n$
  - Cost inflation $\left(\frac{I_2}{I_1}\right)$
  - Material factors (F_M)
  - Pressure factors (F_P)

$$C_2 = C_1 \left(\frac{A_2}{A_1}\right)^n \left(\frac{I_2}{I_1}\right) (F_M F_P)$$

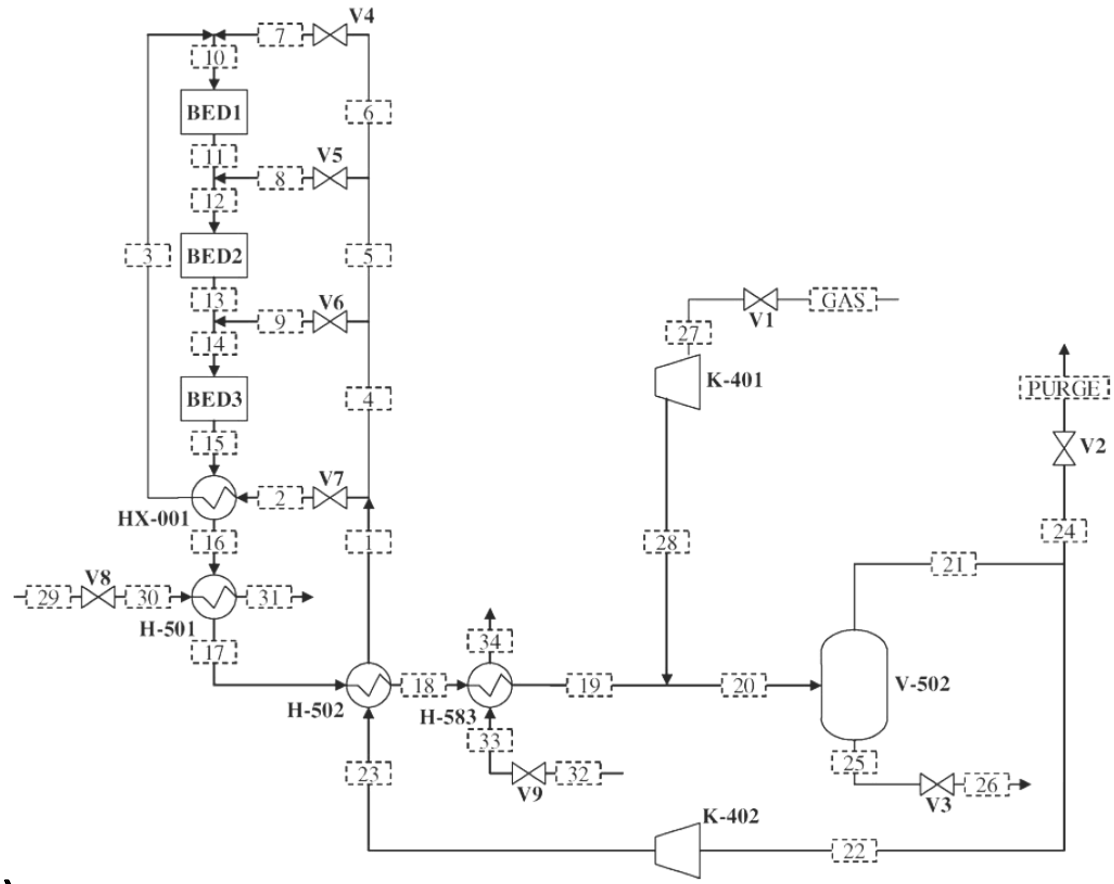
Grass Roots Cost Estimate

- Bare module cost (BM) = direct and indirect costs for a piece of carbon steel equipment at STP
- Contingency fees and costs = 18% of BM
- Site development, auxiliary buildings, off-sites and utilities = 50% of BM

$$C_{GR} = 1.18 \sum_{i=1}^{n} C_{BM,i} + 0.50 \sum_{i=1}^{n} C_{BM,i}^{o}$$

Ammonia Synloop Equipment (300t/d)

- Compressor train for syngas (1 bar-150 bar)
- Recirculating compressor
- Flash vessel
- 4 heat exchangers
- Synthesis reactor
- C_{GR} = $32M ($2010)



Source: Araujo, A. and S. Skogestad (2008). "Control structure design for the ammonia synthesis process." Computers and Chemical Engineering **32(12): 2920–2932.**

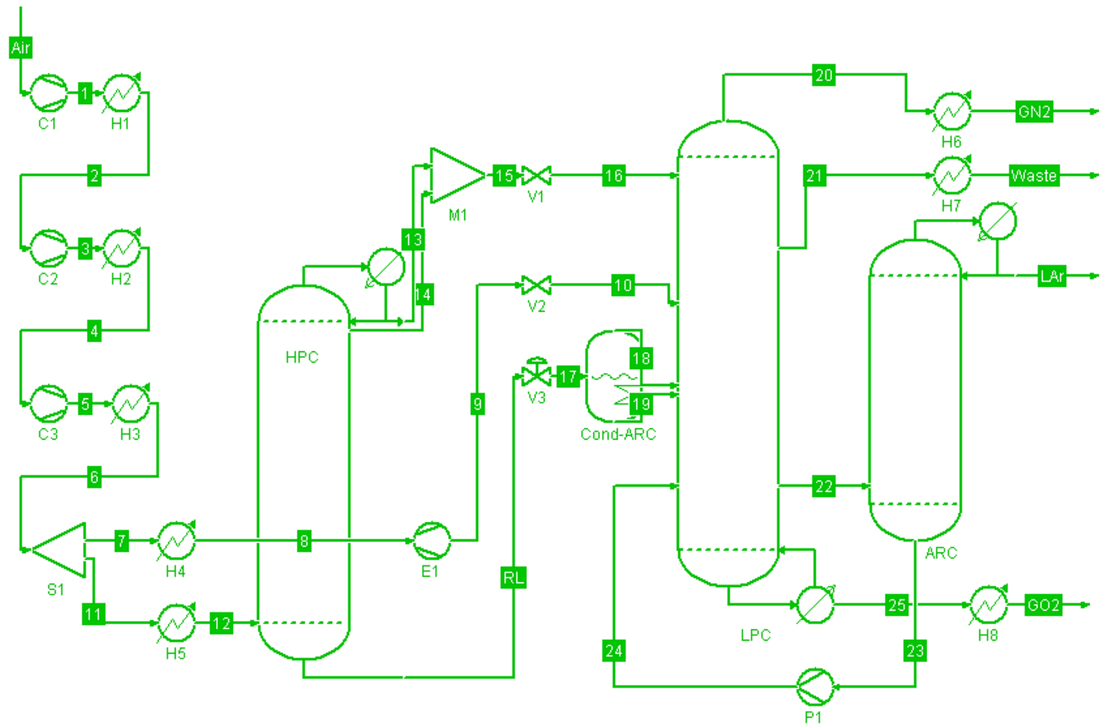
Cost of Hydrogen Production

- Electrolyzers provide all hydrogen
  - Ancillary equipment includes tanks, compressors, scrubbers, dryers
- Analysis based on the DOE's "H_2A"
  - Includes quotes from Norsk Hydro (Now Statoil)
  - Costs include all necessary equipment for H_2 production ($2002)
- C_{GR} = $218M ($2010)

Source: Steward, D., T. Ramdsen, et al. (2008). H2A Production Model, Version 2 User Guide. Golden, CO, National Renewable Energy Laboratory**: 69.**

Cost of Air Separation Equipment

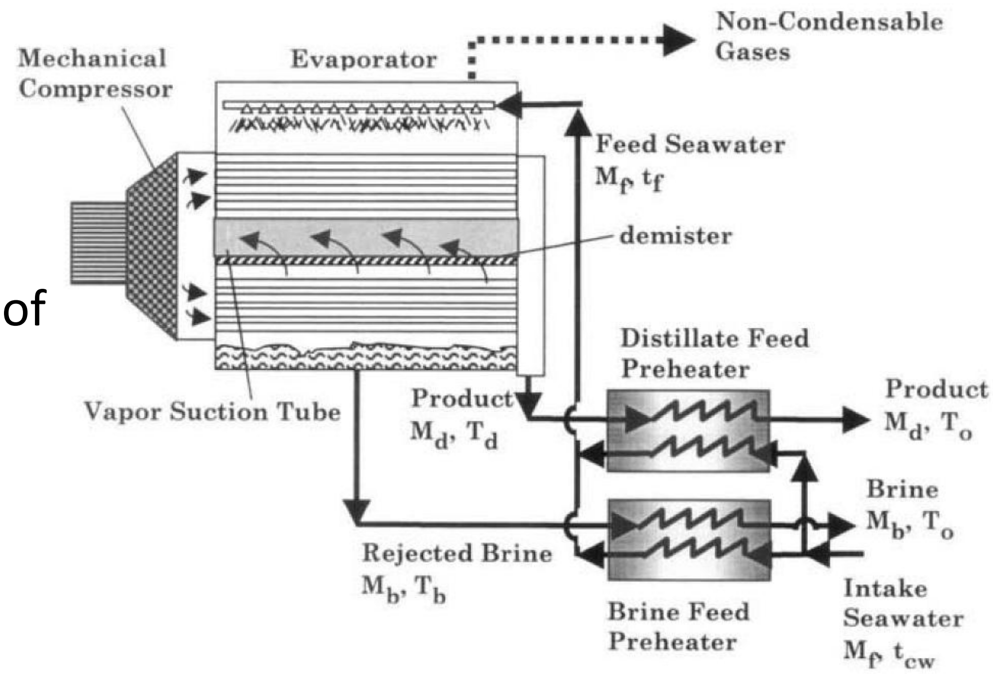
- Based on proprietary spreadsheet and quotes courtesy of Universal Industrial Gases
- Costs mostly from compressors and heat exchangers
- $12M for a 250 t/d GN_2 plant ($2010)



Source: Bian, S., M. a. Henson, et al. (2005). "Nonlinear State Estimation and Model Predictive Control of Nitrogen Purification Columns." Industrial & Engineering Chemistry Research **44(1): 153-167.**
http://www.chemsep.com/downloads/data/CScasebook_ASU.pdf

Mechanical Vapor Compression

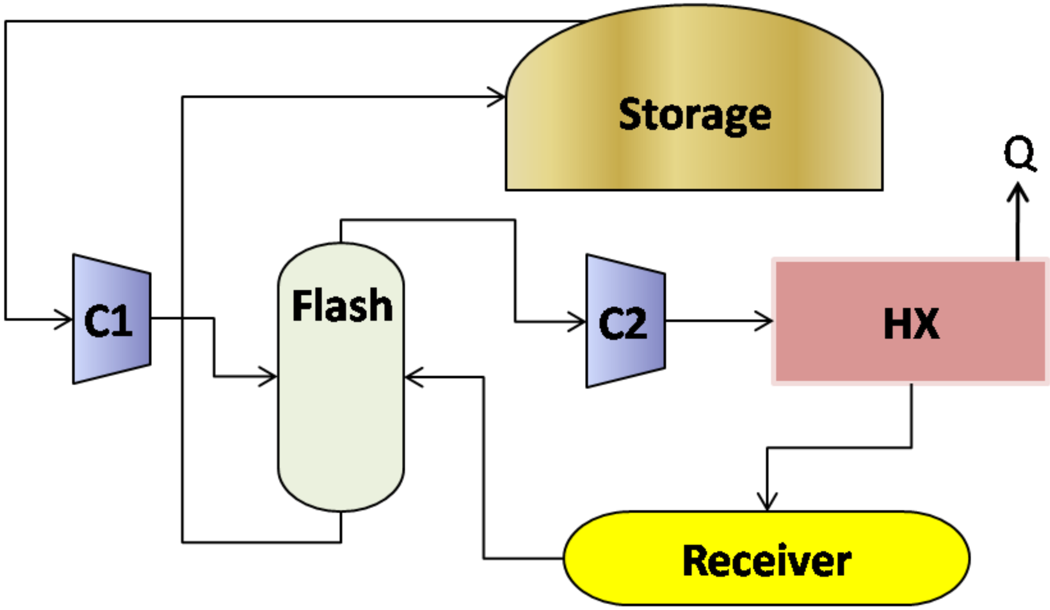
- Electrical compressor
- Large heat exchanger (evaporator)
- Preheaters and pumps
- Specific energy: 0.7 kWh/m^3 of H_20
- C_{GR} = $21.7M ($2010)



Source: El-Dessouky, H. T. and H. M. Ettouney (2002). Fundamentals of Salt Water Desalination. New York, Elsevier.
Fiorenza, G., V. K. Sharma, et al. (2003). "Techno-economic evaluation of a solar powered water desalination plant." Energy conversion and management . **44** (Compendex): 2217-2240.

Ammonia Storage

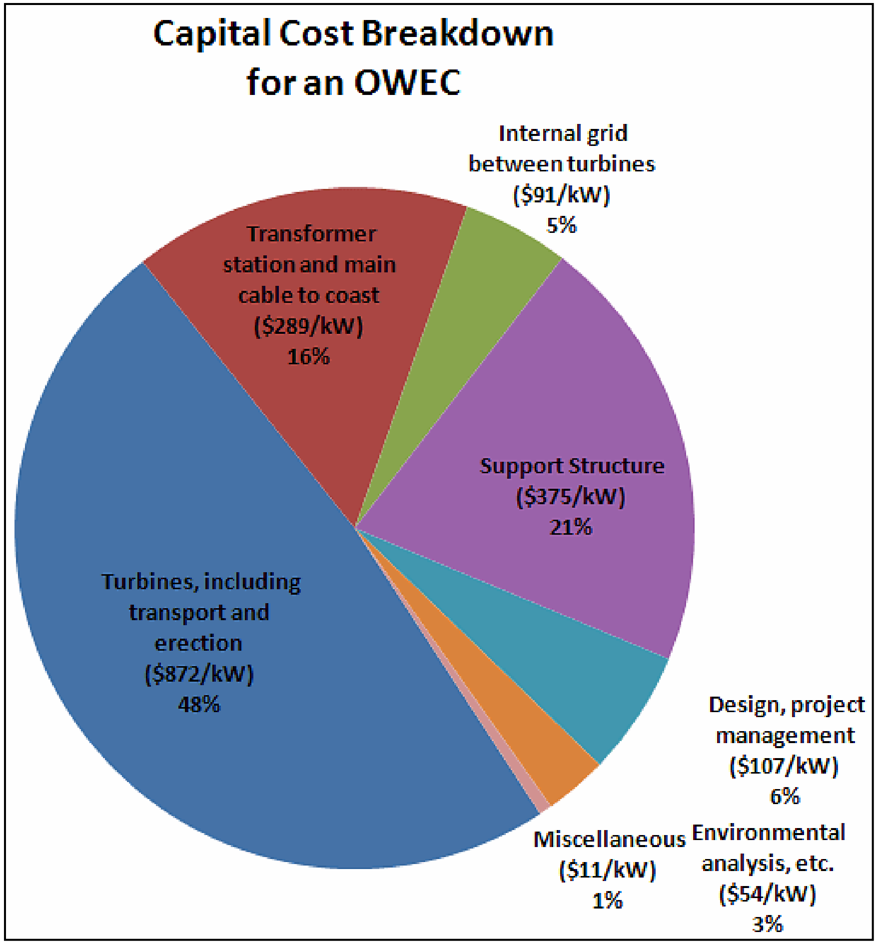
- 300 t/d plant requires 9000 t storage.
- Sizing of compressors, etc dependent of heat transfer
- C_{GR} = \$16M (\$2010)



Source:Webb, D. "LARGE SCALE AMMONIA STORAGE AND HANDLING." Retrieved February 13, 2011, from www.irc.wisc.edu/file.php?id=21.

Offshore Wind Economics

- Capital Costs
  - RNA Model
  - Support Structure
    - Tower
    - Foundation
    - Jacket
  - Electrical
- Other Costs
  - O&M ≈ 2% of Cap Cost
  - Decommissioning ≈ $55,000/MW



Source: Morthorst, P. E., J. Lemming, et al. (2010). Development of Offshore Wind Power – Status and Perspectives. Offshore Wind Power. J. Twidell and G. Gaudiosi. Brentwood, Essex, UK, Multi-Science Publishing Co. Ltd.: **1-13.**

Offshore Wind Costing Methods

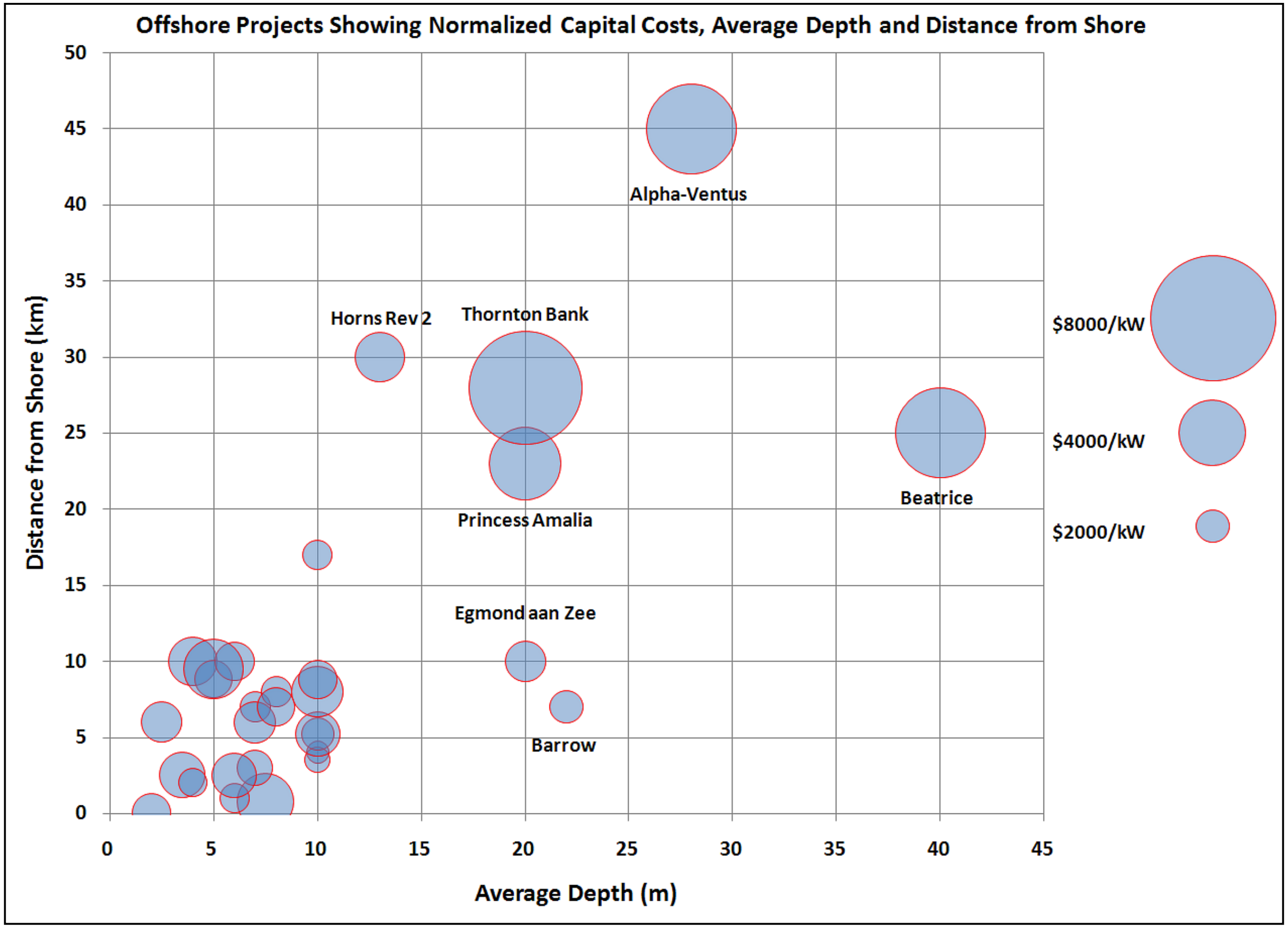
- Basic → \$/kW for each system
- Intermediate → cost ∝ amount of material
  - – Empirical relationships

RNA	$m_{RNA} = 0.6892D^{2.5} + 5.76D^{2.1}$
Tower	$m_{tower} = c_{tower} D^{2.8} \left(\frac{Z_h}{D}\right)^{1.7} \left(\frac{P}{A}\right)^{0.6}$
Pile	$m_{pile} = \rho_{steel} L_{pile} \frac{\pi}{4}\left[D_{pile}^2 - \left(D_{pile} - 2t_{wall}\right)^2\right]$
Electrical	$C_{HVAC} = N_{Cables}\left[\left(0.00168V + 1280 + cc_{laying}\right)L + 0.668V + 36000 + C_{xfrm}\right]$

Sources: Bulder, B. H., F. Hagg, et al. (2000). Dutch Offshore Wind Energy Converter - Task 12: Cost Comparisons of the Selected Components. Petten, The Netherlands, Energy Research Centre of the Netherlands**: 40.**

Elkinton, C. N. (2007). Offshore Wind Farm Layout Optimization. Mechanical and Industrial Engineering. Amherst, MA, University of Massachusetts. **Doctor of Philosophy: 326.**

Depth/Distance Influence on Capital Costs



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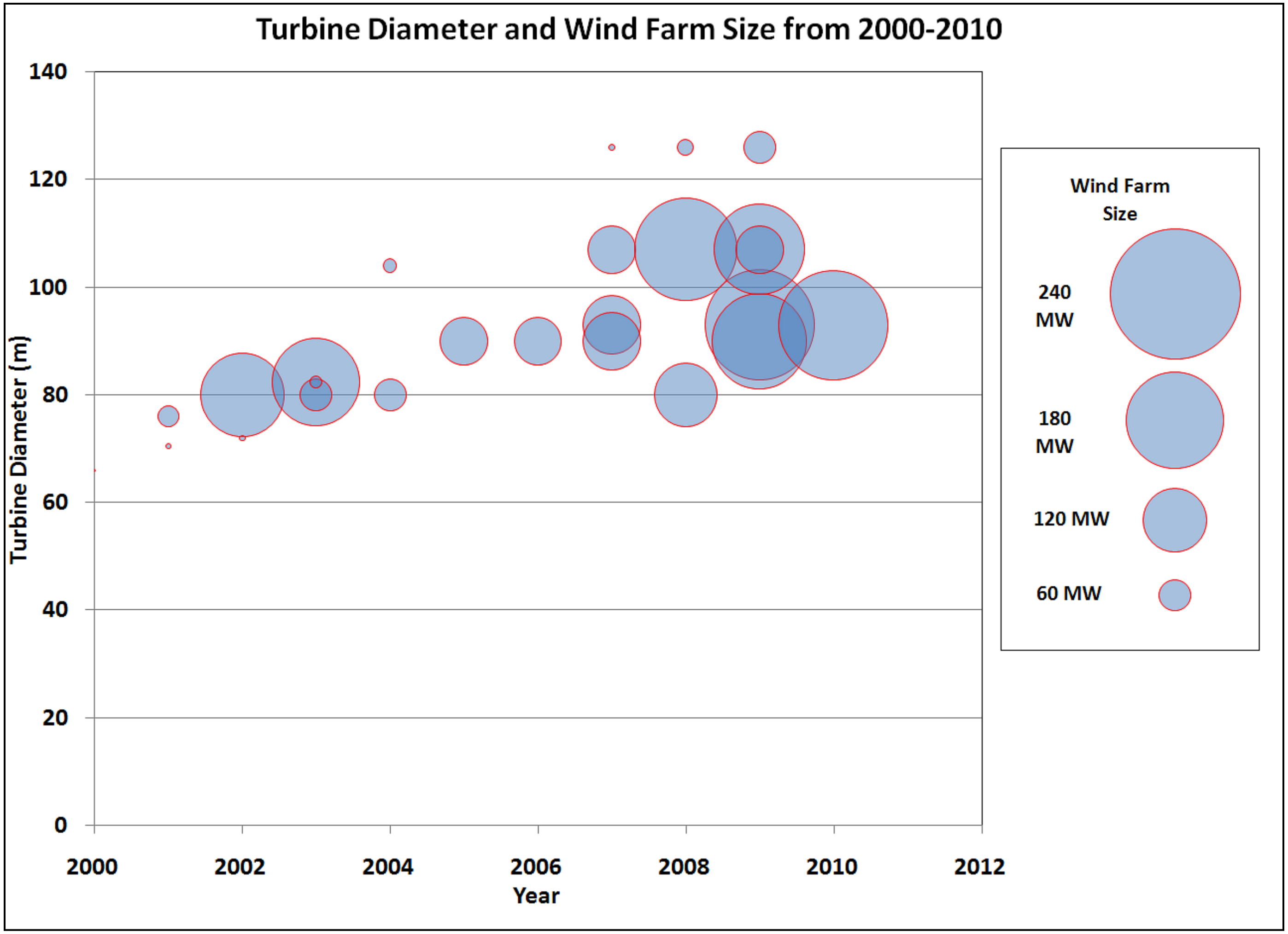
Offshore Trends



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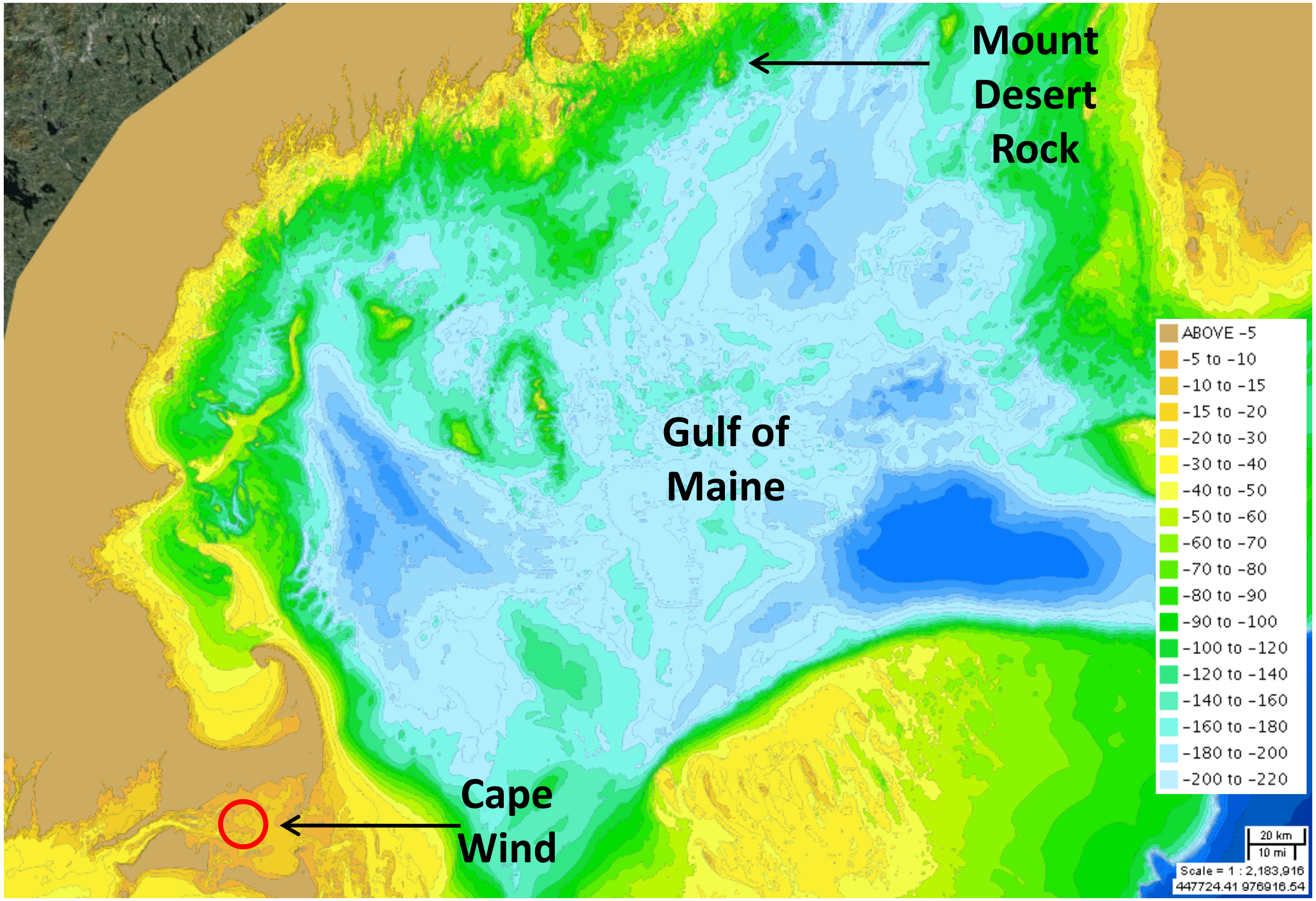
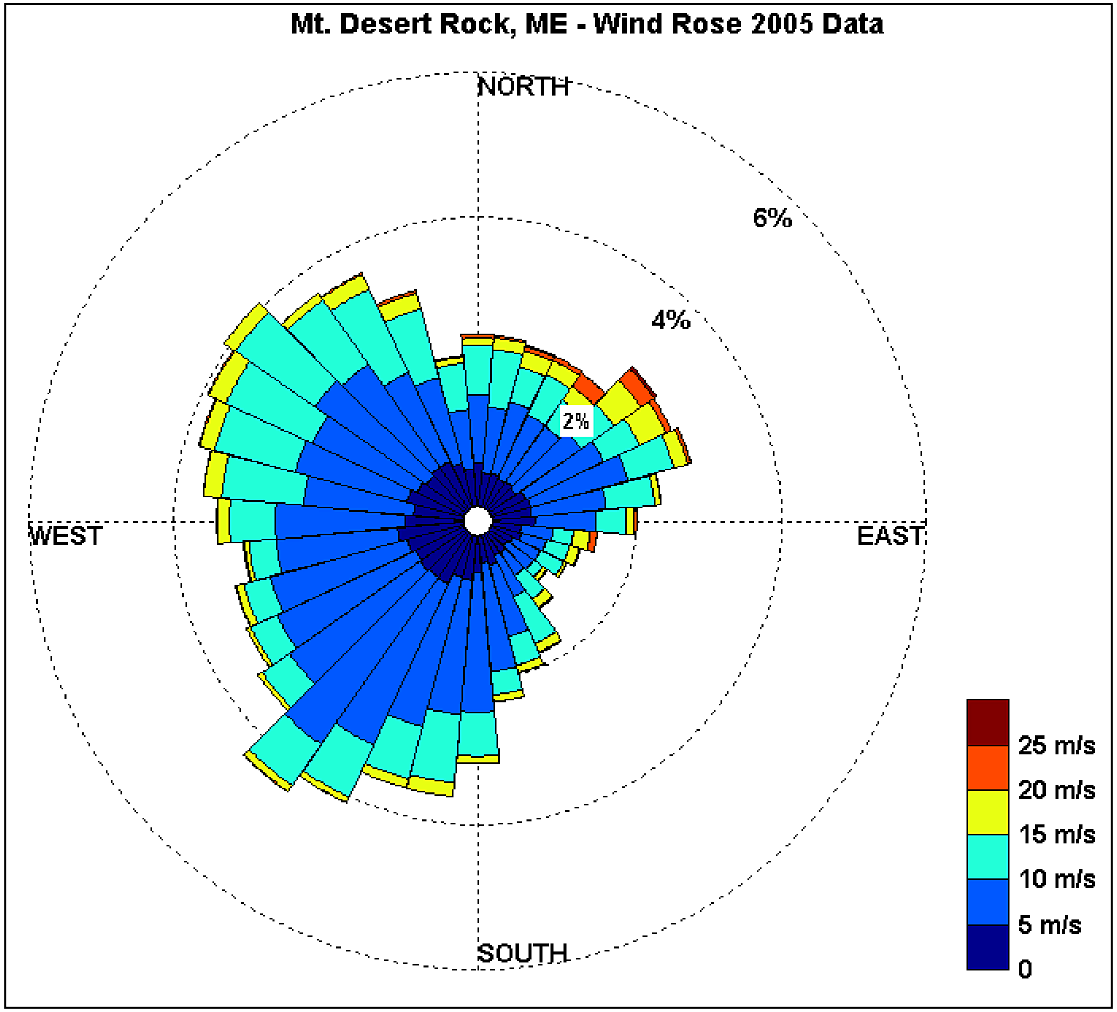
Case Study - Gulf of Maine



Source: http://maps.massgis.state.ma.us/map_ol/oliver.php

Wind at Mt. Desert Rock

- 10 minute data taken at 22.6 m
- Mean wind speed estimate @ 90m = 9.47 m/s
- Standard Dev = 4.76 m/s
- Nor'easter winds?



Source: National Data Buoy Center (2011). "NBDC - Station MDRM1." Retrieved July 12, 2011, from http://www.ndbc.noaa.gov/station_page.php?station=mdrm1.

Baseline Offshore Wind-NH_3

- All electric, 300 t/d ammonia facility
  - Located on shore
  - 145 MW required
  - Grid backup – ISO-NE hourly sell data/Electric Power Monthly buy data
- Offshore wind specifications
  - 10 meters deep, 10 km offshore, 10D spacing
  - 3 MW machines, 90m hub height, 100m diameter
  - Monopile substructure
  - 98 turbines (~200% of the required power)
- Capital Costs: $768M for offshore wind; $290M for ammonia facility
- Total O&M = $28.6M excluding utilities

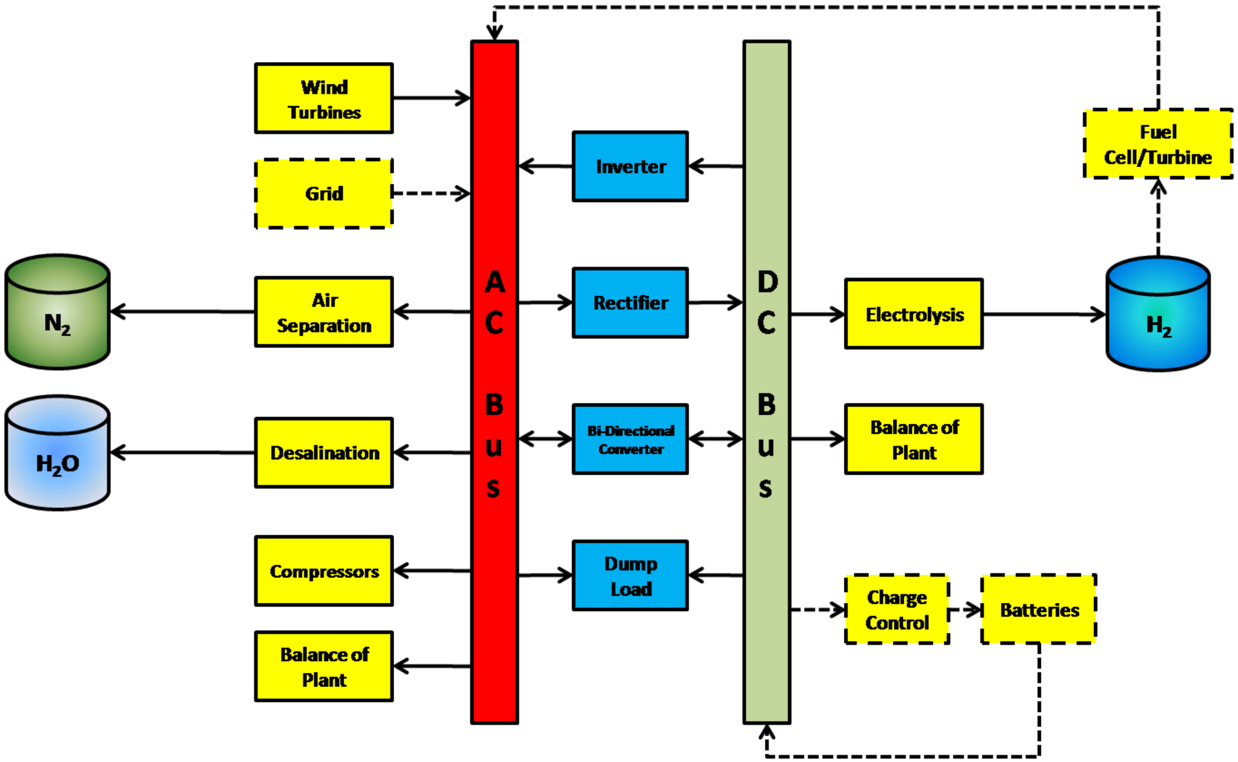
Levelized Cost of Ammonia (LCOA)

- Define the levelized cost as the sum of the capital costs and the O&M divided by the annual production ($/ton).
  - Primarily used in electricity markets
  - LCOA = ~$880/ton for conventional steam reforming plant

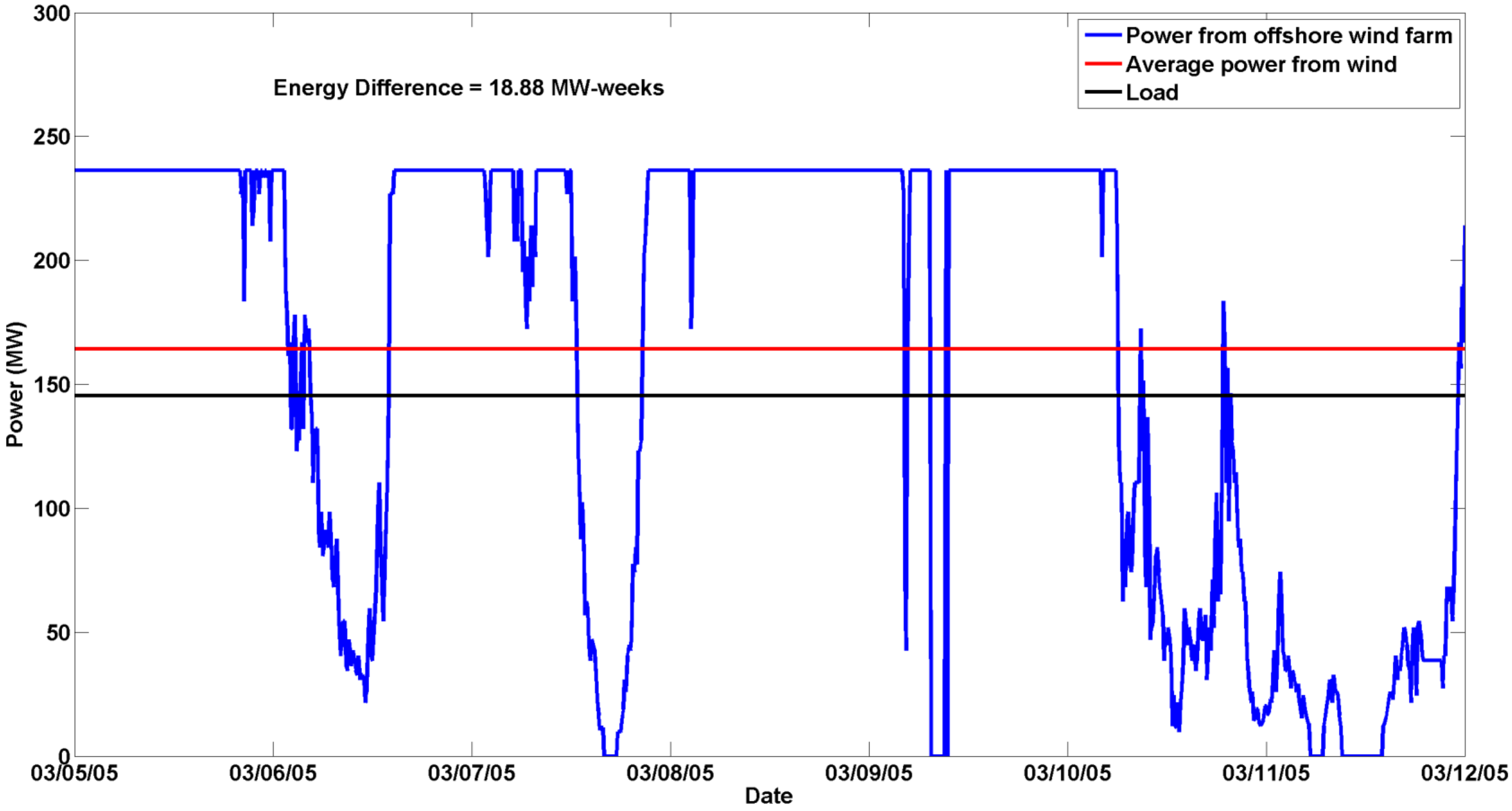
$$LCOA = \frac{\sum Capital\ Costs + \sum O\&M\ Costs}{Total\ Annual\ Ammonia\ Production}$$

Wind/NH_3 as a Hybrid System

- 10 minute energy/mass balance
- System sizing
  - Offshore wind
  - ASU
  - Electrolysis
- Formulate a control strategy
  - Load range dependent



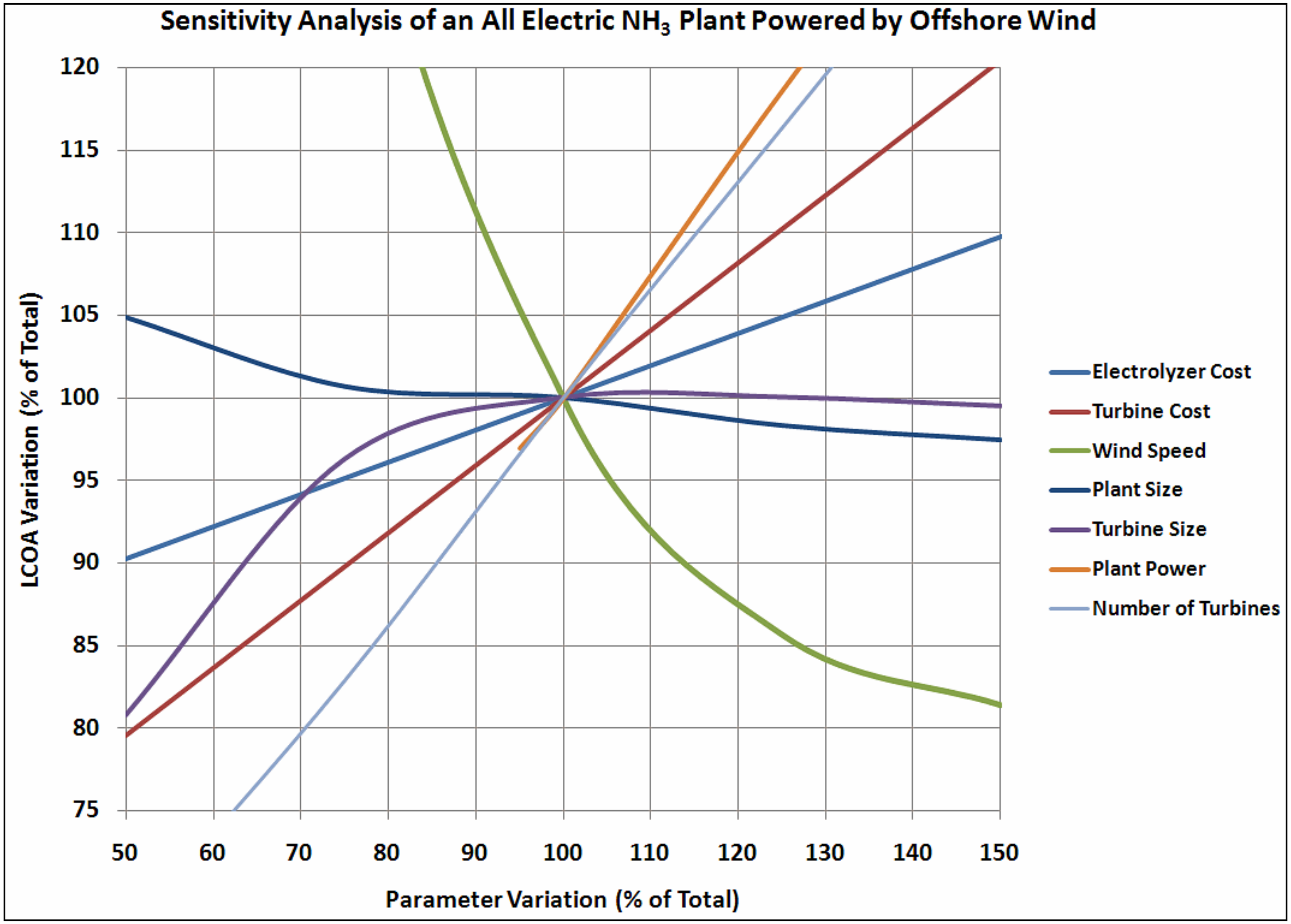
Gulf of Maine Simulation Example



Gulf of Maine Baseline Simulation Summary

- Average Power = 117.65 MW
- Capacity Factor = 0.40
- Electricity Purchased = $24.6M
- Electricity Sold = $18.54M
- LCOA = $11315/ton (LCOA = ~$880/ton for conventional steam reforming plant)
- Energy Required = 41.9 GJ/t
  - 8.02 GJ/t from the grid
  - 33.88 GJ/t from wind
- Saves 85 ktons of CO_2/y and 14 t NOx/y

Sensitivity Analysis, Baseline LCOA = $11,315/ton



Conclusions

- High penetrations of offshore wind require large scale storage – ammonia.
- Industrial scale wind powered ammonia is possible, but grid backup is required.
- Levelized cost is high relative to modern industrial NG ammonia plants.

References

1. Scheinberg, P. F. (1998). SURFACE TRANSPORTATION: Issues Associated With Pipeline Regulation by the Surface Transportation Board. Transportation Issues - Resources, and Economic Development Division. Washington, D.C., Government Accounting Office**: 6.**
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26. Source: http://maps.massgis.state.ma.us/map_ol/oliver.php
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Questions?

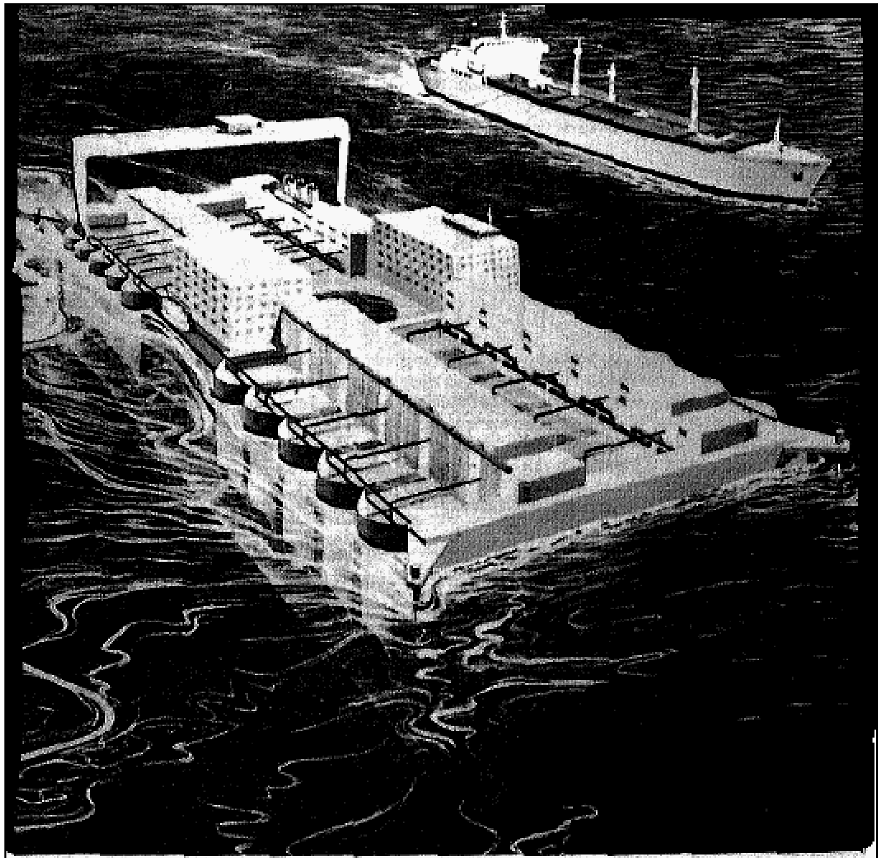
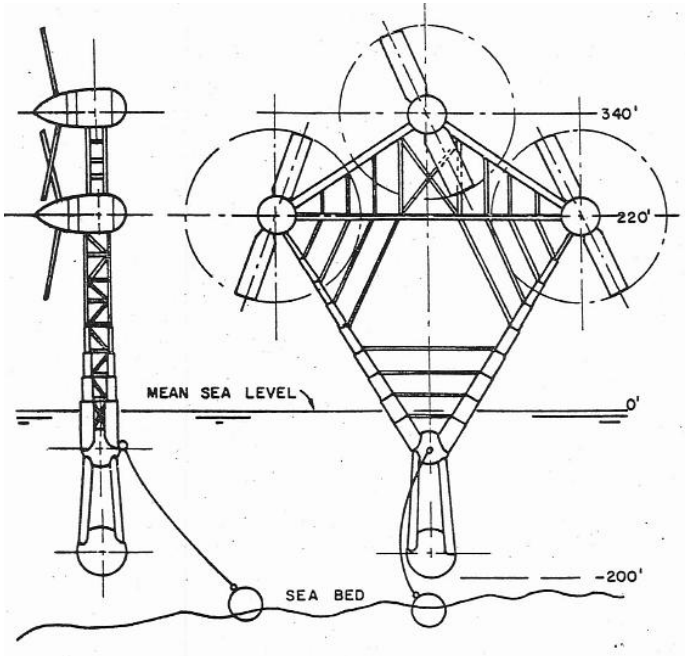


FIG. 1. The APL baseline design for a 100-MWe (net), demonstration size, Ocean Thermal Energy Conversion (OTEC)/ammonia plant-ship. The ammonia tanker in the background would pick up ammonia once a month.

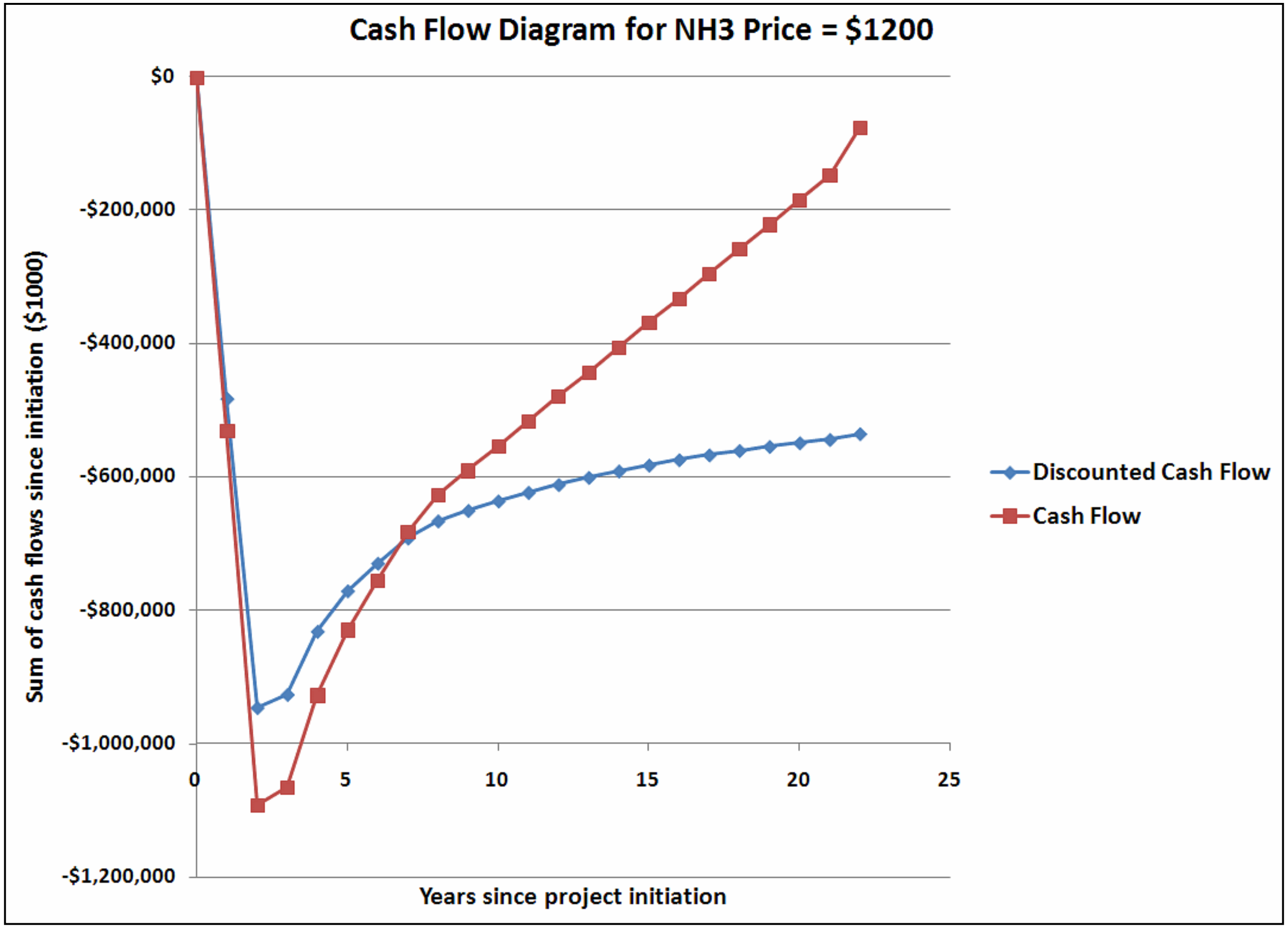


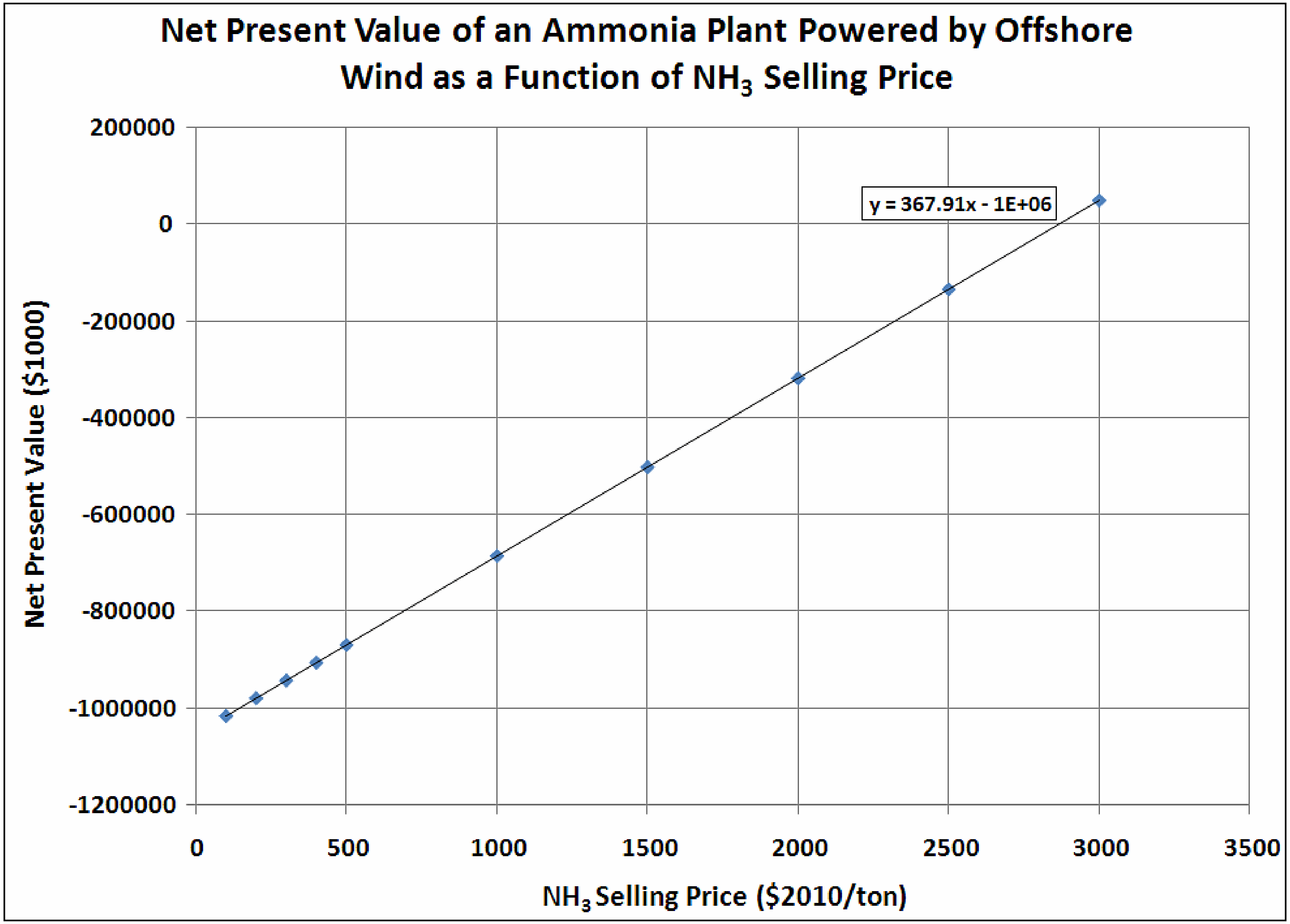
PROPOSED 3-WHEEL FLOATING WIND STATION
200 FOOT DIAMETER

Sources: Dugger, G. L. and E. J. Francis (1977). "Design of an Ocean Thermal Energy Plant Ship to Produce Ammonia via Hydrogen." International Journal of Hydrogen Energy **2: 231-249.**

Heronemus, W. E. (1972). Pollution-Free Energy from Offshore Winds. 8th Annual Conference and Exposition, Washington, DC, Marine Technology Society.

Appendix


Cash Flow Diagram for NH3 Price = $1200
$0
-$200,000
-$400,000
-$600,000
-$800,000
-$1,000,000
-$1,200,000
Sum of cash flows since initiation ($1000)
0
5
10
15
20
25
Years since project initiation
Discounted Cash Flow
Cash Flow


Net Present Value of an Ammonia Plant Powered by Offshore Wind as a Function of NH3 Selling Price
y = 367.91x - 1E+06
200000
0
-200000
-400000
-600000
-800000
-1000000
-1200000
Net Present Value ($1000)
0
500
1000
1500
2000
2500
3000
3500
NH3 Selling Price ($2010/ton)