Integrated System Analysis of Offshore Wind Projects

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Offshore Wind Farm

Prinses Amaliawindpark
June 2008

Wind turbines:	60 Vestas V80 / 2 MW
Capacity:	120 MW
Water depth:	19 - 24 meters
Distance from shore:	23 kilometers
Surface area:	14 km²
Hub height:	59 meters
Rotor diameter:	80 meters

Annual power production: 435 GWh
CO2-emissions avoidance: 225.000 tons/year
Enough to power: 125.000 households

Complex System

Relatively New Technology

Various, Interrelated Uncertain Parameters

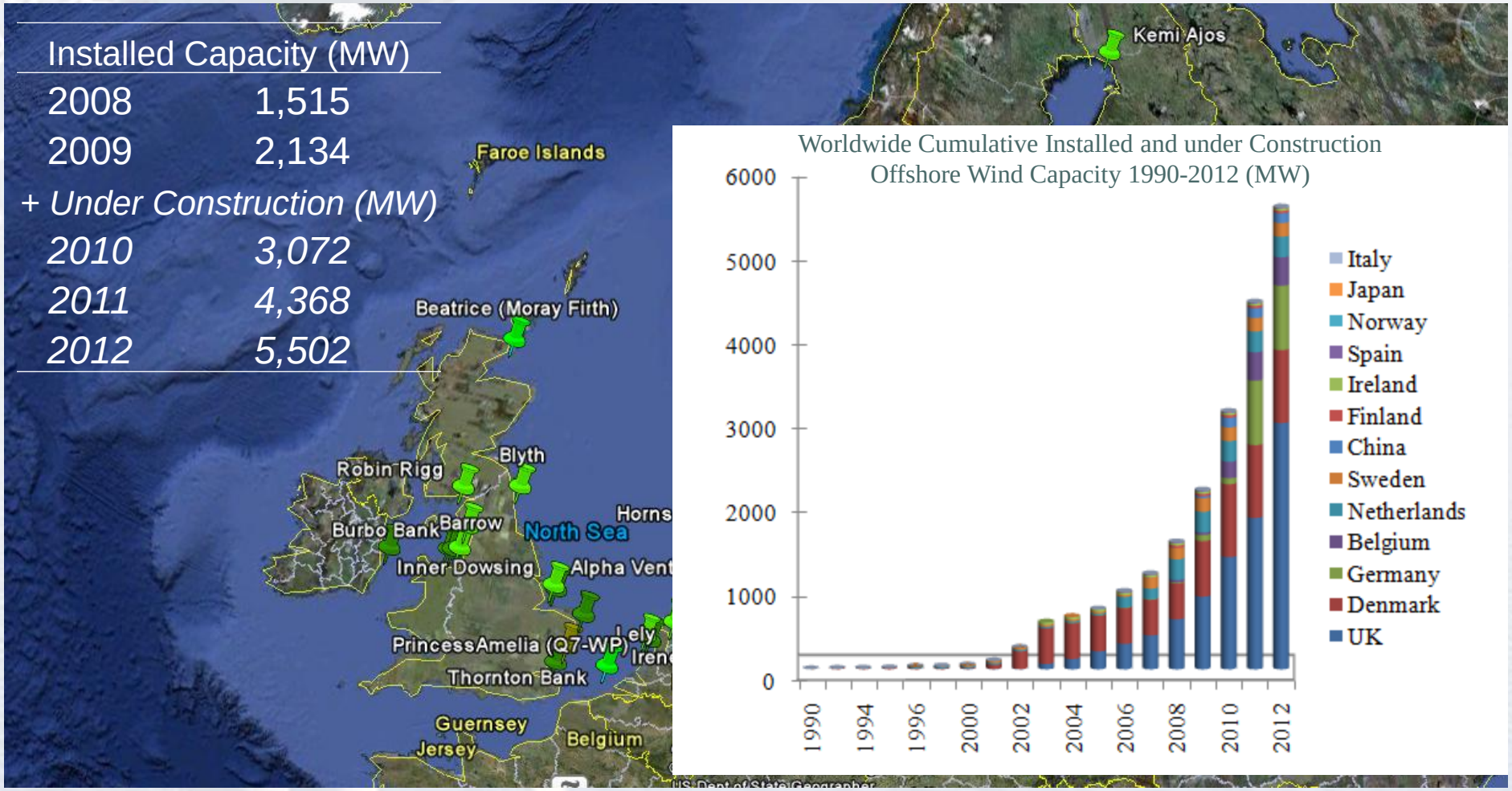
High COE

Inadequate, Traditional LCC

http://www.q7wind.nl/en/nieuws_fotos.asp

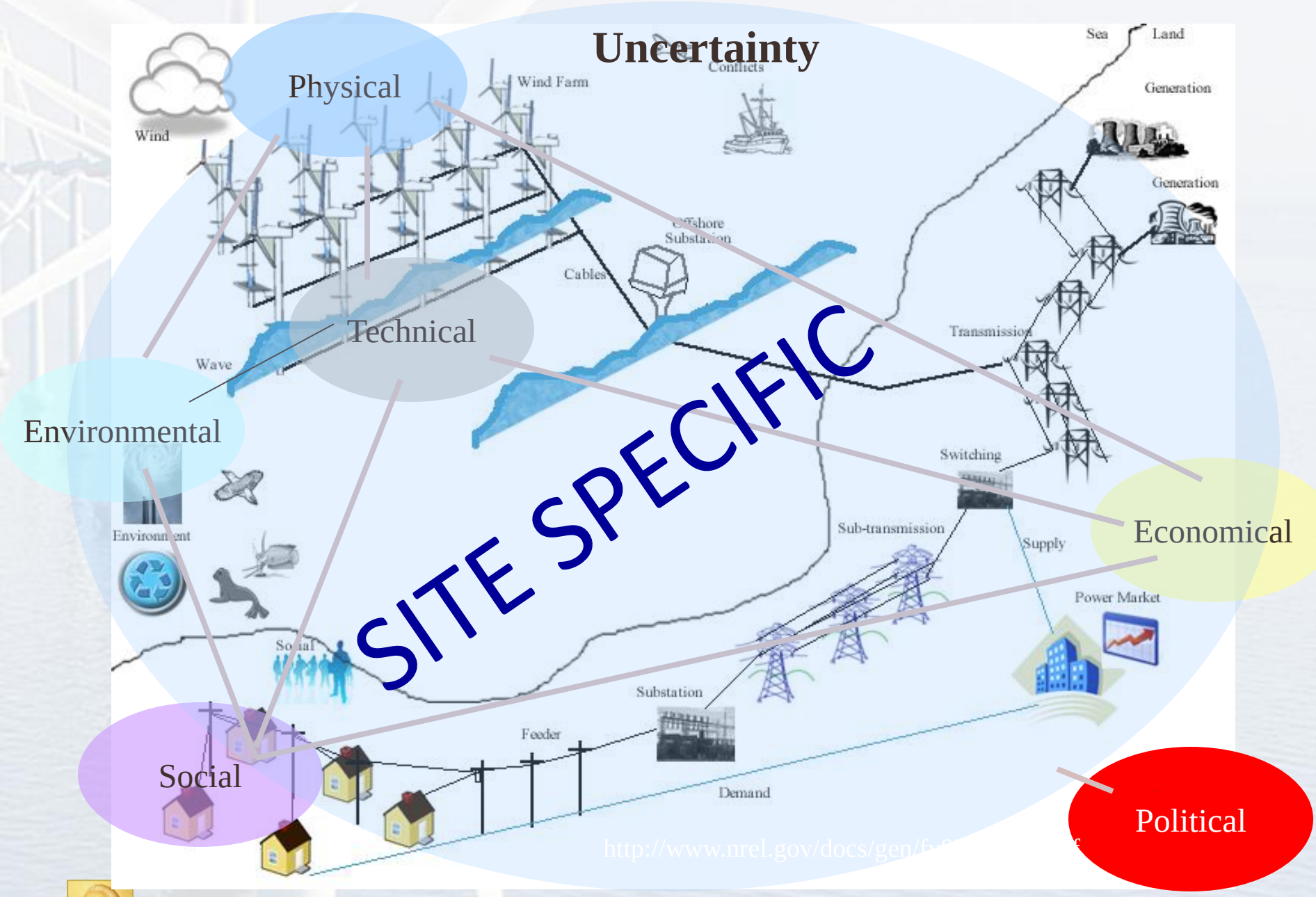
Offshore Wind Plants

Installed Capacity (MW)	
2008	1,515
2009	2,134
+ Under Construction (MW)	
2010	*3,072*
2011	*4,368*
2012	*5,502*

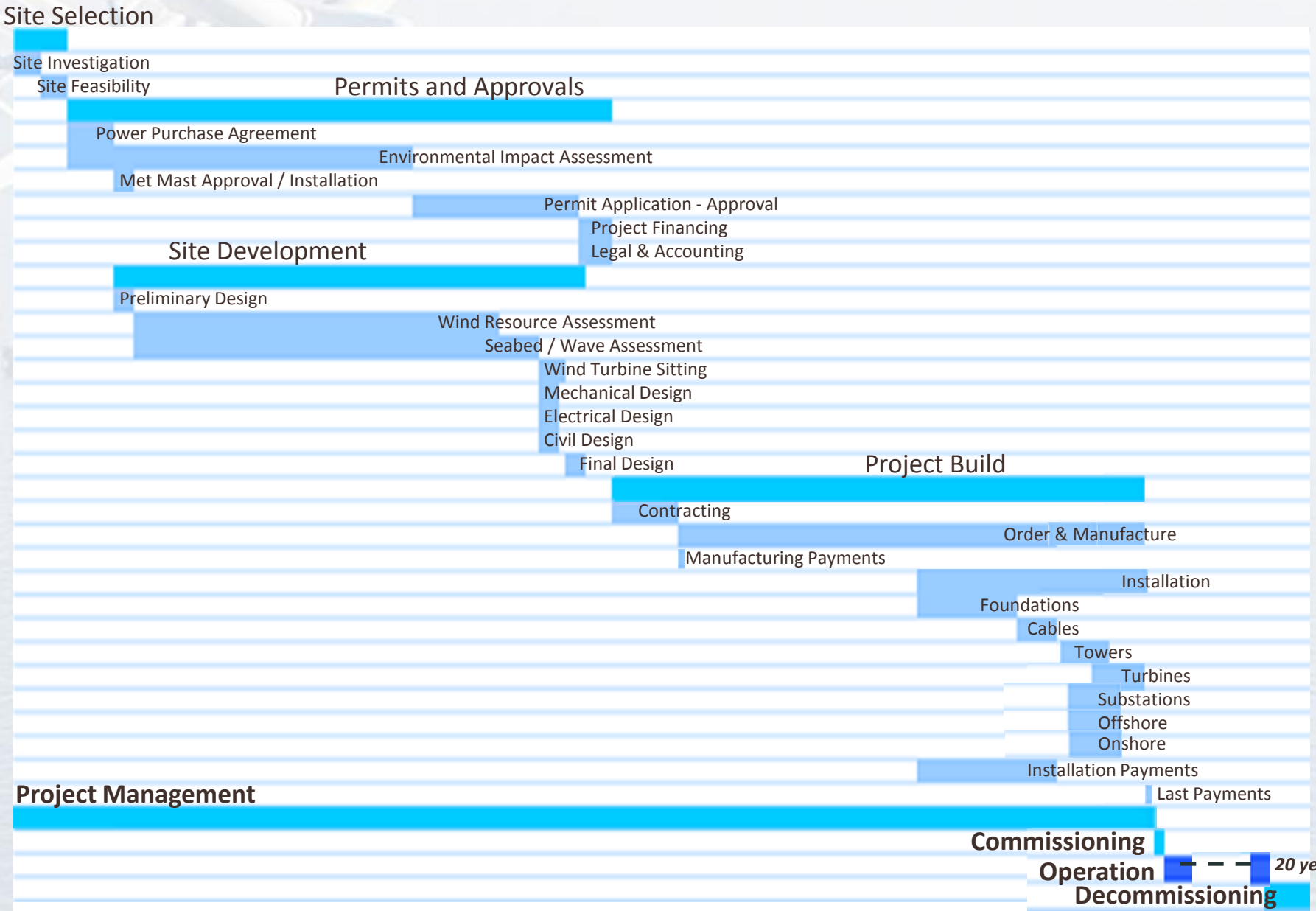


Offshore Wind Plants

http://www.4coffshore.com/offshorewind/


Uncertainty
Physical
Technical
Environmental
Economical
Social
Political
SITE SPECIFIC
Wind
Wind Farm
Conflicts
Sea
Land
Generation
Generation
Offshore Substation
Cables
Wave
Transmission
Switching
Environment
Sub-transmission
Supply
Power Market
Substation
Feeder
Demand
http://www.nrel.gov/docs/gen/f

Life-Cycle of an Offshore Wind Project



Offshore Wind Energy
Models, Projects, Tools

- NASA MOD
- Sunderland Model – University of Sunderland
- OPTI-OWECS – TUDelft
- WINDPACT – NREL, DOE
- OWECOP – ECN
- DOWEC – NEG Micon, LM Glasfiber, ACZ, ECN
- OWFLO – UMASS, GE, DOE
- RETSCREEN – Energy Diversification Research Laboratory, Canada
- Others

Research Questions

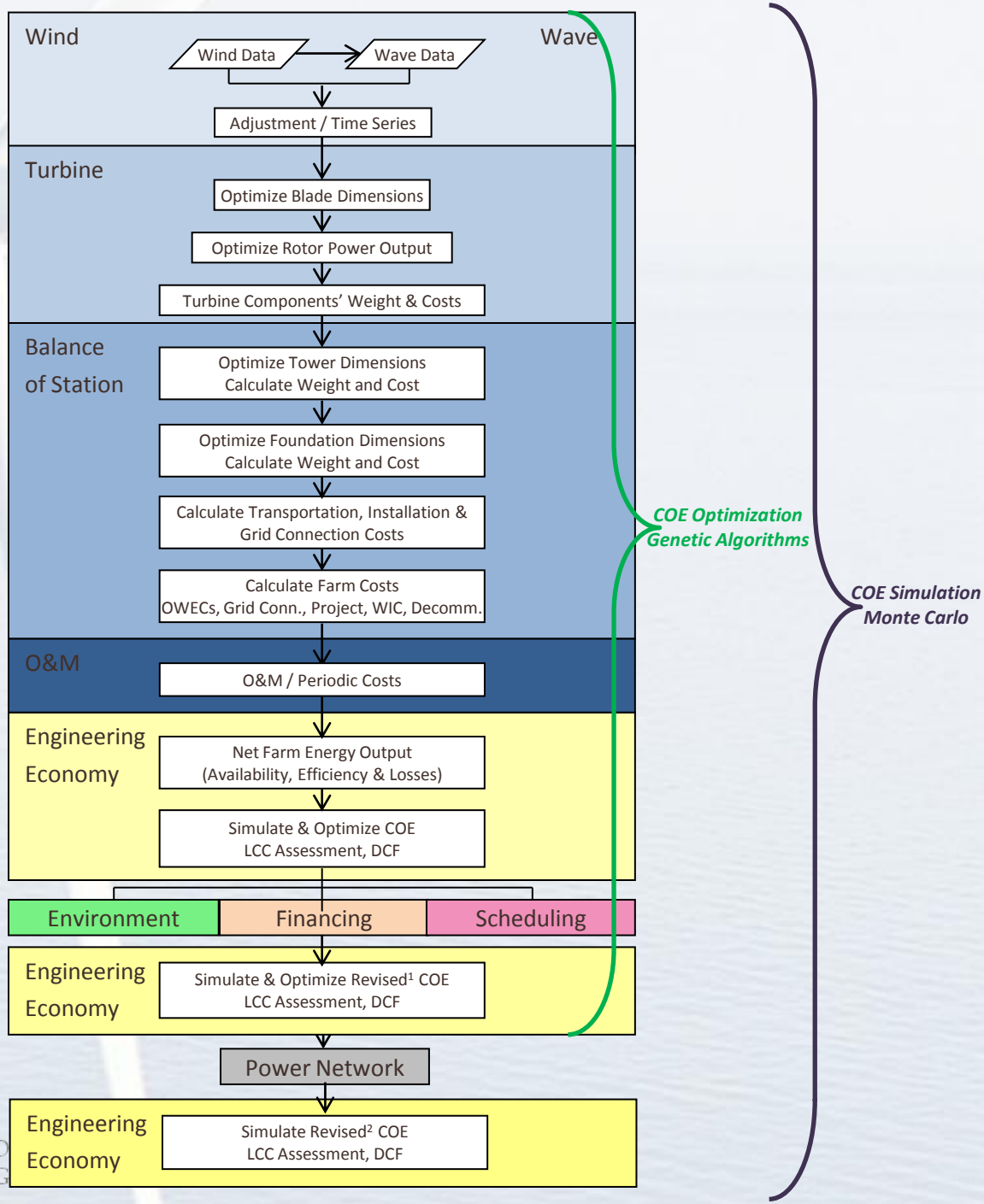
- Which cost drivers have the most impact on the wind generated cost of electricity?
- To what extent can a wind generated cost of electricity be usefully characterized by a probability distribution?
- What are the best financing methods and the impact of different financing structures on the cost of wind generated electricity?
- To what extent can scheduling and project management variation effect the cost of the wind generated electricity?
- How can a model best characterize the power market structure affects with respect to the grid-generated cost of the wind generated electricity?
- How can a model characterize CO_2 cap and trade system (e.g., tradable Renewable Energy Credits) with respect to the cost of wind generated electricity?

OFfshore Wind Integrated Cost

OFWIC

- Integrated
- Uncertainty
- Cost of Electricity
- Environment
- Financing
- Scheduling
- Power Network
- Risk Analysis
- Optimization

OFWIC



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SCHOOL OF ENGINEERING

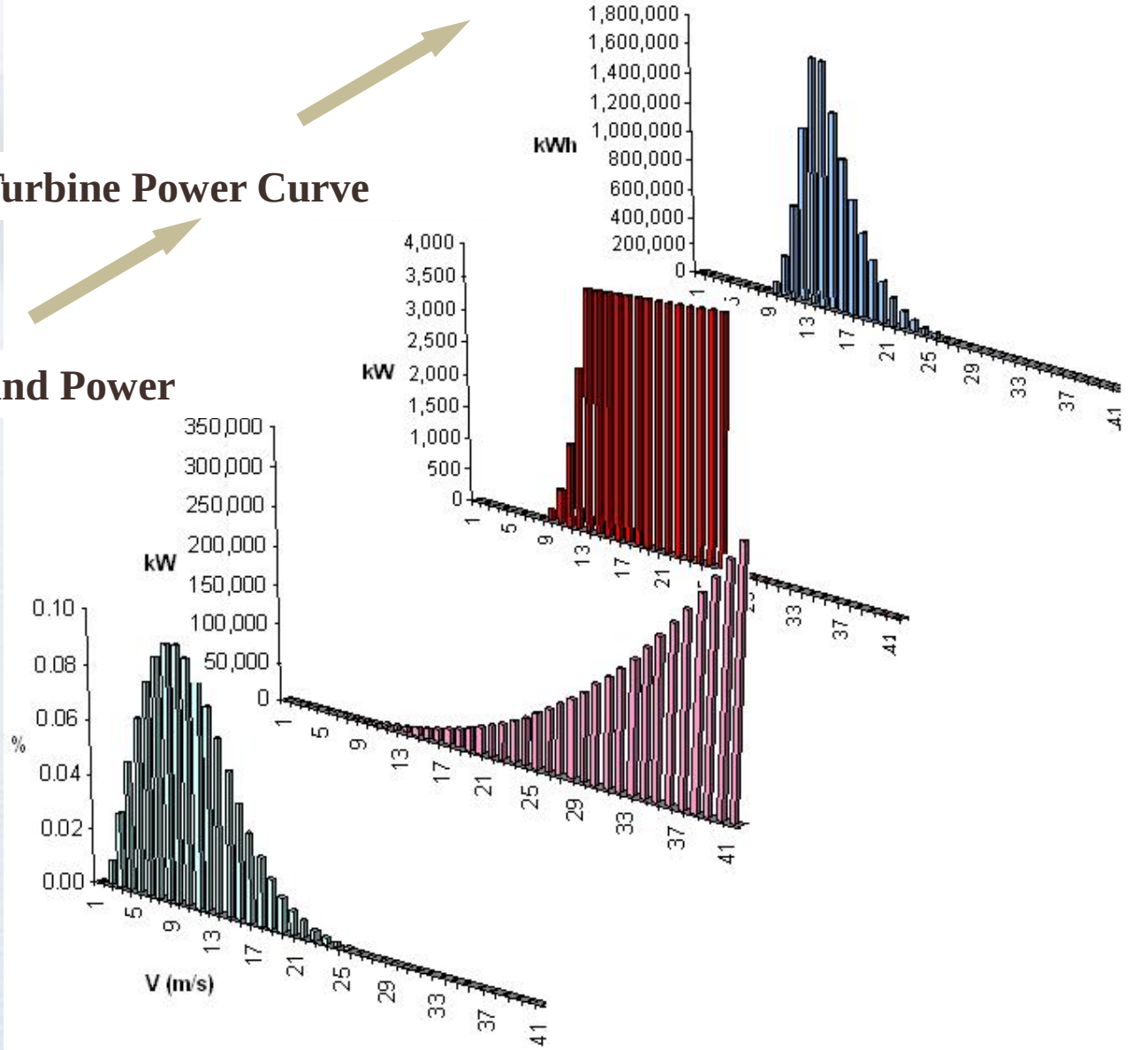
Energy Output

Annual Energy Output

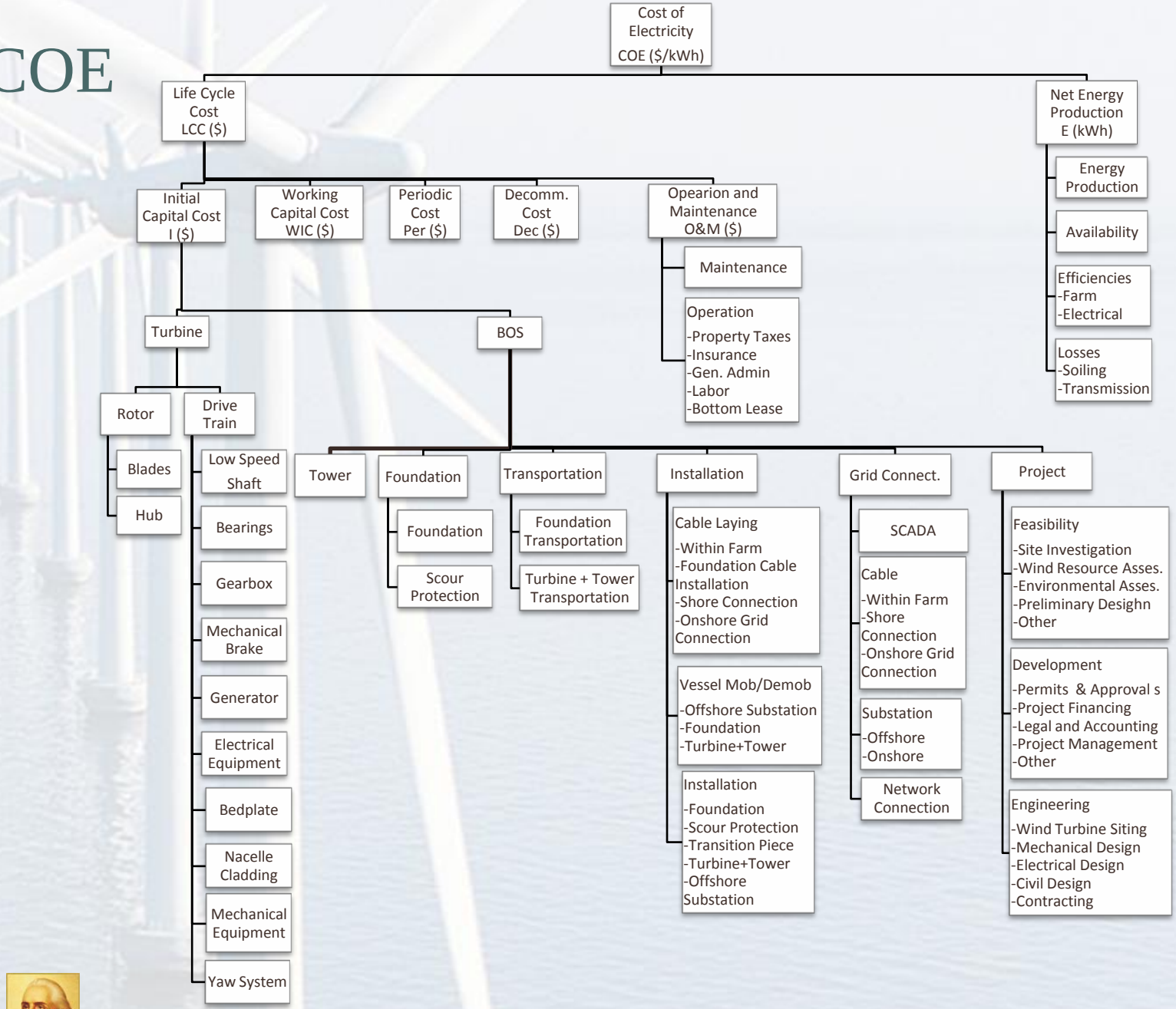
Turbine Power Curve

Theoretical Wind Power

Wind Speed



COE


Cost of Electricity
COE ($/kWh)
Life Cycle Cost
LCC ($)
Net Energy Production
E (kWh)
Initial Capital Cost
I ($)
Working Capital Cost
WIC ($)
Periodic Cost
Per ($)
Decomm. Cost
Dec ($)
Opearion and Maintenance
O&M ($)
Energy Production
Availability
Efficiencies
-Farm
-Electrical
Losses
-Soiling
-Transmission
Maintenance
Operation
-Property Taxes
-Insurance
-Gen. Admin
-Labor
-Bottom Lease
Turbine
BOS
Rotor
Drive Train
Blades
Hub
Low Speed Shaft
Bearings
Gearbox
Mechanical Brake
Generator
Electrical Equipment
Bedplate
Nacelle Cladding
Mechanical Equipment
Yaw System
Tower
Foundation
Transportation
Installation
Grid Connect.
Project
Foundation
Scour Protection
Foundation Transportation
Turbine + Tower Transportation
Cable Laying
-Within Farm
-Foundation Cable Installation
-Shore Connection
-Onshore Grid Connection
Vessel Mob/Demob
-Offshore Substation
-Foundation
-Turbine+Tower
Installation
-Foundation
-Scour Protection
-Transition Piece
-Turbine+Tower
-Offshore Substation
SCADA
Cable
-Within Farm
-Shore Connection
-Onshore Grid Connection
Substation
-Offshore
-Onshore
Network Connection
Feasibility
-Site Investigation
-Wind Resource Asses.
-Environmental Asses.
-Preliminary Desighn
-Other
Development
-Permits & Approval s
-Project Financing
-Legal and Accounting
-Project Management
-Other
Engineering
-Wind Turbine Siting
-Mechanical Design
-Electrical Design
-Civil Design
-Contracting

Environment Module

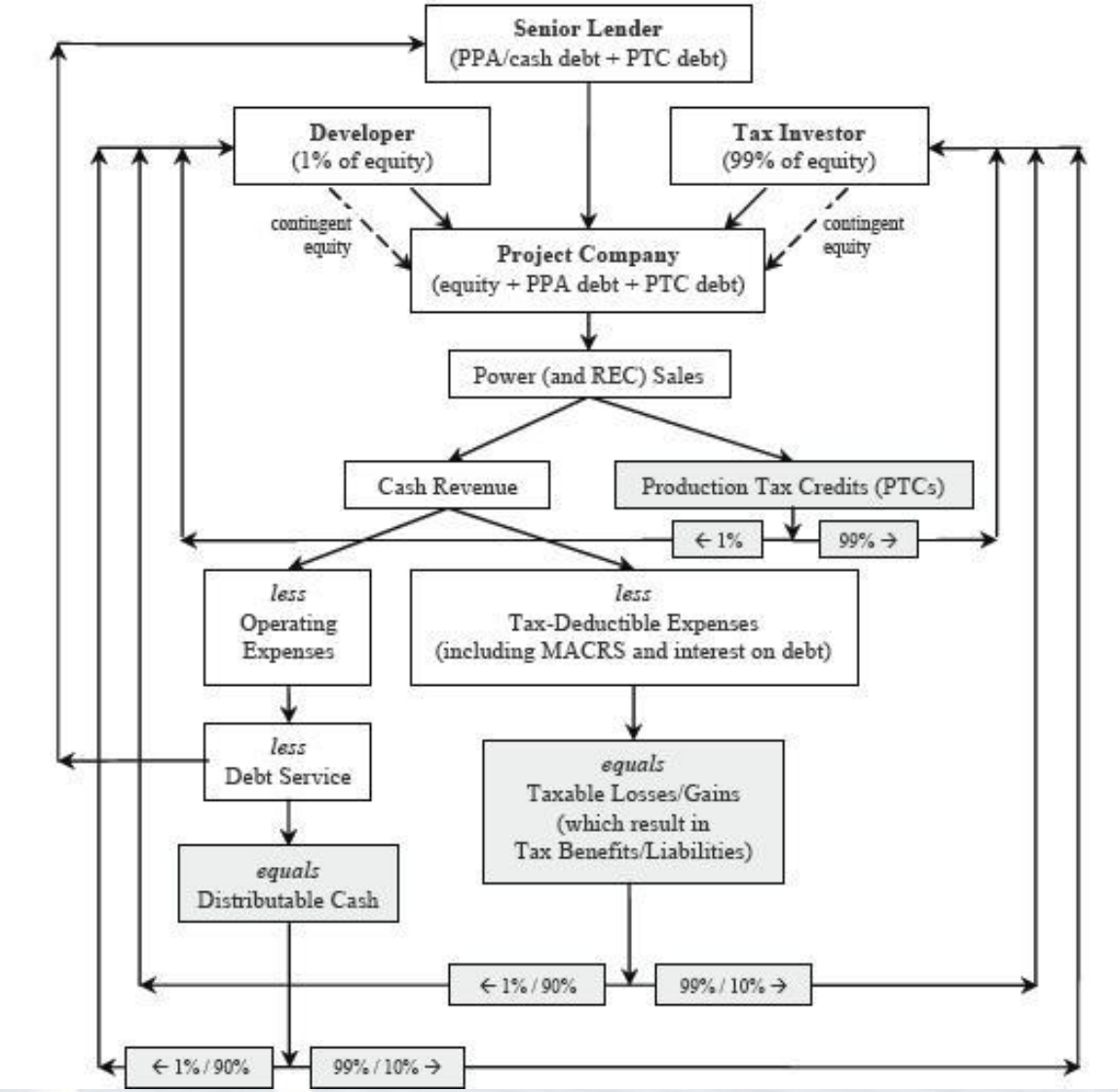
- **REC**
- REC escalation factor
- **Avoided Emissions**
- Replaced generation type
  Biomass, Coal, Diesel, Geothermal, Hydro, Natural Gas, Nuclear, Oil
- CO_2 emission ton/MWh
- CH_4 emission ton/MWh
- N_2O emission ton/MWh
- Fuel conversion efficiency
- Transmission and distribution losses
- GHG emission factor tCO_2/MWh
- **Cost of avoided emissions**

Financing Module

- Back Leveraged
- Cash & PTC Leveraged
- Cash Leveraged
- Corporate
- Institutional Investor Flip
- Pay-As-You-Go
- Strategic Investor Flip

Financing structures are adopted from report
"*Wind Project Financing Structures: A Review & Comparative Analysis*"
http://eetd.lbl.gov/ea/emp/reports/63434.pdf

Cash & PTC Leveraged



Scheduling Module

- Allocation of Funds during Construction (AFUDC)
- Interest During Construction (IDC)
- Task Durations
- Project Scheduling
- Gantt Chart

Scheduling Input Variables

Menu

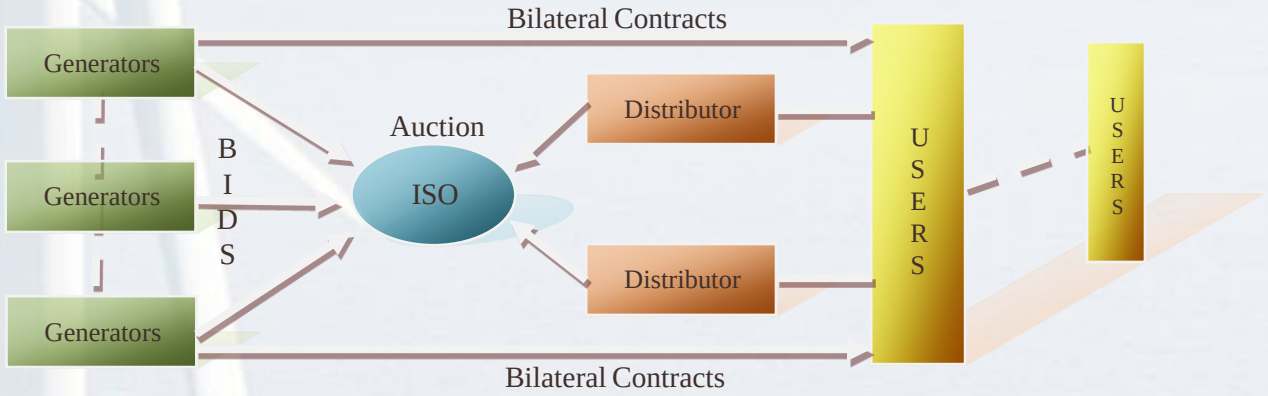
Project Initiation Date	1/2/2009	
Commissioning Date	10/9/2012	
Construction Time	3.77 years	
Cost of Capital	10.16%	0.03%
Equipment Escalation	2.98%	0.01%

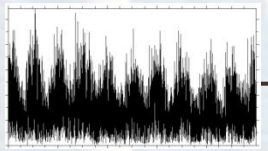
								$174,660,891	$1,644,796,437
WBS	**Task Name**	**Duration**	**Start**	**Finish**	**Predecessor**	**12/31/2008**	**Escalated**	**IDC**	**ICC**
1	**Site Selection**		**1/2/2009**	**3/1/2009**					
1.1	Site Investigation	30	1/2/2009	1/31/2009	1	$724,916	$724,974	$319,291	$1,044,265
1.2	Site Feasibility	30	1/31/2009	3/1/2009	1.2	$724,916	$726,669	$312,018	$1,038,687
2	**Permits and Approvals**		**3/1/2009**	**11/8/2010**					
2.1	Power Purchase Agreement	30	3/1/2009	3/30/2009	2	$1,449,832	$1,456,736	$609,541	$2,066,278
2.2	Environmental Impact Assessment	365	3/1/2009	2/28/2010	2	$4,349,495	$4,370,209	$1,828,624	$6,198,834
2.3	Met Mast Approval	20	3/30/2009	4/18/2009	2.1	$2,899,663	$2,920,285	$1,190,197	$4,110,482
2.4	Met Mast Installation	5	4/18/2009	4/22/2009	2.3	$724,916	$731,189	$292,832	$1,024,021
2.5	Permit Application	1	2/28/2010	2/28/2010	2.1, 2.2	$8,698,989	$9,000,421	$2,591,219	$11,591,640
2.6	Application Approval	225	2/28/2010	10/10/2010	2.5	$1,449,832	$1,500,070	$431,870	$1,931,940
2.7	Project Financing	30	10/10/2010	11/8/2010	2.6	$10,873,736	$11,455,314	$2,447,050	$13,902,364
2.8	Legal & Accounting	30	10/10/2010	11/8/2010	2.7	$7,249,158	$7,636,876	$1,631,367	$9,268,243
3	**Site Development**		**3/30/2009**	**5/29/2010**					
3.1	Preliminary Design	20	3/30/2009	4/18/2009	2.1	$1,449,832	$1,460,143	$595,098	$2,055,241
3.2	Wind Resource Assessment	365	4/22/2009	4/21/2010	2.4	$1,449,832	$1,462,850	$583,680	$2,046,529
3.3	Wave Assessment	365	4/22/2009	4/21/2010	2.4	$724,916	$731,425	$291,840	$1,023,265
3.4	Wind Turbine Sitting	20	4/21/2010	5/10/2010	3.2, 3.3	$1,739,798	$1,807,638	$488,533	$2,296,171
3.5	Mechanical Design	20	4/21/2010	5/10/2010	3.2, 3.3	$1,739,798	$1,807,638	$488,533	$2,296,171
3.6	Electrical Design	20	4/21/2010	5/10/2010	3.2, 3.4	$1,739,798	$1,807,638	$488,533	$2,296,171
3.7	Civil Design	20	4/21/2010	5/10/2010	3.2, 3.5	$1,739,798	$1,807,638	$488,533	$2,296,171
3.8	Final Design	20	5/10/2010	5/29/2010	3.4, 3.5, 3.6, 3.7	$1,739,798	$1,810,406	$477,722	$2,288,127
4	**Project Build**		**11/8/2010**	**9/25/2012**					
4.1	Contracting	30	11/8/2010	12/7/2010	2.6	$2,899,663	$3,061,893	$625,602	$3,687,495
4.2	Order & Manufacture		**12/7/2010**	**7/28/2012**					
4.2.1	Turbines	200	12/7/2010	6/24/2011	4.1				
4.2.2	Towers	200	12/7/2010	6/24/2011	4.1				
4.2.3	Foundations	200	12/7/2010	6/24/2011	4.1				
4.2.4	Cables	200	12/7/2010	6/24/2011	4.1				
4.2.5	Substations		**12/7/2010**	**7/28/2012**					
4.2.5.1	Offshore Substation	600	12/7/2010	7/28/2012	4.1				
4.2.5.2	Onshore Substation	200	12/7/2010	6/24/2011	4.1				
4.3	Manufacture Payments		**12/7/2010**	**12/7/2010**					
4.3.1	Turbines	1	12/7/2010	12/7/2010	4.1	$351,883,799	$372,439,706	$72,659,868	$445,099,574
4.3.2	Towers	1	12/7/2010	12/7/2010	4.1	$142,838,381	$151,182,535	$29,494,446	$180,676,981
4.3.3	Foundations	1	12/7/2010	12/7/2010	4.1	$55,362,189	$58,596,268	$11,431,641	$70,027,910
4.3.4	Cables	1	12/7/2010	12/7/2010	4.1	$35,984,900	$38,087,021	$7,430,459	$45,517,480
4.3.5	Substations	1	12/7/2010	12/7/2010	4.1				
4.3.5.1	Offshore Substation	1	12/7/2010	12/7/2010	4.1	$30,975,000	$32,784,459	$6,395,973	$39,180,432
4.3.5.2	Onshore Substation	1	12/7/2010	12/7/2010	4.1	$3,472,000	$3,674,823	$716,927	$4,391,750
4.4	Installation		**6/24/2011**	**12/17/2011**					
4.4.1	Foundations	45	6/24/2011	8/7/2011	4.2.3				
4.4.2	Cables	45	8/7/2011	9/20/2011	4.2.4, 4.4.1				
4.4.3	Towers	45	9/20/2011	11/3/2011	4.2.2, 4.4.2				
4.4.4	Turbines	45	11/3/2011	12/17/2011	4.2.1, 4.4.3				
4.4.5	Substations		**9/20/2011**	**9/25/2012**					
4.4.5.1	Offshore Substation	60	7/28/2012	9/25/2012	4.4.2, 4.2.5.1				
4.4.5.2	Onshore Substation	45	9/20/2011	11/3/2011	4.4.2, 4.2.5.2				
4.5	Installation Payments		**6/24/2011**	**11/3/2011**					
4.5.1	Turbines	1	11/3/2011	11/3/2011	4.4.4	$34,748,371	$37,771,790	$3,575,216	$41,347,006
4.5.2	Towers	1	9/20/2011	9/20/2011	4.4.3	$25,846,035	$27,995,497	$3,009,566	$31,005,063
4.5.3	Foundations	1	6/24/2011	6/24/2011	4.4.1	$47,895,850	$51,512,713	$6,884,851	$58,397,564
4.5.4	Cables	1	8/7/2011	8/7/2011	4.4.2	$49,005,495	$52,893,241	$6,373,706	$59,266,946
4.5.5	Substations		**9/20/2011**	**9/25/2012**					
4.5.5.1	Offshore Substation	1	7/28/2012	7/28/2012	4.4.5.1	$9,816,000	$10,902,867	$213,142	$11,116,009
4.5.5.2	Onshore Substation	1	9/20/2011	9/20/2011	4.4.5.2	$2,592,000	$2,807,561	$301,818	$3,109,379
4.6	Last Payments	1	9/25/2012	9/25/2012	4.4	$483,911,482	$540,051,967	$2,008,927	$542,060,895
5	**Project Management**	**1362**	**1/2/2009**	**9/25/2012**		$18,122,894	$18,124,353	$7,982,270	$26,106,623
6	**Commissioning**	**15**	**9/25/2012**	**10/9/2012**		$13,468,231	$15,030,734	$0	$15,030,734
7	**Operation**	**7300**	**10/9/2012**	**10/3/2032**					
8	**Decommissioning**	**60**	**10/3/2032**	**12/1/2032**					

Payment Breakdown %	
Manufacture Payments	70%
Installation Payments	80%
Last Payments	Remaining

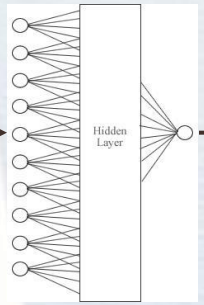
Power Network Module

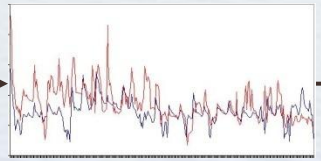
OFWIC Power Market Model



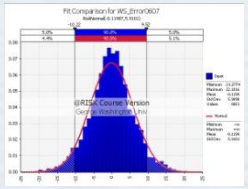


Historical Time Series
LMP, Load, WS





Forecasted Time Series
LMP, Load, WS

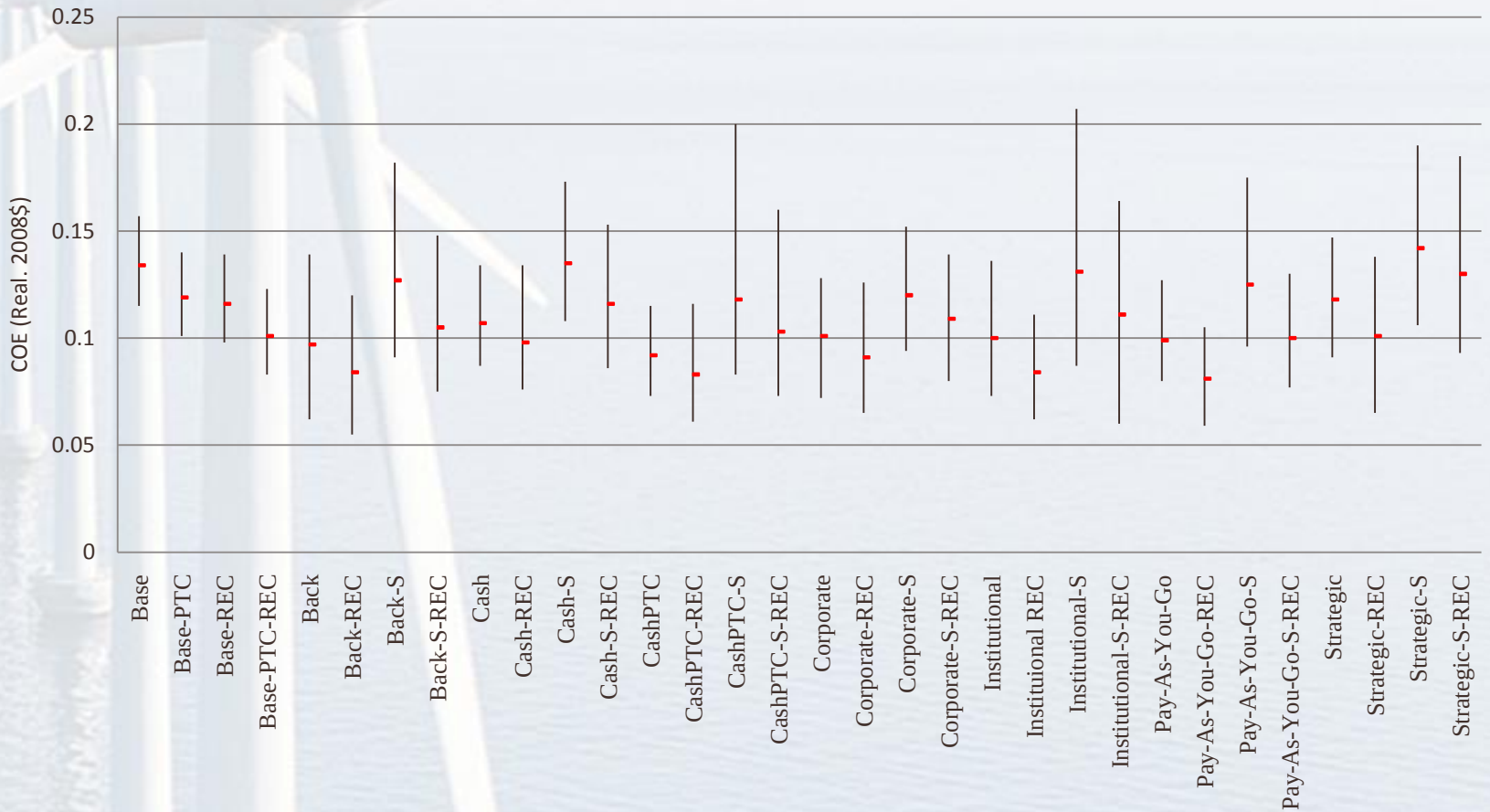


Forecast Errors
LMP, Load, WS

Simulation - Optimization

- Parametric optimization
- Complex, large stochastic system
- Formulation of objective function is difficult
- Non-linear probabilistic elements
- Simulation-based evaluation of the objective function
- Genetic algorithms

Case Study


0.25
0.2
0.15
0.1
0.05
0
COE (Real. 2008$)
Base
Base-PTC
Base-REC
Base-PTC-REC
Back
Back-REC
Back-S
Back-S-REC
Cash
Cash-REC
Cash-S
Cash-S-REC
CashPTC
CashPTC-REC
CashPTC-S
CashPTC-S-REC
Corporate
Corporate-REC
Corporate-S
Corporate-S-REC
Institutional
Instituuional REC
Institutional-S
Institutional-S-REC
Pay-As-You-Go
Pay-As-You-Go-REC
Pay-As-You-Go-S
Pay-As-You-Go-S-REC
Strategic
Strategic-REC
Strategic-S
Strategic-S-REC

Future Work

- More sophisticated and analytic models for
  - O&M cost estimation
  - Farm efficiency and transmission loss estimations
  - Updated component weight and cost estimations
- Expanded model scope to include
  - Power flow problem
  - Future foundation designs
  - Different pollutant trading
  - Different feed-in tariffs
  - Different point of views, e.g. other generators, market itself, ISO and public.
- To analyze nationwide and hybrid scenarios
- Sensitivity analysis including financing and power network parameters
- A real life comparison

Questions

http://www.hornsrev.dk/Engelsk/default_ie.htm