AC 2008-733: RENEWABLE ENERGY FOR LEARNING BARGE

P. Paxton Marshall, University of Virginia

Farhad Omar, University of Virginia

Alexander Hydrogen Martin, University of Virginia

James Durand, University of Virginia

Renewable Energy for Learning Barge™

American Society for Engineering Education 2008 Annual Conference

Introduction

Learning Barge™ is joint project of the schools of architecture and engineering at the University of Virginia to design and build an energy self-sufficient floating classroom that offers an interactive, hands-on learning experience focused on ecological restoration, preservation, and the environmental impact of human activities. The barge will be sited on the Elizabeth River in tidewater Virginia. The Learning Barge™ will serve the residents of the Elizabeth River watershed and Hampton Roads' population of 1.6 million through a unique curriculum developed by science coordinators and teachers from Portsmouth, Chesapeake and Virginia Beach School Districts, doctoral students from UVA's Curry School of Education, and the Elizabeth River Project staff.

An estimated 19,000 learners, including K-12 students and teachers, diverse community groups, families, children, adults, and people from all backgrounds are anticipated to visit the Learning Barge annually and participate in activities centered around wetlands, water, sustainable practices, art & literature, and history & geography. They will also gain knowledge about energy sustainability through alternative sources of energy provided by photovoltaic solar panels, wind turbines, and solar thermal space heating for the classroom produced by an evacuated tube heating system. A monitoring system with a large display will provide feedback on energy generation and consumption onboard the Learning Barge™ to collect accurate data on the performance of the solar and wind systems, and to teach visitors about conservation and renewable energy.

Multidisciplinary Collaboration

The project is conducted through classes taught by Phoebe Crisman of the School of Architecture and Paxton Marshall of the School of Engineering and Applied Science at the University of Virginia. Design is scheduled to be completed at the end of 2007 with construction and launch scheduled for the spring and summer of 2008. The engineering team has consisted of two electrical engineers, two civil engineers and one engineering science major. Jim Durand, adjunct professor of mechanical engineering has advised the thermal team. Thus far about 20 architecture students have been involved with the architectural design. The engineering and architecture teams meet weekly to collaborate on their designs.

The project has provided students with significant learning experiences due to the collaborative interactions with students of different disciplines, and the real world constraints of a design that will actually be built and must meet a budget.

The Electrical System

The Learning Barge™ electrical system is designed to provide electricity for the barge, and to educate the public about alternative sources of energy, through implementation of photovoltaic panels and wind turbines. In developing this system, there were three main objectives to achieve: generating energy, storing it, and distributing it.

Generating Electricity

Design of the electrical system of the barge started with a load analysis of the early spring – late fall seasons, our worst-case scenario because the energy required by the barge is at maximum and the solar input is minimum. We neglected the winter season because the barge will not be operated in the winter.

In designing an electrical system that relies on intermittent sources such as solar and wind it is essential to understand the load requirements of the barge. Any appliance that is connected to an electrical circuit and consumes power is defined as a load. To determine the maximum power consumption on the barge we can add the total wattage consumed by each individual load. The following table shows a summary of the loads onboard the barge and their respective wattage.

Components (Loads)	Quantity	Watt / item (Watt)	Instantaneous Power (Quantity * Watt/item) (Watts)
Navigation Light	1	55	55
Navigation Light	1	55	55
Navigation Light	1	55	55
Navigation Light	1	55	55
Window Wall Light	5	1	5
Table Light	3	1	3
Bathroom Light	2	15	30
Armature Lighting	9	15	135
Radiant Floor Pump	2	187	374
In Window Light	3	7.5	22.5
Composting Toilet Fan	2	7.2	14.4
Bathroom Exhaust Fan	2	7.2	14.4
Classroom Fan	1	200	200
Bilge Pump	1	2000	2000
LCD Data Display	1	15	15
Skiff Boat Battery	1	600	600
Total			3633.3

Table 1 Load Components & Instantaneous Power Consumption

Table 1 shows that most of the components are light fixtures with minimal power usage, however the biggest power consumers are the radiant floor pumps, the bilge pumps, the skiff boat, and the classroom fan.

The next step is to analyze the operational hours of the barge and its components. The barge will be operational from 9am to 5pm five days a week from mid March to mid November. The barge will not be open to students during the winter because the Elizabeth River Project does not conduct onsite restoration and preservation programs in winter. The following table shows the seasonal number of hours of each individual load.

	Early Spring or Late Fall	Summer	Winter
Component & Use	Normal Hours / Day	Normal Hours / Day	Normal Hours / Day
Navigational Light 01	0	0	0
Navigational Light 02	0	0	0
Navigational Light 03	12	9	14.5
Navigational Light 04	0	0	0
Window Wall Lights	2	2	0
Window Lights	2	2	0
Bathroom Lights	4	4	0
Armature Lights	2	2	0
Classroom Lights	4	4	0
Radiant Floor Pump	5	0	0
Composting Toilets	24	24	24
Toilet Exhaust Fans	8	8	0
Classroom E. Fan	4	4	0
Bilge Pump	30 min	30 min	30 min
Skiff Boat Battery	7.6 min	7.6 min	7.6 min
LCD Display Monitor	8	8	0

Table 2 Seasonal hours of operation of each load

To better understand the size of a system, it is useful to carry out an analysis of the daily energy consumption. Table 3 shows an hourly analysis of the loads during a normal operational day in the spring and fall.

Hourly Energy Consumption Late Fall & Early Spring																	
	NAV Light 1	NAV Light 2	NAV Light 3	NAV Light 4	W. Wall Lights	W. Lights	B. Lights	A. Lights	C. Lights	R. Pump	Comp. Toilets	T. E. Fan	Classroom Fan	Skiff boat Battery	Bilge Pump	Disp. Monitor	Total
Quantity	1	1	1	1	5	3	2	9	3	2	2	2	1	1	1	1	
Wattage/item	55	55	55	55	1	1	15	15	7.5	374	7.2	7.2	200	600	2000	15	
Total Wattage	55	55	55	55	5	3	30	135	23	374	14.4	14.4	200	600	2000	15	3633.8
Normal Day - Late Fall & Early Spring																	
8:00	0	0	0	0	0	0	0	0	0	374	14.4	0	0	0	0	0	201.4
9:00	0	0	0	0	0	0	30	0	0	374	14.4	14.4	7.2	0	0	15	268
10:00	0	0	0	0	0	0	30	0	0	374	14.4	14.4	7.2	0	0	15	268
11:00	0	0	0	0	0	0	30	0	0	374	14.4	14.4	7.2	0	0	15	268
12:00	0	0	0	0	0	0	30	0	0	374	14.4	14.4	0	0	0	15	260.8
13:00	0	0	0	0	0	0	30	0	23	374	14.4	14.4	0	0	0	15	283.3
14:00	0	0	0	0	0	0	30	0	23	0	14.4	14.4	0	0	0	15	96.3
15:00	0	0	0	0	5	3	30	135	23	0	14.4	14.4	7.2	0	0	15	246.5
16:00	0	0	0	0	5	3	30	135	23	0	14.4	14.4	7.2	300	0	15	547
17:00	0	0	0	0	5	3	30	135	23	0	14.4	14.4	7.2	0	0	15	246.5
18:00	0	0	0	0	0	0	0	0	0	0	14.4	0	0	0	0	0	14.4
19:00	0	0	0	0	0	0	0	0	0	0	14.4	0	0	0	0	0	14.4
20:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
21:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
22:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
23:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
0:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
1:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
2:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
3:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
4:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
5:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
6:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
7:00	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0	0	0	69.4
7:59	0	0	55	0	0	0	0	0	0	0	14.4	0	0	0		0	69.4
																	3616.8

Table 3 Late Fall / Early Spring normal operational day (Ayman [14] with Modifications)

Based on analysis in table 3 the Learning Barge will require about 3.7 kilowatt-hours of energy per operational day.

After identifying each individual load and determining their power consumption, the most important analysis is to understand the solar radiation we receive each day. Table 4 provides a thirty-year average, from 1961 to 1990, obtained from the National Renewable Energy Laboratory (NREL) [1]. The average solar radiation, in the Money Point area where the barge will be located, from March to September is over four hours. However, the average of direct solar exposure is 2.5 hours or less in November, December, and January, therefore; the system needs to be sized accordingly in order to provide sufficient energy during those months.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of hours of solar insolation	2.3	3.0	4.1	5.1	5.8	6.2	5.9	5.4	4.5	3.5	2.5	2.0

Table 4 shows the average of hourly solar radiation based on the data from NREL [1]

Based on the data from table 1 in November each PV panel provides an average of 0.15 kilowatt * 2.5 hours = 0.375 kilowatt-hours of energy per day. Dividing 3.7 kilowatt-hours by 0.375 kilowatt-hours will give us the number of panels (approximately 10 in this case) needed – without any wind turbines - to support the operation of the barge. However, since we are using two wind turbines as sources of energy we can reduce the number of panels to 8.

The second source of generating energy is wind turbines. Wind speed is very variable. However, analyzing a long-term pattern of wind speeds throughout a year will allow us to understand their behavior and based on that predict the output of a wind turbine. The wind turbines we have chosen (Air-X 400) do not start with wind speeds lower than 3.1 meters per second. The Air-X 400 turbines are rated 400 watts at twenty-eight meters per second wind. Figure 1 shows the relationship between wind speeds and the wind turbines power generation capability.

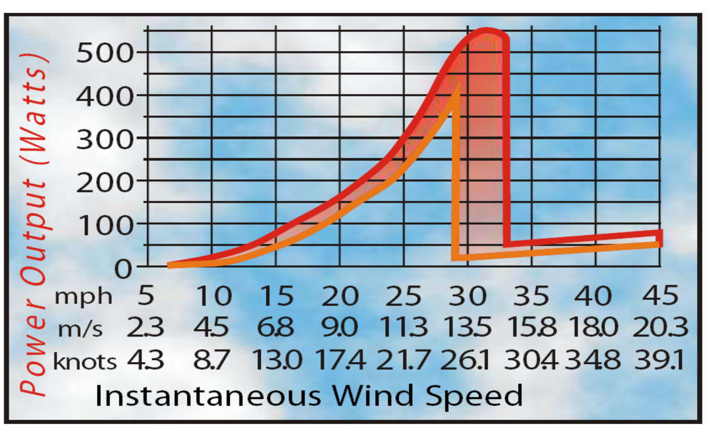

Figure 6 – Air-X power output graph [13]

The national oceanic and atmospheric administration (NOAA) collects and monitors the wind speed every six minutes throughout the year in Money Point [2]. In order to properly analyze the wind speed, we determined the portion of the month wind speeds were above 3.2 meters per second (the lower speeds do not contribute any output) and the average of those speeds (see Table 2), we determined an average speed of 4.5m/s occurring 35% of the time (10.5 days/month). From Figure 1, an Air-X 400 Watt wind turbine would generate 20 watts of instantaneous power with a 4.5 m/s wind, providing an average daily energy output of 168 watt-hr.

Year / Month	2006		2005		2004		2003		Average	
	Average Speed of Speeds over 3.2 m/s	Percentage of month with speeds over 3.2 m/s	Average Speed of Speeds over 3.2 m/s	Percentage of month with speeds over 3.2 m/s	Average Speed of Speeds over 3.2 m/s	Percentage of month with speeds over 3.2 m/s	Average Speed of Speeds over 3.2 m/s	Percentage of month with speeds over 3.2 m/s	Average Speed of Speeds over 3.2m/s	Percentage of month with speeds over 3.2m/s
January	5.73	42.3	5.68	48.0	5.224	48.5	5.47	42.0	5.53	45.2
February	4.80	32.3	4.47	40.9	4.62	38.1	4.83	36.2	4.68	36.9
March	4.88	49.2	4.88	41.9	4.85	46.9	4.85	35.7	4.86	43.4
April	4.51	40.9	5.07	48.4	4.72	49.0	4.41	39.2	4.68	44.4
May	4.45	37.9	4.46	39.1	4.26	37.0	4.61	26.5	4.44	35.1
June	4.30	33.0	4.12	30.1	4.14	30.4	4.24	23.5	4.20	29.3
July	4.10	27.1	4.06	19.4	4.32	19.5	4.33	31.2	4.20	24.3
August	4.03	27.3	4.12	20.4	4.29	23.4	4.19	23.4	4.15	23.6
September	4.49	28.3	4.41	31.6	4.78	30.0	5.31	32.0	4.74	30.5
October	4.54	32.4	4.37	38.2	4.13	27.5	4.55	24.2	4.40	30.6
November	5.17	37.1	4.66	38.0	4.62	31.9	5.06	33.9	4.88	35.2
December	4.72	29.3	4.46	35.9	4.81	43.7	4.55	41.3	4.63	37.5

Table 5 – Wind Data for 4 years obtained from NOAA [4].

Since November is the operational month with the least solar generation, we will use that month to determine our wind requirements. Table 5 tells us that we can expect an average wind of 4.9 m/s over 35% (about 10 days) of the month.

Energy Storage

Since the barge completely operates off the grid, we need a medium to store energy when the generation is insufficient to supply the loads. For our initial design we assumed a need for three days of energy backup storage. Since the total load of the system is 3.7 kilowatt-hr per day, the total energy required for three days is equal to 3.7 kilowatt-hr * 3 days = 11100 watt-hr. Dividing 1386011100 watt-hr by a 24 volt system will give us the amp-hr capacity of a battery array of 463 amp-hr.

We identified 12V deep discharge batteries rated at 250 A-hr. We decided to compromise a little on backup energy in favor of economy and chose four 12V, 250 A-hr batteries that will give us approximately 2.5 days of backup power. The batteries will be connected as two parallel strings of two batteries in series to provide 24 volts for our loads.

Providing backup power source

In case of an emergency or lack of sufficient solar radiation, the Learning Barge™ electrical design incorporates a 11.5 KW Quiet Diesel™ model MDKBM AC (alternating current) generator that provides sufficient energy to run two high power bilge pumps as well as supplying power to the system. The MDKBM generator is capable of delivering 95.5 Amps of current at 120 Volts at 60 Hz. The AC generator is connected to the main electrical system via an AC to DC converter. In order to supply enough current to charge our battery system we used a converter. The VSCP-2K4 is a 2400 Watt AC-DC converter that accepts 120/240 Volt AC and outputs over a wide range of voltages and currents.

Final design

Considering the analysis, a combination of eight solar panels rated at 200 watts and two wind turbines rated at 400 watts will provide sufficient energy to the barge, and four 250 amp-hr batteries will provide sufficient storage for two and half days of full barge functionality without sun or wind.

Cost analysis of Main Components

Key #	Quan.	Description	Remarks & Manufacturer	Model #	Price $
1	8	24 Volts Solar Panels	GE - 200 Watt / item	GE-PVP-200	8800
2	1	(MPPT) Maximum Power Point Tracker – Charge Controller	Appllo Star Charge	T80	700
8	4	Deep Cycle Batteries	Concord Batteries	PVX-2580L	2848
24	2	Wind Turbines	400 Watts – 24 Volts Southwest Windpower	Air-X Marine	1600 Total = 14000

Table 6 Major components of electrical system

Solar Hot Water Heating System

Our solar hot water heating system on the Learning Barge™, unlike most residential applications, is used for space heating. In developing this system, there were two main designs to establish. First was the part of the system that collected and stored the energy used to heat the Barge's classroom. Second was the system used to deliver the stored heat to the classroom space. These design deliberations included extensively collaborative discussion between the Engineering and Architecture members of the Learning Barge™ team.

Collection and Storage of Energy

There are two components of this section of the system, the collection array and the water storage tank. In design simulations, our team varied the size of both collector array and the water tank to achieve optimum robustness. For an energy collection system we decided to use evacuated tube technology. To store this energy we selected a basic, well-insulated water tank.

Much deliberation was put into what type of collector to use. The Architecture students were looking for a technology that was both aesthetically pleasing and resistant to the corrosive saltwater environment of the Elizabeth River. As engineering students, we were looking for an efficient system that could provide the requisite heat to the poorly insulated classroom space (three walls of floor to ceiling single-paned hurricane glass with an R-value of one). Both parts of the team found a compromise in evacuated tube technology. This technology provided a high level of solar panel efficiency (~94%), an interchangeable tube system for easy repair, and a collector that absorbs solar radiation even in overcast weather conditions. This system also only required a basic water tank for storage. After establishing these two technologies, the team's task was then to determine the size of these two systems.

We conducted a thermal analysis of the Barge in the Elizabeth River climate to find the worst case heat load. This analysis showed that in the months of November and March (the Barge will not be occupied from December to February) there are days where the classroom space will need around 20,000 BTU/hour, after accounting for the heat given from passive design and human-produced activity. With this analysis in mind, our "ideal" design criteria include:

- The system does not reject too much solar heat in the heating months of October, November, March, and April (heat rejection hours < 200)
- The tank does not take too long to thermally fill (< 5 days to fill)
- The tank takes at least 3 days to thermally empty
- The system meets at least 95% of the heating requirements when the active solar system is needed to heat the space.
- The storage tank temperature stays above 120 degrees at all times during the heating months.
- The storage tank temperature drops below 140 (below one third thermally full), only about 10% of the hours when heat is required from the active solar system.

We can think of this system as the collector filling the water tank with heat to a maximum amount, not unlike filling a cup with water. Here our maximum fill amount is having all of the water in the tank heated to 191 degrees Fahrenheit (a temperature providing a safety margin below boiling). The minimum fill level is 120 degrees (it is hard to effectively heat the space with water temperatures below 120). In our thermal analogy, when the classroom needs to be heated we are pouring water out of the cup. When the sunlight is hitting the collector the cup is being filled.

The first of the above "ideal" design criteria address the amount of heat we have to get rid of, or "dump," when all the water in the storage tank is heated to the maximum allowable temperature (when the tank is "thermally" full). The criteria also address the time needed to thermally fill up (heat tank water) and thermally empty (continual release of heat into the classroom space, and heat loss from the tank).

Working with the Architecture team, we determined there are two possible designs that would meet the "ideal" criteria. These two designs show the design criteria statistics for different evacuated tube collector arrays sizes and storage tank sizes.

Collector Area	Criteria	500 Gallon Storage Tank
		Normal (Single Glazing)
60 ft^2	Days to empty	3.3
	Days to Fill	8.4
	% Ht hrs < 140 ^oF	8
	Low Temp	126
	% heat needs met	100
	Hrs heat rejected	174

a

Collector Area	Criteria	500 Gallon Storage Tank
		Double Glazing
30 ft^2	Days to empty	3.4
	Days to Fill	13.1
	% Ht hrs < 140 ^oF	26
	Low Temp	118
	% heat needs met	100
	Hrs heat rejected	74

b

Table 7: (a) Recommended collector and storage tank size for single glazing glass walls; (b) Recommended collector and storage tank size for double glazing glass walls.

Table 7(a) shows the recommendation of 60 ft^2 of collector area and a 500 gallon storage tank for single glazing glass walls (R = 1). Table 7(b) gives the recommendation if the glass walls were changed to double glazed (R = 2) as 30 ft^2 of collector area and a 500 gallon storage tank. One of these design recommendations will be followed based the financial constraints such as donations of double glazed glass.

Now that the collection and storage of heat has been discussed, the next section will step through the design choices for delivery of this heat.

Delivery of Heat to Classroom

The initial design for heat delivery submitted by the Architecture team was the idea of a traditional radiant floor system. This system involved heating a 4" concrete slab under the entirety of the classroom to provide heat to the poorly insulated space. After consulting installers of traditional radiant floor systems, we discovered that this type of system would take any where from 1 to 3 days to start providing heating to the classroom space. This slow response time was inadequate for the required heat of the space. We only need to heat the classroom space when students and visitors are on the Barge (i.e. five hours a day; five days a week). If a radiant floor were installed, we would be providing roughly 140 hours worth of heat for a heat load of only about 25 hours. This inflexibility in heating response was the primary reason behind not using the traditional radiant floor system in the Barge.

This second design was borne out of a need for faster response time in heating the classroom space. This system included having radiant piping with heater fins (akin to a traditional hot water radiator) below the wood decking of the classroom. To provide maximum heating response to the space, metal grating would be placed above where the radiant pipes traveled under the floor. Having metal grating would allow heat to travel unimpeded into the classroom without first heating up the concrete or the wood decking. After extended discussions with the Architecture team, we discovered one of the major pitfalls of this system was the fear of corrosion and cleaning. If saltwater were to be trapped under the metal grating, it could eat away at the radiant piping and fins thus presenting a major design flaw. In addition, the decking must be removed every three years to allow for cleaning of the Barge. Installing radiant piping under the decking would complicate this cleaning process and would likely require the piping to be removed for each cleaning which could also cause potential problems.

The third design consideration was heating the space using radiant ceiling panels. This possibility would alleviate more of the concerns about corrosion and address the heating responsiveness issue. AeroTech, the manufacturer for these radiant ceiling panels, provided information on the system including its capacity to run off of solar hot water heated water, such as ours provided by the evacuated tube system. This option seemed very promising until it came time for pricing. The Learning Barge™ has community support but is running on a meager budget. The price of radiant panels was going to run close to $3,000. This price was out of the working range of the project, so this design was eliminated.

The final design that was settled on by the team was to provide heating using the Myson Whispa II kickspace heaters (WHII 5000). These units are comprised of a hot water radiator and a fan to distribute the heat into the space. Three of these units will be installed in the false bottoms of cabinets, also known as the kickspace. The dimensions of the heating units are 4" x 14.25" x 16", so as not to be invasive in the classroom. These units provide 5000 BTU/hour per unit. Meaning we will be able to deliver 15,000 BTU/hour, the amount of heating needed according to the thermal analysis. This delivery capacity will provide the heat load coverage needed in the cold days of November and March, when the Barge will be having visitors. The heaters provide a resistance to corrosion by being placed out of the direct path of visitors and substantially improve upon the heating response time for the classroom.

Final Design

The final design solar hot water heating design for the Learning Barge™ includes an evacuated tube collector array (either 30 ft^2 or 60 ft^2, depending on glazing of glass walls), a 500 gallon storage tank, and three kickspace heaters. This design provides a robustness, in light of economic concerns, that gives the Barge the heating capacity that it needs. The design was developed through expansive conversation between both the Engineering and Architecture teams, which provided a more informed, and ultimately a more appropriate system.

Design I (Single Glazed Windows):

Material	$6,090	
Labor	$1,315	
Overhead	$530	
Profit	$585	
Total	$8,520	(Without donations)
Total	$2,290	(With full donation from Apricus and Altenergy Inc. for Labor, Overhead, and Profit)

Design II (Double Glazed Windows):

Material	$4,290	
Labor	$1,315	
Overhead	$530	
Profit	$585	
Total	$6,720	(Without Donations)
Total	$2,290	(With Full Donation from Apricus and Altenergy Inc. for Labor, Overhead, and Profit)

Table 8: Cost analysis of solar thermal system

Note, the cost does not include a cost estimate for the glass that would be used. This additional cost for double-glazing will likely be close to ~$10,000 .

Conclusions

The Learning Barge project provided students with an opportunity to engage in a real-world design/build activity, in collaboration with architects and engineers of other disciplines. The design required trade-offs on cost, performance, and appearance. The environmental education mission of the barge provided strong motivation for the team and we are all looking forward to its launch in summer 2008 and its contribution to spreading awareness of environmental processes.

Notes:

[1] National Renewable Energy Laboratory. “Solar Radiation Data Manuel”

< http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/sum2/13737.txt > April 22, 2007.

[2] National Oceanic & Atmospheric Administration. “Money Point, VA Meteorological Observation”

<http://tidesandcurrents.noaa.gov/data_menu.shtml?stn=8639348%20Money%20Point,%20VA&type=Meteorological%20Observations > March 3, 2007.

[3] Alternate Energy Store. “Southwest Air X Wind Turbine”

< http://store.altenergystore.com/mmsolar/others/Air_X_Marine_User_Manual.pdf > March 3, 2007.

[4] El-Barasi, Ayman I. "Learning Barge Resources." Collab. 28 Sept. 2007. University of Virginia. 16 Nov. 2007 https://collab.itc.virginia.edu/portal/site/784e720a-83c3-497e-0047-d52b4d4bc5d5/page/8c1aa6dd-9c70-4dc4-8084-8464a517875b