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Desalination and Water Purification Research and Development Program Report No. 145

Techno-Economic Feasibility Study of Wind-Power Desalination for a Community Scale Distributed Generation Application

U.S. Department of the Interior
Bureau of Reclamation

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14. ABSTRACT
This work involves an investigation of the possibility of using wind generated electricity for the desalination of sea water to provide potable water to a coastal community in New England. The work included the development of a computer based simulation model. The model includes wind turbine performance, reverse osmosis desalination, water storage, and economics. Consideration was given to operation of the system in a "distributed generation" mode, in which the capacity of the electrical network could be a limiting factor. The wind turbines in this study were assumed to be offshore wind turbines

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Prepared for Reclamation under Agreement No. 05FC811175

by

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Acronyms and Abbreviations

COE	cost of energy
ERD	energy recovery device
FCR	fixed charge rate
GE	General Electric
gpd	thousand gallons per day
HMLP	Hull Municipal Light Plant
kgal	one thousand gallons .
kg/m^3	kilograms per cubic meter
kPa	kilopascal
kV	kilovolts
kW	kilowatt
kWh	kilowatt hours
LMP	locational marginal price of electricity
LWD	light and water department
M	meter
m/s	meters per second
mgd	million gallons per day
MMWEC	Massachusetts Municipal Wholesale Electric Company
MW	megawatts
N/m^2	newtons per square meter
O&M	Operation and Maintenance
PTC	production tax credit
REC	renewable energy certificates
REG	Renewable energy generators
REPI	renewable energy production incentive
RO	reverse osmosis
TDS	total dissolved salts

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1. Abstract

This report summarizes the work undertaken under Desalination Research Task C, Agreement Number 05FC811175. The project developed *DGWindDesal*, an hour-by-hour, techno-economic computer simulation model of a community-operated electrical and water system. The model was developed to consider the specific requirements of Hull, Massachusetts, which already has two utility-scale wind turbines and is actively investigating the possibility of developing an offshore wind project. In this simulation, the water is assumed to be produced by sea water desalination and a significant fraction of the electrical energy requirement is provided by wind turbines. The model's desalination plant is assumed to use reverse osmosis (RO). Any electricity not provided by the wind turbines is purchased from an external utility. Any excess electricity produced by the wind turbines is sold to that utility or is used to desalinate water that may be stored temporarily. Inputs are provided in hourly files for wind speed, regular electrical load, water requirements, purchase rates, and sales rates.

2. Background/introduction

This project modeled producing desalinated water using renewable-energy-based electricity and a reverse osmosis system in a distributed generation application. The project:

(1) Developed a simulation model to assist in designing a desalination system run by (see comment) renewable energy distributed through the grid-connected (distribution level) desalination systems

(2) Applied the model to help the Town of Hull, Massachusetts, acquire such a system

The Town of Hull has a municipal electric company and was particularly well suited to undertake the project. The results of the study will also be generally applicable to other community-sized desalination systems.

It should also be noted that during the course of the study summarized in this report, one graduate student (who has since received an M.S. degree) was partially supported. Additionally, three papers were written describing some aspects of the study. These include Manwell et al. (2007), Manwell et al. (2008), and McGowan and Manwell (2008).

2.1. General overview of technology

2.1.1. Renewable-energy-powered desalination

Water desalination is common throughout the world where fresh water is in short supply and sea water or brackish water is available. This water can be converted to potable form through desalination. Desalination is most often accomplished through either a thermal or a membrane process. The ultimate energy source for the desalination is most commonly fossil fuels—used either directly as in thermal process or indirectly, as in the production of electricity—which is in turn used in reverse osmosis or vapor compression systems.

It is possible to power desalination systems from renewable energy sources. Again, these desalination systems can use either thermal or membrane processes. In this report, a renewable energy source is defined as one that is ultimately based on the sun (such as direct solar radiation), wind, falling water, biomass, or tidal currents. There is much interest in the use of sunlight or wind for powering desalination, since the applicable technologies have been rapidly evolving and are becoming commercially viable in many situations.

Total worldwide renewable energy powered desalination installations amount to less than 1% of that of fossil fuel desalination plants (Delyannis, 2003). Initial efforts to apply renewable energy to desalination involved solar-thermal distillation plants, but no similar plants have been constructed in recent years (Delyannis, 2003). Advances in membrane technology in the 20^{th} century have made RO progressively more attractive for desalination, regardless of the energy source. RO is appealing due to its low specific energy requirements, modular plant size, and electric-only power requirements. Presently 62% of the desalination capacity powered by renewable energy uses reverse osmosis based systems (Tzen and Morris, 2003). Furthermore, most renewable energy powered desalination research revolves around RO desalination powered by photovoltaic panels or wind turbines, with wind energy being favored for the larger installations. See, for example, GE Global Research (2005).

2.1.2. Considerations in using renewable energy for desalination

A number of factors can affect the design or operation of a desalination system using renewable energy. The most important of these factors are discussed below. These factors apply differently depending on the situation. Accordingly, renewable-energy-based desalination systems are grouped into four categories.

The primary factors that can affect the design or operation of a desalination system using renewable energy sources include:

1. Renewable energy sources, particularly wind and solar radiation, fluctuate significantly over many time scales. The fluctuations all include a random component.

2. Conversion technologies using renewable energy sources are in general non-dispatchable. That is, they operate when the resource is available (wind or sunlight), and do not operate otherwise. The maximum output at any given time is limited by the strength of the resources (e.g., wind speed or intensity of radiation). In general, the only control option is to forgo or curtail production.

3. Due the fluctuating nature of the resource and the non-dispatchability of wind turbines and solar photovoltaic panels, some form of storage is often considered when using those technologies. In the case of desalination, storage could, in principle, be either convertible electrical storage (e.g., batteries) or end-use storage (e.g., water).

4. In addition to storage, another approach to dealing with the fluctuating nature of the resource is to:

    a. "Hybridize" the energy supply by operating a renewable technology in conjunction with one more other types of generators: either conventional generators or other renewable generators.

    b. Apply load management by adjusting the timing or power level of the applied load. For desalination, this could mean operating certain RO modules according to the availability of the resource as well as the water demand at the given time. Load management is sometimes carried out in conjunction with storage.

5. Short-term resource fluctuations can sometimes affect the operation of the overall system. In that case, additional control equipment may be needed to ensure proper functioning. These can include power smoothing storage or "dump loads."

6. The economics of renewable-energy-based desalination systems can be significantly affected by the combinations of demands for energy and water. For example, if the renewable energy resource is used to displace purchased electricity at one point in time, its value may be greater than if the generated electricity must be sold due to a mismatch in demand. Furthermore, in some cases, the option may exist to either purchase water or produce it a particular time. The marginal production vs. purchase cost will affect the decision of how to operate a plant. Finally, sometimes various incentives are available to foster developing renewable energy sources. These may include Renewable Energy Credits or Production Tax Credits. These may affect the sizing and operation of renewable-energy-based desalination plants.

7. When a renewable energy source and a desalination plant are connected to a utility grid, they may both be connected at the distribution voltages, resulting in "distributed generation" application. In such cases, network specifics may affect how large the renewable energy generators can be or how they can be operated.

2.1.3. Types of renewable energy based desalination systems

Renewable energy based desalination systems can be separated into four categories. The categories are based on the likely impact of the factors discussed above. The systems are:

1. Renewable energy generators (REG) and desalination plant connected to a large utility network, with the REGs connected at transmission level voltages.

2. REGs and desalination plant connected to the distribution system of a large utility network.

3. REGs and desalination plant in an isolated electrical network, such as an island grid.

4. REGs and desalination plant directly connected, with no additional grid.

Systems in the first category are physically essentially the same as conventional, grid-connected desalination systems. These renewable generators at transmission-level voltage would generally be located some distance from the desalination plant. If the desalination plant were located close to the generators, then they could have some characteristics of Category 2 (see below). Otherwise, there would be few, if any, issues of substance distinguishing these systems from conventional desalination systems.

Systems in the second category have renewable energy generators and desalination plant connected to the distribution system and a distribution voltage (typically 13 kilovolts [kV] or less). The case study (Town of Hull) fits into this category. In principle at least, a community in this category could at times: (1) purchase or sell electricity, (2) produce water by desalination, (3) purchase or sell water, (4) distribute water immediately,

(5) store or release water. At any given time, decisions would need to be made regarding which of these should be done. In Category 2 systems, technical issues associated with the amount of generation that could be connected could, in effect, impose an upper limit on the amount of generation that could be installed or on the amount of power that could be exported from the system during times of high generation and low loads. Limitations could be regulatory as well as technical. Economic factors could also be significant in Category 2 systems.

Systems in the third category include those on islands or isolated communities. There could be significant technical issues in such systems, affecting both electrical stability of the network and satisfactory operation of the desalination system. Maintaining the electrical stability may be ensured by use of equipment common to wind/diesel or other renewable energy based hybrid power systems (Manwell et al., 2002). These could include a supervisory control system, dump loads, power-limiting of the generators (e.g., pitch control on wind turbines), and electrical energy storage. Load control, particularly of the desalination plant, is also an option. This would presumably be done in RO systems with multiple modules, so that one or more modules would be turned on or off as called for by the situation. It should be noted, however, that cycling would be done relatively slowly so as not to adversely affect the module membranes. It is also expected that with the exception of varying the number of operating modules, an RO unit would be run as it normally is. That is, the pressures would remain essentially constant, as would the flow rates within each module. The effect of short-term fluctuations of the renewable energy generator would in general be compensated by a conventional generator (typically diesel in these situations) or through some type of power smoothing storage. A number of analytical investigations or demonstration projects have involved wind-driven RO systems for autonomous or non-grid connected situations. The economics of such systems can be strongly affected by the combination of the water requirement and the availability of energy. A recent example of a study of such a system is one undertaken at UMass for Star Island in New Hampshire (Henderson et al., 2004).

The fourth category of system is the free-standing, direct coupled renewable generator-desalination system. These are typically smaller systems, and in some ways are the most problematic as the possible impacts from short-term fluctuations in the wind on the desalination system must be dealt with directly. These are technically interesting systems, but sufficiently different from the type of systems of most relevance for the present project that they have not been considered further. Discussion of various aspects of such systems may found, however, in articles or reports by Miranda and Infield (2002), Thompson and Infield (2002), Fabre (2003), Carta, et al. (2003, 2004). Adapting RO to work with wind turbines was also investigated by the University of Massachusetts researchers in the 1980s (Warfel et al., 1988).

2.2. Desalination opportunities at Hull, Massachusetts

Hull, Massachusetts, is a town located at the end of an isthmus jutting out into Boston Harbor. The local supply of water is limited. Hence, town residents obtain their water by purchasing it from a supplier on the mainland. It is delivered to the town by pipeline. The cost of water is now approximately $8.67 per one thousand gallons (kgal). Because of the already high cost of water six years ago (when it was $7/kgal), the Town of Hull commissioned a study of the options for producing their own water via desalinating seawater (see Woodward and Curran, 2002a, 2002b). According to this study, the average water demand of the town is 1 million gallons per day (mgd), and the peak water consumption is 2.5 mgd. That study also concluded that (1) Hull could produce water via desalination for a significantly lower price than was then being paid and (2) there are at least three sites where a desalination plant could be sited.

The water studies referred to above assumed that the water would be produced by electrically driven RO, consuming 19 kilowatt hours (kWh) per kgal. The peak load of the desalination plant would be approximately 2 megawatts (MW), and the average would be 0.8 MW. The all-in cost of electricity, in accordance with then current rates, was $0.08/kWh. The operating cost due to electricity would have amounted to approximately $1.52/kgal.

With the assistance of the University of Massachusetts, the Town of Hull has already installed a 660 kW wind turbine (Manwell et al., 2003) and a 1.8 MW turbine (Manwell, et al., 2006). The two of these turbines together supply approximately 12% of Hull's electricity. The Town is now in the midst of a feasibility analysis and permitting processes that could result in the installation of up to four offshore wind turbines (about 3.6 MW each) (Manwell et al., 2007). The total wind generation could then be close to 17 MW, which actually exceeds the average electrical load of the town at the present time. One major factor that will be considered in the decisions regarding the offshore wind project will be the effect on the electric load of the town by the possible addition of a desalination plant.

Hull is not the only community interested in acquiring a desalination plant and operating it in conjunction with wind turbines. A number of other communities in the United States and around the world are interested in something similar. In many of these locations, a number of factors could affect the design of the project. Most of these would be relevant in Hull, making it an attractive site on which to base a more general study, such as been undertaken here. These factors include:

1) Variation in wind resource over the year
2) Variation in water demand over the year
3) Time of day pricing of electricity
4) Use of water storage
5) Possible sale of water
6) Curtailment of water production during times of low demand
7) Restriction of capacity of transmission/distribution system within or into the community

As described in the next section, the primary activity undertaken in this project consisted of a developing a techno-economic analytical modeling study for a utility-scale wind driven RO desalination plant. The initial case study for this model was the Town of Hull.

The resulting analytical model, however, is now general enough to address many of the above factors for other locations as well.

2.3. Techno-economic modeling of hybrid energy systems

The type of desalination plant that the Town of Hull is considering is a form of hybrid energy system. Isolated hybrid energy systems have been investigated over the last two decades. The University of Massachusetts, under contract to the National Renewable Energy Laboratory has developed the most comprehensive engineering and economic simulation tool for such systems that yet exists, *Hybrid2* (see Manwell et al., 1997) or http://www.umass.edu/windenergy/research/topics/tools/software/hybrid2). More recently, there has been interest in grid-connected hybrid energy systems, in which the generators are connected at distribution level voltages, and in which the electrical line serving the load is of limited capacity—such as the proposed Town of Hull project. *Hybrid2* has already been used to model certain types of grid-connected hybrid systems (see Rogers et al., 1999), and the option of further modifying it to allow the modeling of other types of such systems is presently under investigation. Adding the capability to model hybrid systems with desalination plants could be a logical next step.

2.4. Uniqueness of work undertaken

Until now, no software tools have been available that would serve the function of the simulation model that is has been developed here. The closest similar analytical model is one that has been developed in Europe specifically for desalination systems driven by nuclear or fossil power plants (International Atomic Energy Agency, 2001).

Nothing quite like the Town of Hull's proposed wind/desalination system has been built anywhere in the world. While wind turbines supply part of the electricity requirement for a desalination plant on some islands in the Mediterranean, no projects have been of the scale envisaged here. In addition, there are no examples of offshore wind turbines being operated in conjunction with a desalination plant.

It should also be noted that the close cooperation of the local utility (Hull Municipal Light Plant [HMLP]) in the project allows the development, testing, and evaluation of an unusually large distributed generation capacity on a relatively low voltage feeder. This close cooperation should allow any issues to be identified quickly and addressed immediately. Successful resolution of any issues that might arise should be helpful in developing similar projects elsewhere in the future.

2.5. Goals/objectives of the work undertaken

The first goal of the proposed project was to develop the means to simulate and evaluate hybrid energy systems that include renewable energy generators connected at distribution level voltage, a desalination plant, and a limited capacity power line. A second goal was to use the model in a case study that would both demonstrate the model and assist a community in selecting and operating such a system. The goal of the renewable energy component was to ensure stable and reasonable electricity costs for the desalination plant over the course of its lifetime. Although no operational problems are expected, an eventual goal (beyond the scope of the current project) will be to monitor the operation of the wind turbines, the electricity use of the desalination plant, and the power flows into and out of the Town of Hull to (1) verify that there are no issues (assuming that to be the case) or (2) identify any issues that may arise and consider means to address them. It may be the case that in the course of the complete project, it may prove reasonable to install only a single offshore turbine initially, monitor the project, and then add more turbines if so desired.

2.6. Problem to be solved/improved aspects of current technology

This project was intended to help assess the economic benefits of a wind/desalination plant and select the optimum size of the various components. The fundamental question is to identify any operational issues that may be encountered regarding connecting a relatively large wind generation capacity to a relatively low voltage line and to determine if the presence of a desalination plant can have any impact on that operation. In theory, a desalination plant with multiple switchable RO modules and some amount of water storage could be incorporated into a load management control strategy which would be both electrically and economically advantageous. Furthermore, one of the RO modules could be supplied by a variable speed pump to allow the output of the plant to be varied almost continuously.

2.7. Applicability of the project

This simulation tool could be used elsewhere in similar situations. If the tool were to be expanded (e.g., for isolated networks and direct coupled applications), then the tool would have even greater applicability. Thus, this tool could also have a wider applicability to numerous U.S. as well as international locations.

2.8. Economics of the technology

Evaluationg the economics of a wind/desalination project requires considering a number of factors, many of which have been alluded to earlier. This simulation model will be useful in making realistic assessments. Previous estimates included estimates for the cost of water in 2002 at $7/kgal. According to the Woodward and Curran study (2002), using a conventional desalination plant (with the cost of capital amortized at realistic rates and electricity purchased at $0.08/kWh) would result in total water cost $4.20/kgal, which would already have been a significant cost reduction. The electricity cost would be about a third of the total cost. Adding wind energy could actually reduce the cost even further, as long as the unit cost of energy from the wind turbines is less than the cost to purchase that electricity.

3. Technical approach

3.1. Simulation model

We developed a simulation model of grid connected wind turbine desalination system *DGWindDesal* under this contract. The model applies to:

A portion of a larger electrical network with an identifiable electrical load

- Wind turbines connected at distribution level voltages
- A grid connected reverse osmosis based desalination plant
- Water storage

The model includes the capability to use hourly time series data for:

- Wind speed
- Electrical load
- Water usage
- Electricity purchases or sales

The overall model includes sub-models for:

- Wind turbine power generation
- Reverse osmosis system specific energy consumption
- Water storage and release
- Economic evaluation
- Dispatch control system

Structurally, the model has been written as free-standing computer code in Visual Basic 5.0, using modules from *Hybrid2* (Manwell et al., 1997) and the Wind Engineering Minicodes (Manwell et al., 2000) where possible. Other sub-models were written *de novo* for this project. It should be noted that the simulation model, *DGWindDesal*, is presently only available in an in-house form and is not publicly available.

3.2. Structure of *DGWindDesal*

The following sections provide a description of the key features of *DGWindDesal*, including the components models, economics, dispatch, validation, and outputs.

3.2.1. Sub-models of DGWindDesal

This section describes the methods employed in each of the component sub-models.

Wind turbines

In *DGWindDesal,* the user specifies a power curve and the wind speed time series data to calculate the wind power produced by a wind turbine using the wind turbine sub-model.

The power extracted by the wind turbine is a function of the wind speed, the density of the air and the characteristics of the turbine itself. In general the power (W) is given by the following equation:

$$P = \eta C_p \frac{1}{2} \rho \pi R^2 U^3 \tag{1}$$

Where:

η = combined efficiency of electrical and mechanical components
C_p = rotor power coefficient
ρ = density of the atmosphere, in kilograms per cubic meter (kg/m^3)
R= radius of the rotor in meters (m)
U = wind speed in meters per second (m/s)

Equation 1 can be cumbersome to use, so a "power curve" is typically employed to define the performance of a wind turbine. The power curve is the relationship between the average hub-height wind speed and the average generator power, both in the most convenient units, during the averaging time interval, assuming certain standard atmospheric conditions. Also, a wind turbine will have a cut-in wind speed (at which the turbine starts to generate any power), a rated wind speed (at which it starts to generate full rated power), and a high-wind cut-out wind speed (at which it is shut down for safety). Figure 1 illustrates a typical power curve of a pitch regulated, constant speed wind turbine. Other types of wind turbines will have power curves that look different but are still similar in nature.

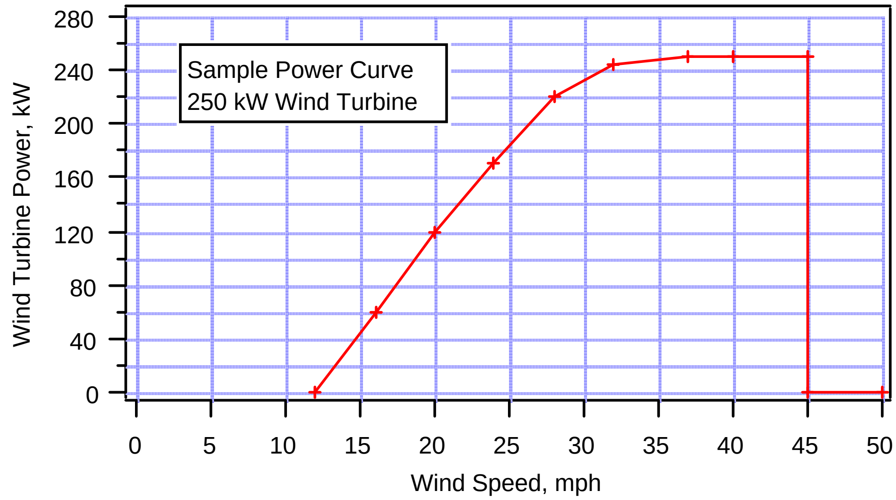

Figure 1.—Sample wind turbine power curve

Input

The primary input to the wind turbine sub-model is a power curve for a single wind turbine. It may either be from a data file or typed in on the screen. The units of the wind turbine power curve should be in m/s and kW. There is one data point pair (wind speed, power) per line.

Multiple wind turbines are considered using a scale factor, which is simply a multiplier.

The input to the simulation itself is hourly average wind speed time series data. This time series data is input from a data file which may be selected by the user. There is one data point per line. The units of the wind speed are in m/s. Power from the turbine at a given wind speed is determined by interpolation.

Output

The output from the wind turbine component model during the simulation is the average power from the wind turbine in kW.

Electrical load

Electrical load (not considering the desalination plant electrical requirement) is input as an hourly text file. There is one data point per line. The electrical load is in units of hourly average kW. The electrical load may be adjusted up or down by a scale factor.

Electrical power system limit

The electrical load in kW for the system is assumed to be normally supplied by single power line. That line may have a capacity limit associated with it. That limit would set an upper bound on how much power could enter the system to supply loads or could leave the system, in the case there is net positive generation in the system for some period of time. *DGWindDesal* allows the user to specify this limit.

Water requirement
Water requirements are input as an hourly text file in units of gallons of water per hour. A scale factor may be applied to adjust the water requirement. A scale factor of 1.0 means that there is no scaling. Such a scale factor can be useful in conducting tests of the code or "what-if" studies.

Water storage
Water storage is modeled by a simple storage tank. Water can be pumped into storage, according to either (1) the amount of water available to store or (2) the remaining capacity of the tank. Water can be taken from the storage according to either (1) the amount of water required or (2) the amount of water remaining in the tank. The water storage tank is measured in kgal. The initial amount of water stored can be adjusted according to an initial fraction. That fraction can be set to any value between 0 and 1.0. There is at present no limit on water pumping capacity and there are no pumping losses assumed.

Reverse osmosis desalination

Desalination process description
Reverse osmosis is a filtration process in which a semi-permeable membrane is used to allow water to pass through while rejecting salts. Osmosis is a naturally occurring phenomenon that can be explained by statistical thermodynamics. If a partially permeable membrane separates a volume of pure water and a salt solution, the result is a gradual flow of freshwater to the salt solution. When mechanical pressure is applied to the salt solution, water can be forced the other way through the membrane. The result is that pure water (the "permeate") can be collected on the other side. This is the reverse of the normal osmosis process, hence the origin of the name "reverse osmosis."

A schematic of a typical desalination plant is shown in Figure 2. The plant includes a number of pumps, filters, pressure exchangers and a bank of reverse osmosis modules. Each module contains a wound semi-permeable membrane. Pure water passes through the membrane. The remainder continues to the brine discharge.

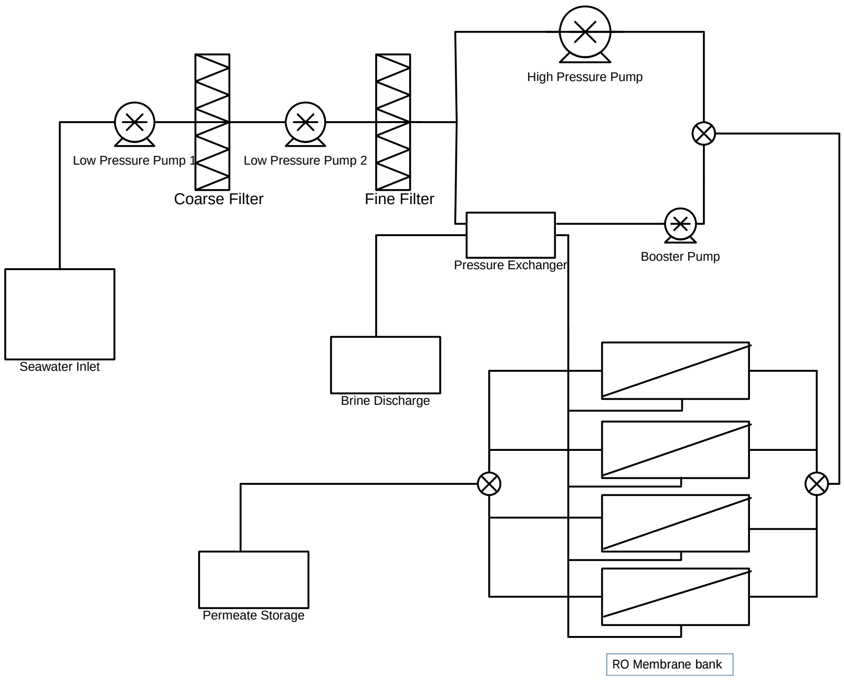

Figure 2.—Seawater desalination

Typical large-scale RO facilities require feedwater pressures in the range of 50-70 Bar to achieve a reasonable flow of product water (Thompson, 2003). It should be noted that the model assumes that the RO plant is continuously adjustable from its rated output down to zero. It is recognized that this is an idealization. The present version of *DGWindDesal* implicitly assumes that such ideal behavior could be approximated to some degree by using multiple modules. The system implicitly modeled by *DGWindDesal* would actually include valves in front of each module and a variable speed high pressure pump (Figure 2). The total volume flow would be decreased when appropriate by shutting one more of the valves, and thus temporarily shutting down flow through the corresponding modules. The speed of the high pressure pump would be adjusted downwards so as to maintain the pressure at the lowered flow rate, while minimizing power consumption. A future version of *DGWindDesal* could consider operation of individual modules in greater detail.

Most current seawater RO system designs are single stage with anywhere from five to eight membrane elements per pressure vessel (Wilf and Bartels, 2004). This model reflects a single-stage, RO system with up to eight membrane elements per pressure vessel. There is an obvious cost advantage in the increased number of elements per vessel. For a typical configuration, a RO system with six elements per pressure vessel requires 33% more vessels than one with eight elements per vessel. The actual number of membrane elements that can be “stacked” in a pressure vessel is a unique characteristic of each membrane. It should be noted that fluid velocity needs to be considered in a real system when eight elements are used in the pressure vessel. That level of detail is not included in *DGWindDesal* at the present time, however.

A single-stage design not only simplifies the RO system model but also helps reduce the overall power consumption by allowing the feed water pressure to be lower than a two-stage system design allows. In older, two-stage RO systems, higher feed pressures were required to reduce concentration polarization (membrane fouling) in the second membrane stage. It is important to note that the single-stage design is not resistant to membrane fouling, but more reasonable feed pressures and flow rates are achievable in such a configuration.

To further reduce the energy requirements of the proposed system, an energy recovery device (ERD) has been implicitly incorporated. Older RO systems included a Pelton turbine ERD that was linked by a shaft to an electrical motor that in turn helped deliver power to a high pressure pump. This method of energy recovery is subject to a variety of losses. The RO model described above includes an improved ER: a pressure exchanger that allows the high pressure brine discharge to be directly used to pressurize the inlet feedwater. This form of energy recovery requires very few moving parts and achieves an overall efficiency of 93% (Andrews et. al., 2006). Using a pressure exchanger in the desalination system results in a substantial gain in energy efficiency.

RO membranes are particularly susceptible to failure and excessive fouling when the inlet water is not properly filtered. Therefore, to remove any substance that could otherwise damage the membrane elements, a pretreatment system consisting of two cartridge type filters is incorporated into the design of the model. The pretreatment system includes two low pressure pumps that pump water through the filters. The system is designed with an open water inlet that draws seawater directly from the ocean for desalination. However, cartridge filters are not effective in removing pollutants such as oil.

Principles of desalination

The pressure required to force a solution through a semi-permeable membrane is called the osmotic pressure. For low concentration solutions, the osmotic pressure, P_π , (bar) can be calculated by van't Hoff's equation (Equation 2):

$$P_\pi = iMCRT \qquad (2)$$

Where:

i = van't Hoff factor (here, approximately 1.8)
M is the molecular weight of salt (58.5 g/mol)
is the concentration (g/liter)
R is the universal gas constant (0.0831447 liter bar/mol K)
T is the absolute temperature (K)

However, equation 2 is less accurate for solutions at higher levels of salt concentrations (Reid, 1966). Seawater contains approximately 35 grams per liter of total dissolved salts (TDS). Such high concentrations cannot be accurately characterized by the van't Hoff equation. Equation 3 gives better results for these higher concentrations. For example, it can be shown by this equation that the osmotic pressure of seawater at standard conditions is approximately 26 bar (2,600 kilopascal [kPa]). This means that the feed water pressure must at least 26 bar before any water can permeate the membrane as shown in Equation 3.

$$P_\pi = \frac{.002654 * C * T_{[K]}}{1000 - C} \qquad (3)$$

The power required to desalinate water is primarily a function of the pressure required to force water through the membrane and the desired flow rate of the permeate. About 7% of the water entering the system passes through the membrane as permeate. The remainder continues through the system and leaves as concentrated brine. Power is required to pump the brine as well as the permeate, thus the pressure across the membrane must be higher than the osmotic pressure to ensure a reasonable flow rate. Typically this is on the order of twice the osmotic pressure. The result is a greater total power expended per unit of permeate than might be expected based on just the permeate flow rate and the osmotic pressure. The total specific energy consumption, $\tilde{E}_{desal,tot}$, in kWh/m^3 can be determined from the following equation:

$$\tilde{E}_{desal,tot} = \frac{(\Delta P_{L_1} + \Delta P_{L_2} + \Delta P_H) + \Delta P_{RO}\ f_p + \Delta P_B (1 - f_p)}{(f_p)(3600000)} \tag{4}$$

Where:

$\Delta P_{L_1}, \Delta P_{L_2}, \Delta P_H$ = pressure rise in first and second low pressure feed pumps and high pressure feed pump
ΔP_{RO} = pressure drop across membrane (approximately twice the osmotic pressure)
ΔP_B = pressure rise across brine pump
f_P = permeate fraction
The 3,600,000 converts newtons per square meter (N/m^2) to kilowatt hours per cubic meter (kWh/m^3).

The net effect is that a typical RO facility nowadays may consume approximately 3.65 kWh/m^3 (14.1 kWh/kgal) of pure water produced, depending on the salinity of the water. This is approximately five times as much energy as would be expected, if only the osmotic pressure is considered. That is to say, the real process operates at a thermodynamic efficiency of approximately 20%. See, for example, Kondili and Kaldellis (2008). For many situations, an even higher specific energy consumption (i.e., lower thermodynamic efficiency) is sometimes assumed. This is intended to take into account additional losses or inefficiencies in the system.

Desalination component model in *DGWindDesal*

For the purposes of *DGWindDesal*, the user can either use (1) predetermined value of energy required per kgal of water, or (2) a linked routine to calculate that input. A default value of 19 kWh/kgal of water has been provided. The linked subroutine includes the equations summarized above.

Figure 3 shows a screenshot of the linked routine. (Note that the output of this routine is directed to the main screen of *DGWindDesal*. The values in this particular illustration correspond to 13.8 kWh/kgal.).

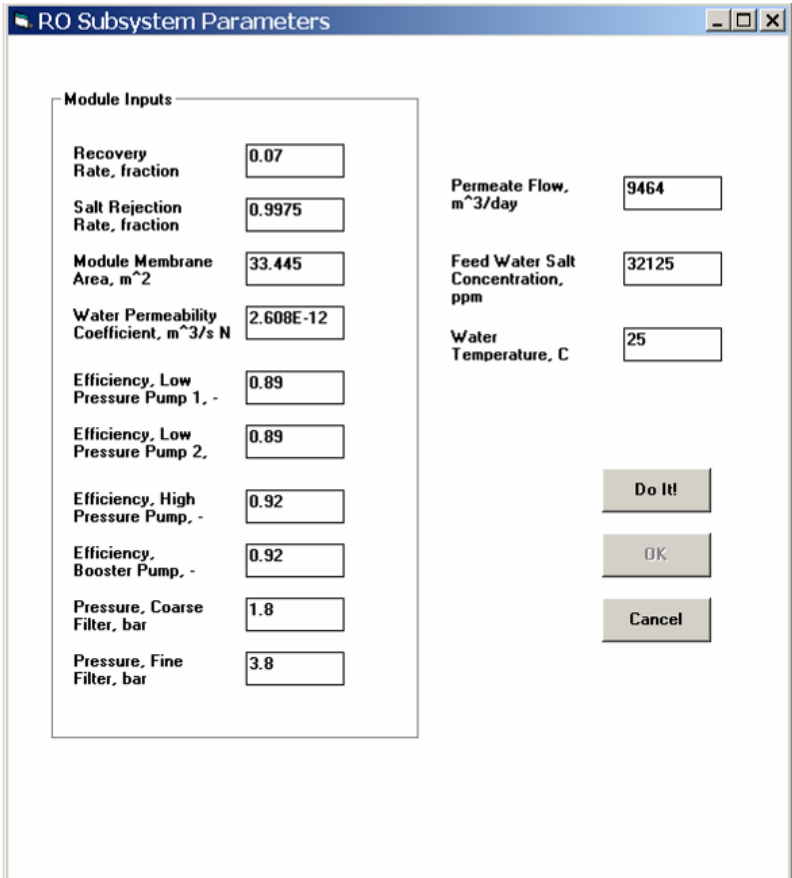

Figure 3.—Sample screen for water desalination energy requirement

3.2.2. Program flow and dispatch

Dispatch refers to how the wind turbines are controlled, how the storage is operated, and the load the power from the turbines is directed to. The main variables that can be controlled within the present configuration of *DGWindDesal* pertain to storage and whether any power in excess of the regular load is used to produce water for immediate use, is used to make pure water for storage, or is sold immediately.

As developed, *DGWindDesal* is intended to model the situation of a municipal utility which normally purchases power from an external utility. The model also presently assumes that the municipal utility operates the water department, so for the purposes of the model it could be considered a “light and water department” (LWD).

In general, the overall program flow proceeds within *DGWindDesal* according with the flowchart shown in Figure 4. After the input data is read in, the first step in each time interval is to calculate the expected output from the wind turbines. This is done in accordance with the wind speed and the wind turbine power curve described previously. The next step is to subtract the available wind turbine power from the electrical load. This results in a net load. There are then two main options:

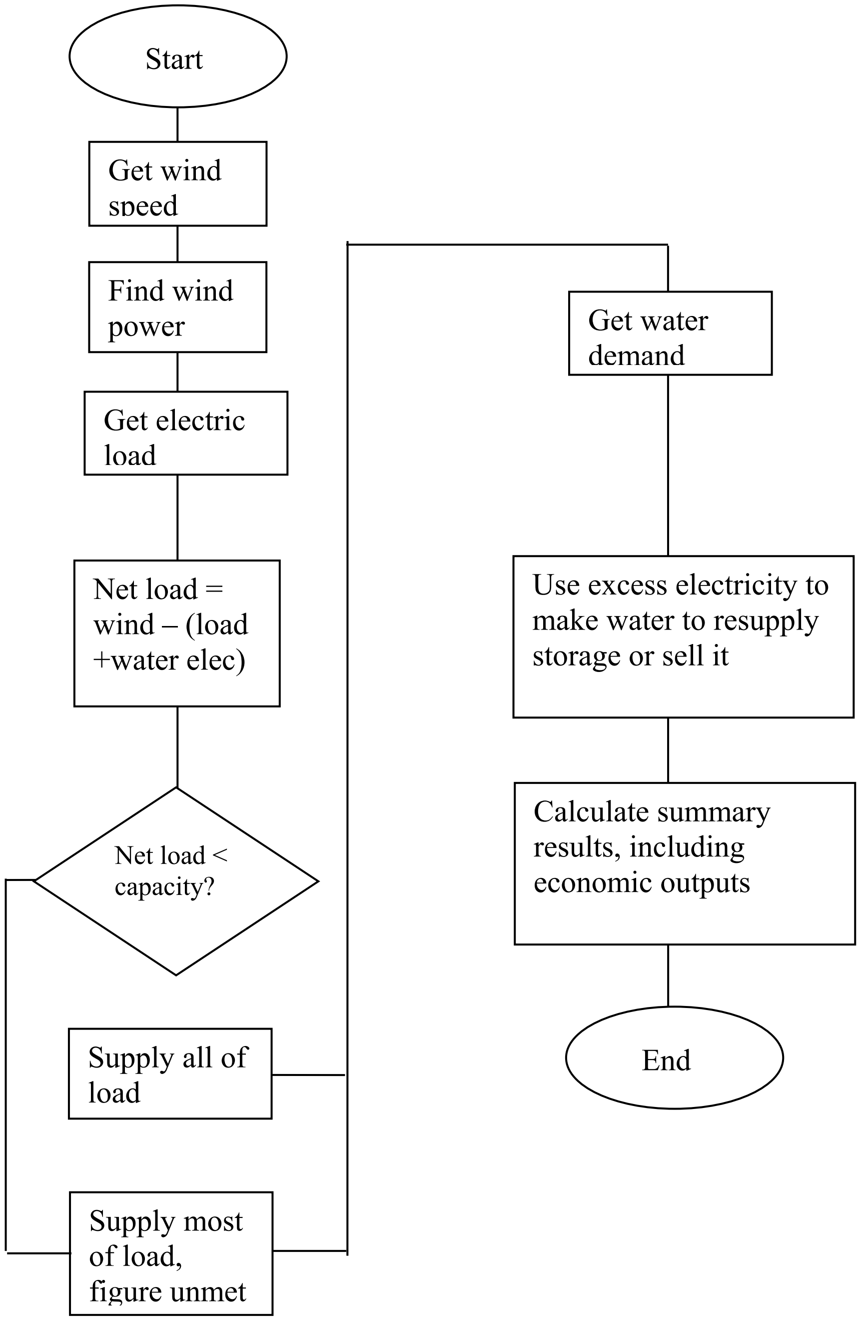

Figure 4.—Overall flow chart of *DGWindDesal*

- If the net load is **greater** than zero, then power is still available to be supplied to the town. Assuming that the capacity of the power lines is large enough, electricity is supplied from the external grid. If the lines are not of sufficient capacity, then a deficit is noted.

- If the net load is **less** than zero, then there is excess wind power that can be used for producing pure water or sold to the external utility. The pure water that is produced can either be used directly (or sold) or it can be stored. Water demand is also considered in each time step, regardless of excess power availability. The water load indicated in the input file must be supplied from storage or water can be purified immediately by using the desalination plant.

What energy is used and water produced within any given time interval depends on the situation, as outlined in the next figure, Figure 5. As shown here, decisions are made according to a "transition price," and the cost to purchase power or the value of power sales, depending on the circumstance. The transition price can be thought of as a nominal cost to make water for storage. So when water is needed when the purchase price is low, then power is bought to make water. If the transition price is high, then it is more economical to take water from storage. After the water load is satisfied, then the question comes as to what to do with the excess power (if any). If the value of power to sell is high, then the excess electricity is sold; if it is low, then the excess is used to treat water to re-supply the storage. Excess power over these demands is sold.

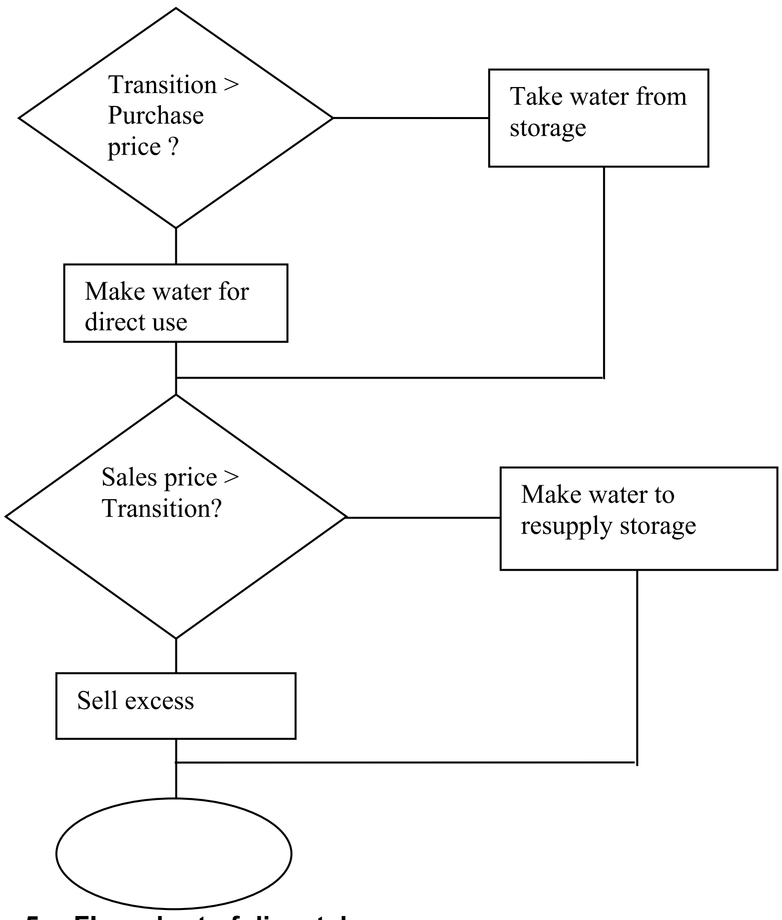

Figure 5.—Flow chart of dispatch

3.2.3. Economics

DGWindDesal includes a fixed charge rate (FCR) economic model. The cost models and economic assessment models are described below.

Cost model

The cost model considers the basic costs of the desalination plant and the wind turbines in terms of fixed costs and variable costs. The fixed costs are independent of the size of the system, while the variable costs vary linearly with the size of the various subsystems. The wind turbine subsystem is characterized by a fixed cost ($), and a variable cost which is based on the rated output of the wind turbines ($/kW). The desalination plant similarly has a fixed cost ($) and a variable cost. The variable cost is based on the rated output of the desalination plant ($/kgal per day). The water storage is assumed to have no fixed cost, but a variable cost which is a function of the capacity ($/kgal).

The provision for operation and maintenance (O&M) is separate from the electricity cost to produce the water. Operation and maintenance for the wind turbines is expressed in terms of cost per kWh of electricity produced ($/kWh). Similarly, the O&M cost of the desalination plant is expressed in terms of cost per unit of water produced ($/kgal).

Fixed charge rate model

The fixed charge rate model is a simplified version of a life cycle costing model, such as described in *Wind Energy Explained* (Manwell et al., 2002). It works by combining all regularly occurring financial costs and their effects into a single parameter, which eventually results in an annual cost. An O&M cost is accounted for separately. Equation 5 shows the calculations for the cost of energy (COE, $/kWh) from a wind turbine.

$$COE = \frac{(C_c)(FCR) + O\,\&\,M}{AEP} \qquad (5)$$

Where:

C_c = capital costs, $

O&M = annual total operation and maintenance costs, $/year

AEP = annual energy production, kWh/year

FCR = fixed charge rate, year^{-1}

The interest rate on the loan is the primary determinant in the FCR method. If the entire capital cost of the project is paid for by a loan, then the FCR times the capital costs would give the annual payment which would be required to pay back the loan with interest. In this case, the FCR would be given by equation 6:

$$FCR = \frac{1-a}{a-a^{N+1}}\,; FCR = 1/N \; if \; a = 1 \qquad (6)$$

Where:

a = 1/(1+i)

i = loan interest

N = period of loan.

Using this model, Table 1 illustrates FCR for a number of interest rates for a 20-year loan period.

Table 1.—Fixed Charge Rate vs. Interest Rate

Interest Rate	FCR
0	0.05000
0.01	0.05542
0.02	0.06116
0.05	0.08024
0.10	0.1175

Value of electricity

Electricity is considered either as a cost or as a potential source of revenue (i.e., a value). The cost or value of electricity as used by *DGWindDesal* is entered as hourly time series. The purchase rate (corresponding to what the municipal utility would pay for purchases from the external utility) would be in one file. The sales rates (corresponding to what the municipal utility would be paid for sales to the external utility) would be in a second file. The units of these input files are in $/kWh.

In addition to the rates discussed above, the program also includes renewable energy incentives. These could be due to the production tax credit (PTC), and renewable energy production incentive ([REPI], which could apply to municipal electric companies), or renewable energy certificates (REC).

3.2.4. Summary outputs

DGWindDesal provides a number of summary outputs, including:

- Average total wind power, kW
- Average wind power sold, kW
- Average purchase power, kW
- Average unmet load, kW
- Cost of wind energy, $/kWh
- Average water load supplied directly, gpd
- Average water from storage, kgal per day
- Average unmet water load, kgal per day

The next group of outputs deals with cost of electricity and water. For comparison purposes, base case results (a desalination plant but no wind turbines) are provided first:

- Base case (load and water) average electricity cost, $/kWh
- Base case water costs, $/kgal

For the case where wind turbines are included, the output similarly includes:

- Average electricity cost, including wind, $/kWh
- Water cost using wind, but no storage
- Water cost using wind, including storage
- Savings due to wind (compared to base case with desalination only), $/kgal
- Savings due to wind and storage (compared to base case with desalination only), $/kgal

Equation 7 provides the calculation method and the expression for base case water costs.

waterCostsBase = (ROCosts * FixedChargeRate + RO_OM_base + loadOnlyRevenue - waterLoadRevenue) / (avWaterDirect * 365) (7)

Equation 8 provides the expression for water costs with storage.

WaterCostsWithStorage = ((ROCosts + StorageCosts) * FixedChargeRate + RO_OM_wind_WithStorage + (windRevenue - Revenue)) / ((avWaterFromStorage + avWaterDirectWithStorage) * 365) (8)

The variable names, which are taken directly from the code, are largely self explanatory.

3.2.5. Validation

For any computer program, it is necessary to perform some checks to verify that the program gives reasonable results. That was done for *DGWindDesal* as well. Much of the basic routines of *DGWindDesal* were derived from the Wind Engineering Mini-Codes and were also traceable to *Hybrid2*. Both of these codes have been thoroughly tested, so when *DGWindDesal* gives similar results in intermediate calculations, they can be assumed to be reasonable. In addition, an Excel program, *Desal tester 2.xls*, was also written to test calculations for the non-storage wind/desalination plant. A number of tests were created to test various parts of the program. Sixteen of the tests are summarized in Appendix A. As can be seen from these tests, all indications are that code performs as expected. The slight difference in the average wind energy prediction between *DGWindDesal* and *Desal Tester 2.xls*, is due to different algorithms used by another program that provides turbine power input to *Desal Tester 2.xls*, *Wind power estimater.xls.* The difference is less than 1%, and it is not deemed significant.

4. Case study: the Town of Hull, Massachusetts

4.1. Recent desalination activities in the Town of Hull

Additional work has been going on recently in the Town of Hull as a follow-on the previous activities described earlier. The work carried out for the Town of Hull by Wright-Pierce (Wright-Pierce, 2007) was most useful in developing the economic cost model and for its input to the economic variables used for representative runs of the economic model. The Wright-Pierce report, funded by the Town of Hull, Massachusetts, was designed to produce a feasibility study for the construction of a desalination facility in the town. This study was also designed to advance the work of two earlier feasibility studies on the same subject. The Wright-Pierce study focused on two different size plants: 2.5 mgd and 4 mgd.

A desalination facility treating seawater in the Town of Hull would be the first plant of this type developed in the Commonwealth of Massachusetts. Wright-Pierce noted that such a seawater desalination project would have new technical and environmental challenges unfamiliar to the regulatory community. Also, this work was designed to provide a detailed assessment of the permitting and design requirements for the project in order to reduce the uncertainty associated with its construction. Thus, the overall objectives of the study were to answer:

1) How would the Town of Hull develop a desalination project?

2) Can the town develop a desalination project and produce high quality drinking water at a good value for the residents?

3) What are the organizational issues associated with owning and operating a desalination facility?

4) What series of steps would be followed to develop a desalination project from inception to an operating facility?

5) Are there any clear legal, technical, or economic impediments that would prevent the Town of Hull from developing a desalination project?

To meet these objectives, the work summarized in this report concentrated on four key focus areas: (1) Project Economics, (2) Business and Organizational Issues, (3) Technical Requirements and Issues, and (4) Environmental and Permitting Issues.

Wright-Pierce (2007) concluded that the desalination of seawater is technically and economically viable for the Town of Hull. That is, the cost to develop a conventional desalination facility is within a reasonable range of cost when compared to current water costs in surrounding communities. In addition, desalinated water could provide future price stability in the Town of Hull, and the desalinated water will become even more competitive in the future as water supply options become increasingly scarce.

Using many of the results of the technical and economic parts of this study, our work was better able to model and obtain accurate cost estimates for the desalination systems components that would be required for a wind-driven desalination system. For example, a summary of the Wright-Pierce calculations for the various sites in the Town of Hull yielded the following economic model cost inputs:

1. For a 2.5 mgd plant (at the best site) costs would be:

Fixed costs = $10,000,000
RO variable cost = $1,200/1,000 gpd
Water storage cost = $1,667/ kgal
O&M costs (values good for 2.5 - 5 mgd plants):
Annual O&M = $200,000 + $160,000 x (plant size in mgd)

For the 2.5 mgd plant, annual O&M would be $600,000, corresponding to $1.64/kgal if operated at 40% load factor

2. For a 4 mgd plant, according to Wright-Pierce (2007), the fixed costs would be only slightly higher than those of the smaller plant, and there would be no change in most variable unit costs. The unit O&M cost would decrease. In summary:

Same RO variable and water storage costs
Fixed costs = $11,300,000
O&M costs would be $840,000, corresponding to $1.44/kgal if operated at 40% load factor

4.2. Recent wind energy activities in Hull

Since the work summarized in this report was initiated, significant wind energy related activities have continued in the Town of Hull. In the spring of 2006, Hull acquired a second wind turbine. This one is rated at 1.8 MW and has a rotor 80 meters in diameter. With this turbine, the installed wind energy capacity has almost quadrupled since the first large turbine was installed in 2001. That first turbine is rated at 0.66 MW. The process leading to and including the installation of the second turbine is described in more detail in Manwell et al., 2006.

With the second wind turbine completed, attention then turned to offshore wind energy. A full-scale feasibility study and permitting activities were initiated. Work already completed or well underway includes:

- Identifying the most suitable sites for the offshore wind farm
- Acquiring and testing specialized monitoring equipment for offshore use

- Wind monitoring on a small island in close proximity to the proposed offshore wind farm

- Wave and current monitoring in the ocean close to the proposed offshore wind farm

- Conducting offshore investigations, including acoustic sub-bottom profiling and side scan sonar

- Preparing an Environmental Notification Form to the Massachusetts Executive Office of Energy and the Environment

- Selecting sites for soil boring and vibracore studies, to be undertaken in the summer of 2008

- Preparation of photosimulations of the proposed offshore wind farm.

Figure 6 illustrates the area being considered for the installation of the turbines and Figure 7 shows a photo simulation of one possible layout.

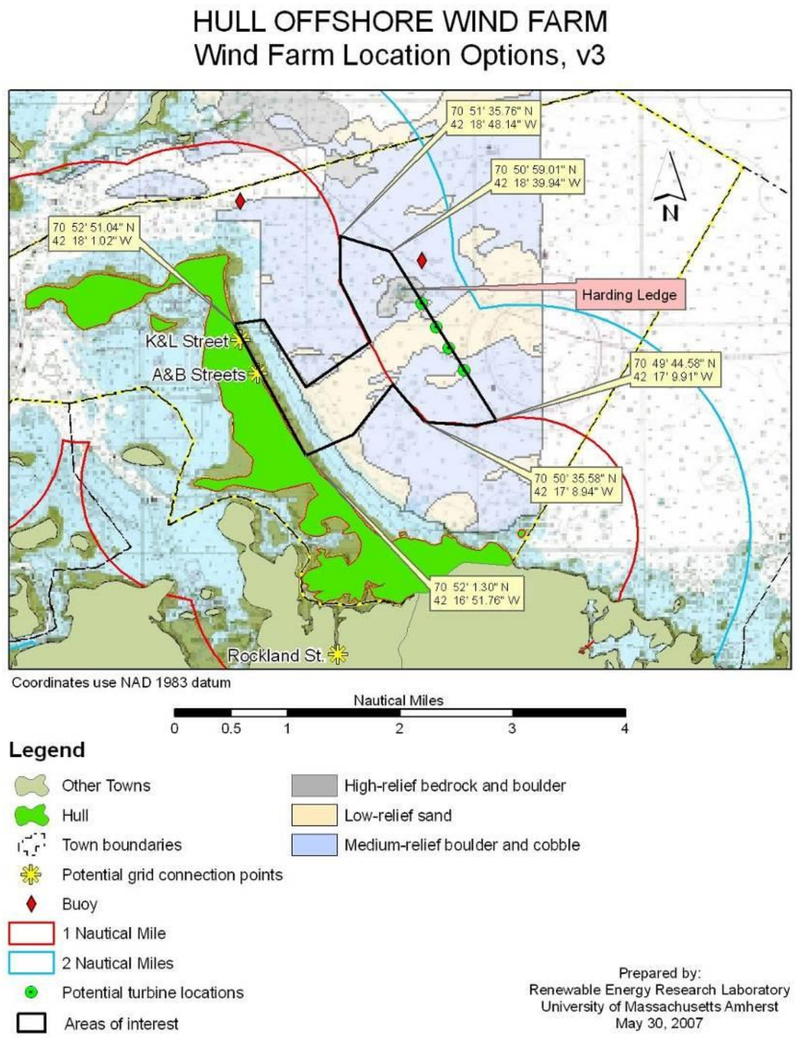

Figure 6.—Area of interest for Hull offshore wind project

Figure 7.—Sample photosimulation of Hull offshore wind project

Many of the activities that have been completed are described in Elkinton et al., 2006 and 2007; Jaynes et al., 2007; and Manwell, 2007. The more recent work was the subject of another paper presented at the American Wind Energy Association annual conference June 2008 (see Manwell et al. 2008).

With the help of the data from these studies, it has also been possible to develop data sets to examine the performance and economic aspects of the proposed project. Where possible, these new data sets have been used to develop a case study of a wind/desalination project for the Town of Hull. This case study is described in the next section

4.3. Case study simulation

A sample case study simulation has been prepared using the model described in this report based on the wind farm and desalination plant being considered for the Town of Hull. Since the offshore wind farm feasibility study has not yet been completed, this case study should only be thought of as an illustration, not as a final result. In particular, the costs of the wind turbines and their support structures is not yet known, and the actual costs of purchased power and value of sold power is not yet certain. The intent is to use the model, once the feasibility study is complete, to help to finalize plans for the desalination plant. For this case study, the inputs described below were used. In general, the files were given a suffix “DSX” to indicate the Desalination eXample. Where possible, cost estimates for the RO plant itself were taken from Wright-Pierce (2007).

4.3.1. Wind turbines

The model assumed that four General Electric (GE) 3.6 MW machines would be used. The total number of turbines was scaled up to 4.6 to approximately account for the two turbines that are already operating on land. The wind turbine power curve is illustrated in Figure 8.

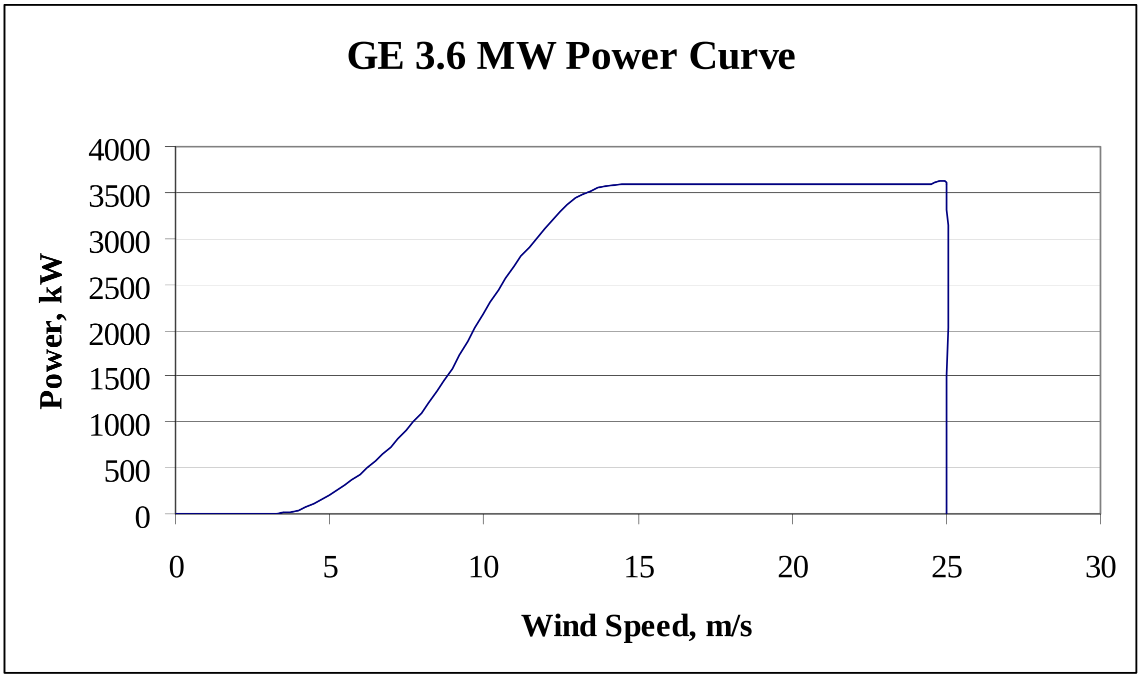

Figure 8.—GE 3.6 MW wind turbine power curve

4.3.2. Wind

The wind file, *Wind DSX.txt,* was derived for 2006 using measurements with a LIDAR on the island of Little Brewster in Boston Harbor, close to the site of the proposed wind farm. The Little Brewster data was then used in conjunction with wind speed data from Logan International Airport to produce a time series for a representative year. The time series has an average of 7.42 m/s, a standard deviation of 3.36 m/s and a maximum of 29.8 m/s. The time series of hourly wind speeds, *Wind DSX.txt,* is shown in Figure 9. There is one data point for each of the 8,760 hours in the year.

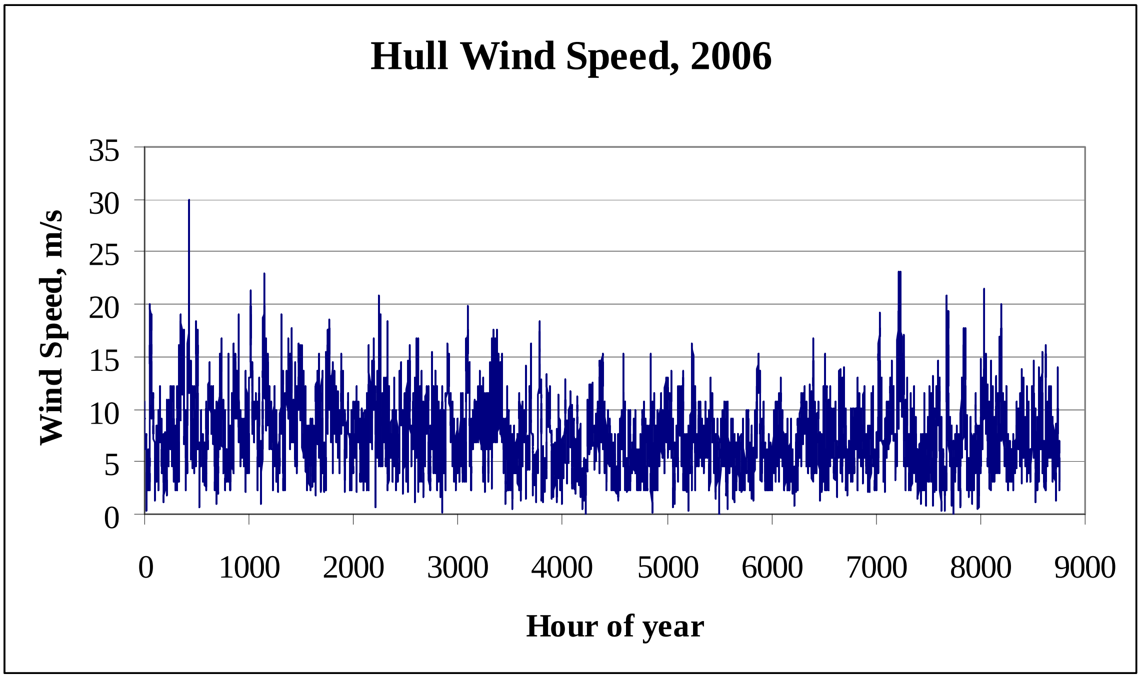

Figure 9.—Hull's wind speed, *Wind DSX.txt*

Another way to illustrate the data is with a histogram to depict the frequency of occurrence of wind speeds within ranges, (e.g., from 0-1 m/s, 1-2 m/s). Figure 10 shows a relative frequency histogram of the data illustrated in Figure 9.

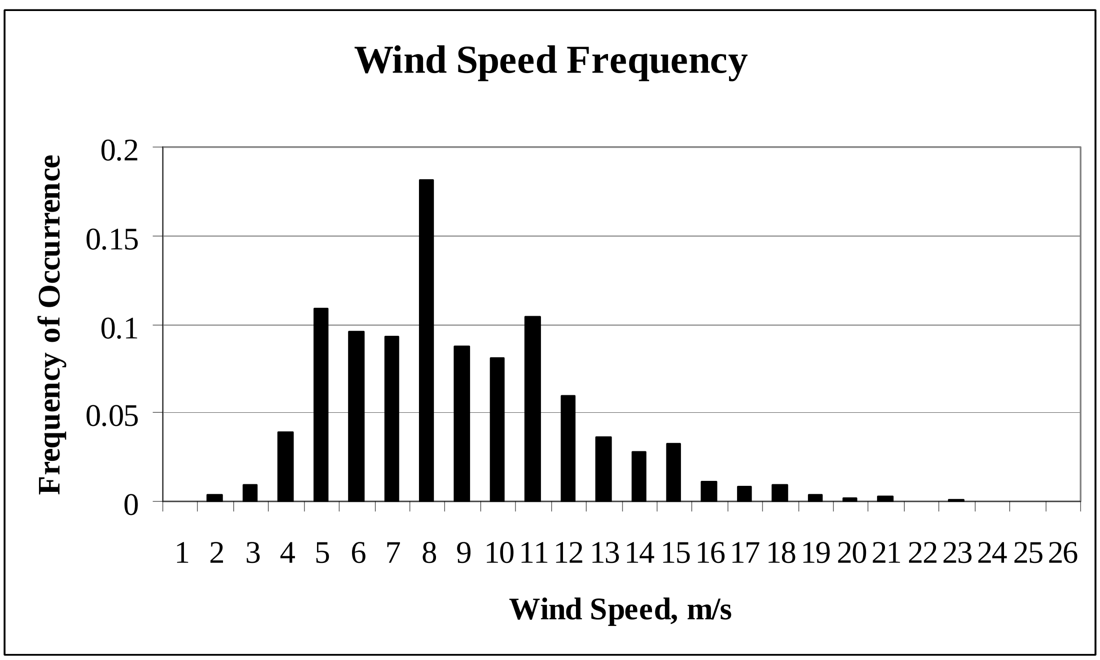

Figure 10.—Wind speed frequency of occurrence

A third way to illustrate the data is via a wind speed duration curve that shows the fraction of time that any given wind speed is exceeded. The wind speed duration curve of the data shown in Figure 9 is given in Figure 11. As can be seen in that figure, the wind exceeds the cut-in wind speed of the GE 3.6 MW wind turbine (4 m/s) for about 84% of the time, so the turbines will be operating most of the time. Conversely, the wind is less than the rated wind speed (14 m/s) most of the time, so the turbines are usually operating at less than their rated output.

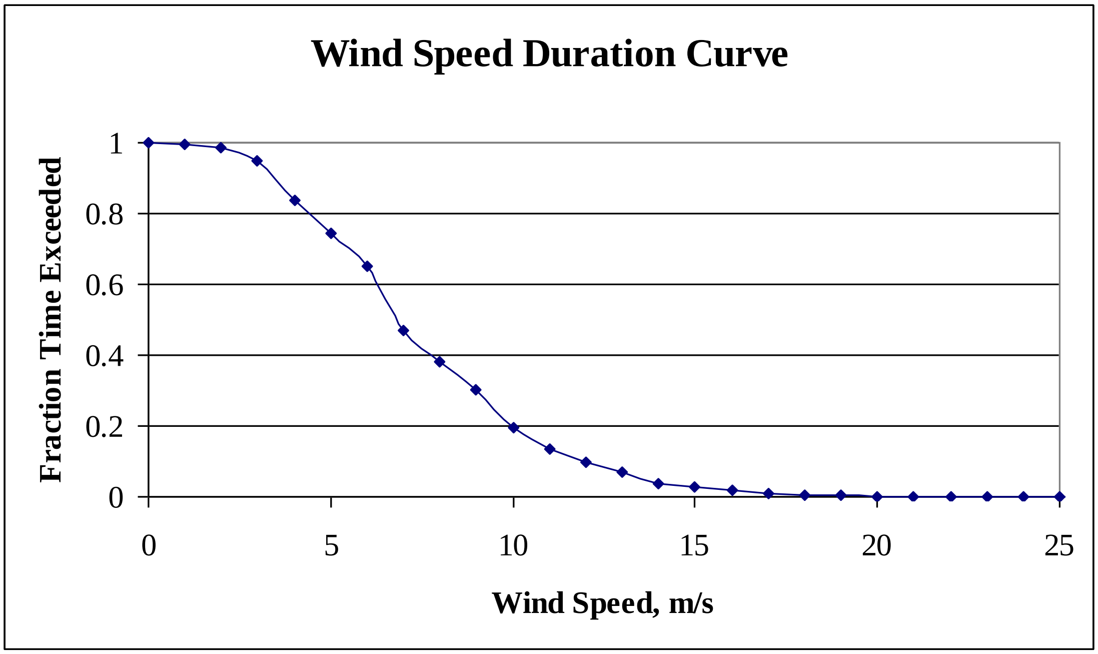

Figure 11.—Wind speed duration curve

4.3.3. Electrical load

The hourly electrical load data for 2006 was supplied by HMLP. The load was an average of 6,269 kW, with a maximum of 14,200 kW. The electrical load data file, named *Load DSX.txt*, is illustrated in Figure 12.

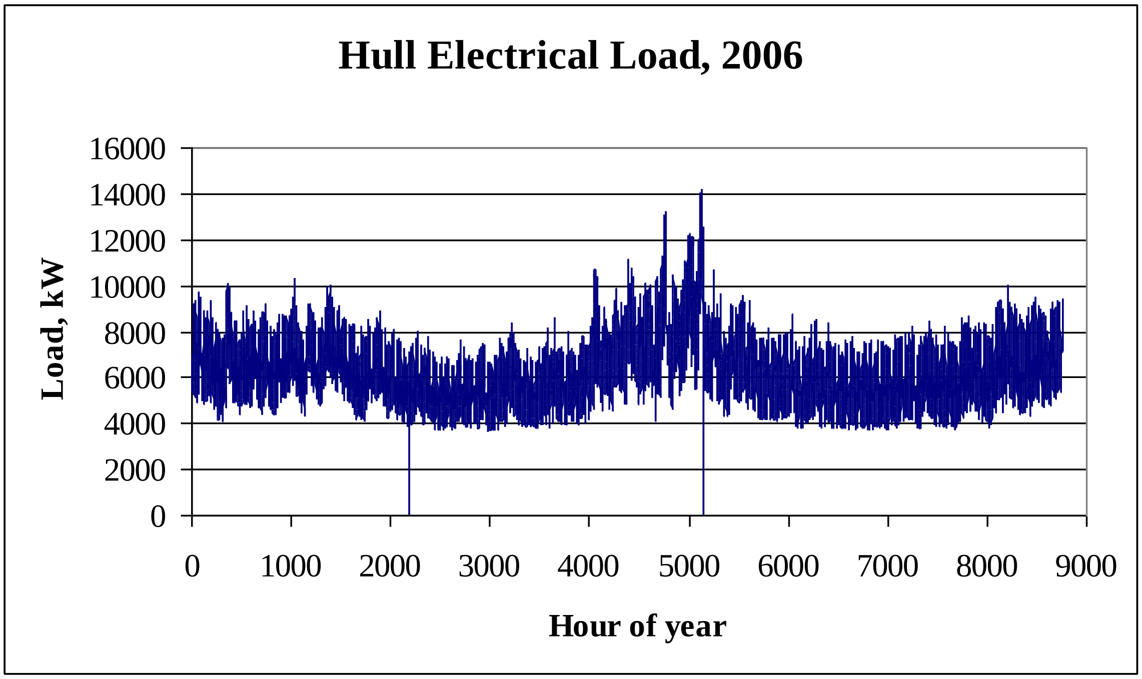

Figure 12.—Hull's electrical load, *Load DSX.txt*

4.3.4. Water load

Hull's water load was estimated by assuming that: 1) the average usage is 1 mgd and 2) the water load is proportional to the electrical load. The time series, therefore, has an average of 41666.7 gallons per hour (1 mgd) and a maximum of 94,380 gallons per hour (2.265 mgd).

4.3.5. Purchase rates

Power purchase rates for this model run were based on hourly energy costs in the New England grid in 2006 (Figure 13). It is recognized that HMLP pays additional charges, but those are essentially fixed through a given year. Only the variable costs were considered for this case study. The purchase rates were an average of $0.0609/kWh with a maximum of $0.2173/kWh. These rates were provided by a representative of the Massachusetts Municipal Wholesale Electric Company (MMWEC), which supplies electricity to HMLP (Lynch, 2008).

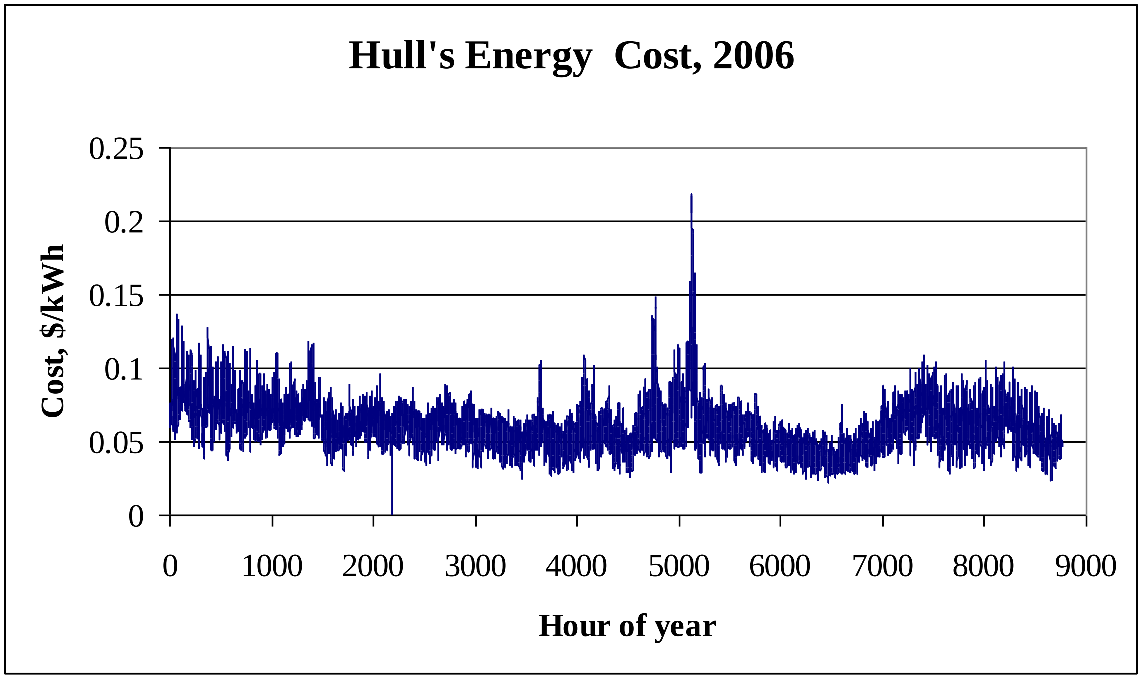

Figure 13.—Power purchase rates, *Purchase DSX.txt*

4.3.6. Sales rates

The rate at which the Town of Hull will be able to sell power is not certain: maybe at the purchase price or maybe less. In any case, there may be additional fixed charges due to transmission, which only apply in one direction, so that effectively HMLP may pay more for purchased power than it will receive from selling power. Accordingly, for this example, it was assumed that the sales price is $0.02/kWh less than the purchase price

For this case study, the following assumptions were made:

RO fixed costs: $10,000,000
RO variable costs $1,200/kgpd
RO O$M: $1.5/kgal
Storage costs: $1,600/kgal
Turbine fixed costs: $1,000,000
Turbine variable costs: $2,500/kW
Turbine O&M: $0.02/kWh
Fixed charge rate: 0.06
Renewable energy incentive: $0.03/kWh
Storage was initially assumed to be 50,000 gal
Reverse osmosis plant energy use: 19 kWh/kgal.

4.3.7. Results

The results of the sample run are shown in the screen shot in Figure 14

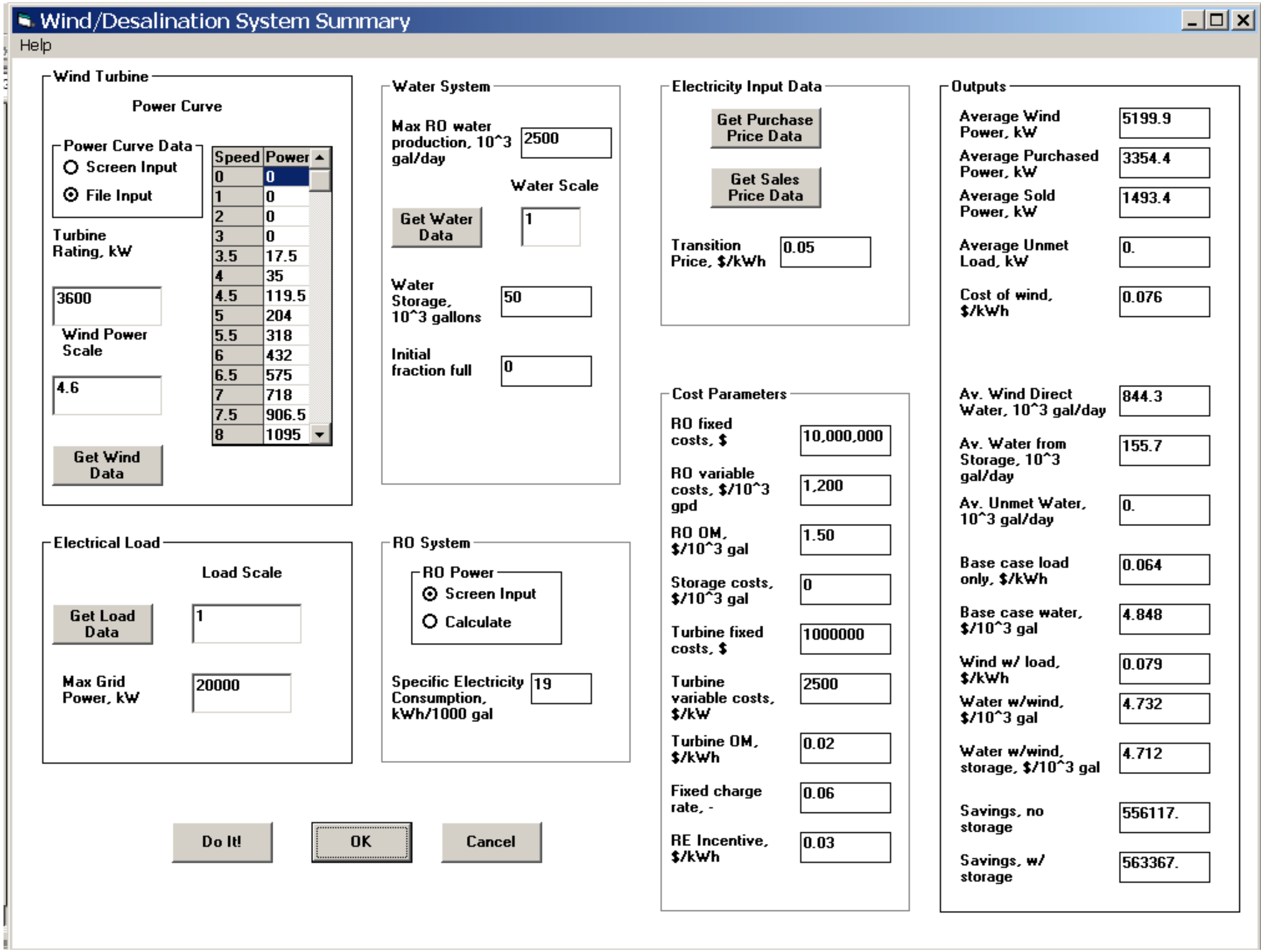

Figure 14.—Output screen for case study

The average wind power (5,200 kW) corresponds to approximately 83% of the average town load (6,269 kW). Some of this wind energy is used by the town; some is used to produce water directly; and some is used to produce water to refill the storage tank. Because of the only partial correlation between the wind and the electrical and water loads, a substantial amount of energy is still purchased (3,354 kW). The electricity which can not be used within the town is sold (1,493 kW). One overall conclusion is that, based on the assumptions used here, expanded wind energy is an economically attractive option for the town. Furthermore, water desalination can result in water costs lower than those that are currently available in the town. Finally, using the wind energy for desalination can result in even greater savings. Those savings can be increased somewhat by using water storage.

The model can elucidate other effects. For example in the original example case, only a small amount of storage is shown, corresponding to about an hour's worth at the average use rate. The amount could be increased, thereby reducing purchases, but the savings would not necessarily increase due to the costs of the storage (Figure 15). Increasing storage results in a gradual reduction in purchases. On the other hand, savings are also reduced, and at a greater rate, so there are no more savings to be had by increasing storage beyond this small amount.

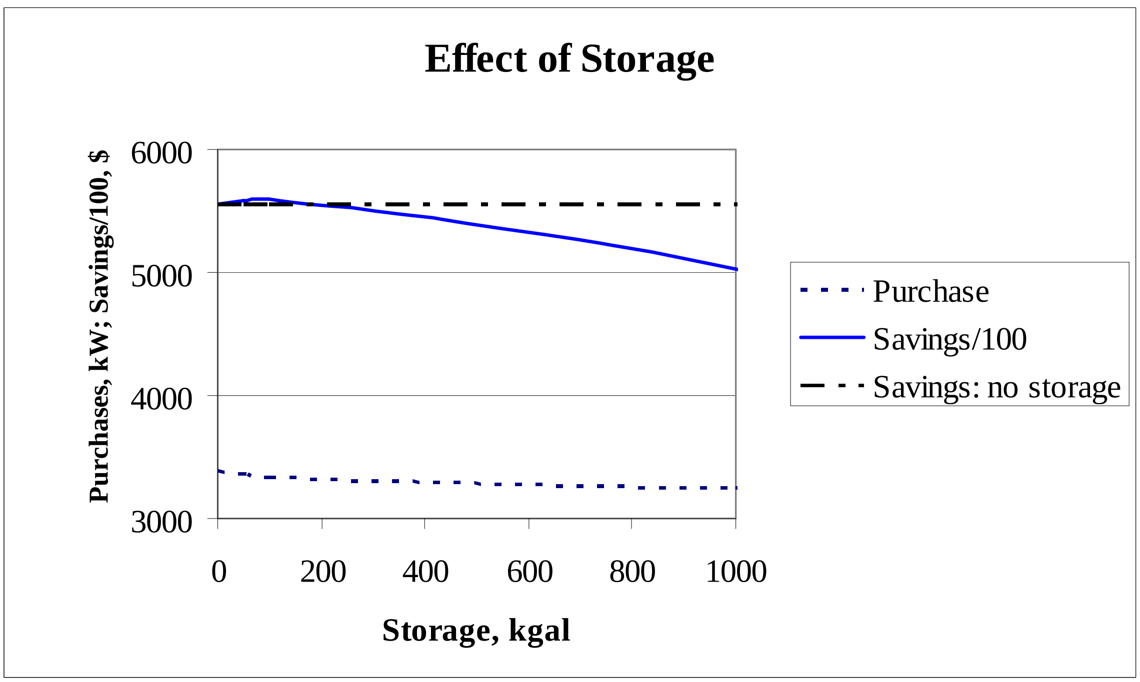

Figure 15.—Effect of storage on power purchases and savings

The price of storage can affect the optimum amount of storage. To illustrate this, all the parameters were kept the same as in the original case study except for the price of storage. Then the amount of storage was adjusted by inspection to find the amount resulting in the greatest savings. The result for five prices varied from no cost to $2,000/kgal (Figure 16). In this example, optimum storage capacity can vary from as much as 1 million gallons (about one day's consumption) to less than 100,000 gallons.

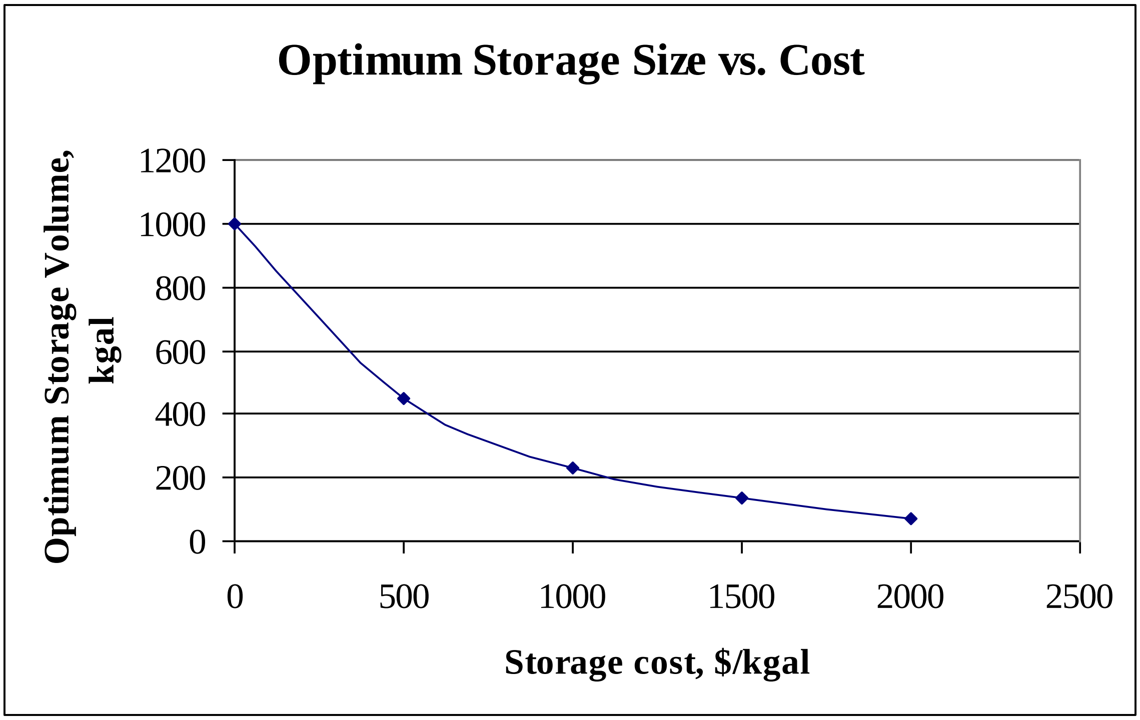

Figure 16.—Effect of cost of storage on optimum amount of storage

4.3.8. Summary of results

This case study illustrates that:

1. Offshore wind energy can make economic sense for a municipal electric company under plausible assumptions

2. Wind-powered desalination can make sense under the assumptions used here

3. Incorporating water storage into a wind/desalination project is a plausible option.

4. The costs to add wind energy and desalination to a community need to be carefully considered to ensure that the benefits outweigh those costs.

5. Conclusions and recommendations

The work described in this report illustrates that it is quite possible to develop a computer model that can assist designers of hybrid wind/electrical load/water supply systems. The work has already been of interest to the Town of Hull. As the feasibility study progresses on the offshore wind energy project, the computer model developed under this contract will continue to be used.

It is also worth noting that many aspects of the work described herein are more generally applicable, and with some additional effort could be made more widely useful. The following are some suggestions of work that could be done.

1. Convert the *DGWindDesal* software to a form which could be more readily used by others. This would entail adding some features which would make it more robust, and then turning it into an *exe* file. There should also be a theory manual and user's manual to accompany such software.

2. For grid-connected applications, generalize the model to be more easily applicable to situations that do not involve a municipal electric company

3. Refine the reverse osmosis component model to more accurately consider issues associated with variable required water production.

4. Extend the model to facilitate the design of isolated network and direct coupled renewable energy/desalination systems

5. Add a full life cycle costing model to *DGWindDesal*

6. Validate the model against a real installation

7. Incorporate the model into the more extensive hybrid power system model, *Hybrid2*

6. Epilogue

Since work on this first project began, and even since the data files for the case study were prepared, costs for many of the parameters of interest have increased substantially. In the final analysis, all these new costs will have to be considered before final decisions are made. It is of interest to note, however, that over the last several years, installed costs for offshore wind turbines have risen approximately 60%. The cost of electricity purchased by the Town of Hull has apparently risen even more. For example, the average locational marginal price of electricity (LMP) in June, 2006, was approximately \$58/MWh, whereas in June, 2008, the LMP was \$107/MWh, an increase of 84%. Note that these rates are provided by ISO New England (ISO, 2008). Similarly, the cost for water to the residents of Hull has increased from \$7/kgal in 2002 to \$7.39/kgal in 2006 to \$8.67/kgal in 2008. The 2006 rate also included a subsidy from the state. It is expected that the costs will increase by another 22% by the end of 2008, and unless the subsidy is renewed the cost of water will be \$10.37/kgal (Russell, 2008). The import of all of this is that sea water desalination is still an option worth seriously considering for the Town of Hull and other similar situations, and providing much of the required electricity from the wind is worth taking seriously as well.

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Appendix A: Validation tests

The following are some tests of the *DGWindDesal*. Unless otherwise specified the data files listed below are used where applicable:

Wind: Wind DSX.txt
Load: Load DSX.txt
Water: Water DSX.txt
Purchase rates: Purchases DSX.txt
Sales rates: Sales DSX.txt
Wind turbine: GE 3_6.txt
These files are described in the Case Study section

Other files were also created for certain tests. These include:

Purchase 0_1.txt
Sales 0_06.txt
Sales 0_15.txt
Sales 0_0.txt
Wind 8 ms.txt
Water 41667.txt

These are all files of 8,760 points, where each point within the file is a constant. For purchases, the value is 0.10; for sales, the values are 0.06, 0.15 and 0.0 respectively (all corresponding to $/kWh); for wind the value is 8 (corresponding to 8 m/s); for water the value is 41,666.7 (gal/hr, corresponding to 1 million gal/day).

Also, scales normally = 1, except where specified

Numbers shown in Expectation and Result are power in kW

The first set of tests deal with wind turbine power, supply of electrical load, water supply and dispatch algorithms. The second set of tests deal with basic economics. These second tests only consider the effect of energy sales or purchases on revenue or savings. Other tests were performed on other aspects of the program, but they are not included here.

The first tests are summarized in Table A-1; the second in Table A-2.

Appendix A: Validation tests

Table A-1.—Performance Tests

Test #	Test	Condition	Expectation	Result
1	Wind turbine power	Wind data file: 4 turbines; no load; no water; use Mini-codes	Same result as mini-codes: 4521.7	As expected
2	Wind turbine power	Same as above, except use Excel file, *desal tester 2.xls*:	Same result as mini-codes: $P_{w,av}$ = 4521.	Close ($P_{w,av}$ = 4514) difference; found to be due to slightly different wind power algorithms
3	Wind energy supplying electric load	Same as above, except load included; use Mini-codes	Same as result as mini-codes: wind: 4521.7, bought: 3035.4, sold: 1287.8	As expected
4	Wind energy supplying electric load	Same as above, except use Excel file	Same result as Excel: 4514, bought: 3047.8; sold: 1293.0	Consistent with Excel file
5	Water supply	Same as above, except water load included; use Excel file *desal tester 2.xls*:	Same as Excel file; wind = 4514, purchased: 3630, sold: 1083	$P_{w,av}$ 4521.7 ; purchased: 3616.8, sold: 1077.6 ; difference due to wind power
6	Water as increased electrical load	Same as 2 above, except load scale = 1.12656	Same power flows as above	$P_{w,av}$ same ; purchased: 3616.2, sold: 1077.2
7	Water from storage	Water load, no electrical load; no wind; storage initial full, capacity of 365 10^6 gallons; dispatch 1b; transition = 0	All water from storage; no power purchased	As expected; also, slightly lowering capacity results in some power purchases
8	Fill storage	No electrical load; 8 m/s wind; wtg scale = 0.723; storage empty, capacity of 365 10^6 gallons; dispatch 2b; transition = 0.2	Water tank is filled, no power sold	As expected; also, slightly increases power results in some sold

Table A-2.—Economics Tests

Test #	Test	Condition	Expectation	Result
9	Base cost of water	No wind, no load, water, no costs; purchases at $0.10/kWh: purchase_01.txt; sales at 0.0	Average water cost = $1.90/kgal	As expected
10	Savings due to wind in no-storage case	As above except constant wind = 8 m/s,	All water from wind; savings due to decreased purchases = $693517; any excess sold, but no revenue from sales	As expected; av wind power = 1095 kW, which greater than load; excess
11	Savings due to full storage	As above, except no wind, storage = 365 million gal, initially full	All water from storage, savings as above since no purchases	As expected
12	Savings due to dispatch	As above, except wind again	All water from wind; excess sold (no revenue); savings as above	As expected
13	Savings due to dispatch	As above, except storage initially empty	As above, except no sales (excess use to supply storage	As expected
14	Non-zero sales price	As above, except sales - $0.06/kWh	Excess = 303.3 kW; savings increased to $852,932	Essentially the same ($852,963)
15	Dispatch change	As above, except transition = $0.08	Excess will be used to supply tank; no sales; savings reduced to $693,517	As expected
16	Reduced wind power	As above, except no storage, wtg scale = 0.5	Some power will be bought; savings reduced to about $479,600	As expected