Wind powered irrigation in Montana

by Joel Cahoon

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Agricultural Engineering
Montana State University

Abstract:
The technical and economical feasibility of wind powered irrigation systems in Montana is considered. The possibilities of incorporating energy conserving irrigation systems, crops, and tillage practices into the wind powered irrigation systems are assessed. The feasibilities of the irrigation systems are determined using six computer models in site specific situations. The results of these models indicate that wind powered irrigation is technically feasible, but not economically feasible. Wind powered irrigation systems are not recommended for production operations in Montana.

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ABSTRACT

The technical and economical feasibility of wind powered irrigation systems in Montana is considered. The possibilities of incorporating energy conserving irrigation systems, crops, and tillage practices into the wind powered irrigation systems are assessed. The feasibilities of the irrigation systems are determined using six computer models in site specific situations. The results of these models indicate that wind powered irrigation is technically feasible, but not economically feasible. Wind powered irrigation systems are not recommended for production operations in Montana.

CHAPTER 1

INTRODUCTION

Using alternative energy sources for irrigation pumping has recently become of interest to agriculturalists. When on-farm economic situations are worsening, any practice that may increase a producers profits is worth considering. This project examines the technical and economic feasibility of wind powered irrigation systems in Montana.

Many researchers have considered the technical feasibility of pumping the required water volumes necessary for irrigation via some sort of wind energy system. This project examines the total system, including the wind powered pumping system, the irrigation system, the cropping practices and the overall economics of the system.

Several energy conserving concepts were evaluated for potential use with wind powered irrigation systems. The reason for these evaluations was that these energy conservation methods, if it were determined that they were applicable, might make wind powered irrigation systems more feasible. The concepts evaluated are: the use of crops with low water requirements, the use of crop production functions (mathematical relationships between crop water use and crop yield) to reduce pump energy requirements, the use of energy saving irrigation systems, the use of conservation tillage practices, and the use of reservoirs for off season pumped water storage. The evaluation of these concepts was accomplished by reviewing the available literature on the topics. Based on this literature, the concepts were evaluated to determine their relative applicability to wind powered irrigation systems. Of the topics evaluated, those which would enhance the feasibility of wind powered irrigation systems were incorporated into the models developed in this project.

Literature concerning wind energy conversion, wind powered water pumping, irrigation system energy use, and wind regime assessment was also reviewed. The models developed in this project, and much of the discussion concerning these topics, are based on the information obtained from this literature.

Several wind powered irrigation system models were examined to establish the technical and economical feasibility of such systems. The types of systems that were modeled are: windmill-reservoir systems, systems that offset existing electrical irrigation loads, and stand alone windmill systems.

The windmill-reservoir system models use a mechanical water pumping piston type windmill to supply water to an off season storage reservoir. The water is conveyed from the reservoir to an appropriate irrigation system. The net return of several crops at each site was estimated and the economic feasibility of the systems as designed determined. Four such models are examined in this project.

A second scenario examined offsetting existing electrical irrigation loads. In this model a wind powered electric generator is used which would lessen the dependence of an existing irrigation system on the utility grid. The economic feasibility of offsetting existing electrical irrigation loads was then assessed.

The third model considered replacing an electrical irrigation pump motor with a small mechanical water pumping piston type windmill. In this model it is assumed that the existing irrigation system is one that will allow large variations in flowrates and pressures, such as a drip/trickle system. The economic merits of using a windmill in place of an electric motor were then assessed.

The products and business references used in this project are not recommended as the sole source of components or information. Products and businesses were cited in this project due to their availability at the time of this research and adaptability to the systems examined herein.

CHAPTER 2

EVALUATION OF ENERGY CONSERVING CONCEPTS

The intent of this chapter is to assess the possibility of incorporating several energy saving concepts into the design of wind powered irrigation systems. The applicability of these concepts to wind powered irrigation systems is based on literature reviewed concerning each topic. These topics are: crop production functions, energy conserving crops, energy conserving irrigation systems, conservation farming techniques, and off season pumped water storage reservoirs. If these concepts are deemed applicable to wind powered irrigation systems, they will be incorporated into the system models.

Crop Production Functions

Reducing the amount of irrigation water applied to a crop may be one method of energy conservation. Before this practice is recommended, the effects of this water reduction must be thoroughly examined. Ideally, the decrease in the crop value as a result of water reduction should be more than offset by the resultant savings due to energy reduction. This theory violates the common notion that the optimum production level should be the maximum production level, regardless of the cost of production. For this reason the reduction of irrigation water application has only recently been introduced as an alternative method of maximizing production profit. (Heady and Hexam, 1978)

Crop production functions are mathematical relationships between crop input variables and yield or production. Many researchers have developed crop production functions for a given crop at a given location. It is the authors feeling that these types of production functions are developed rather blindly, as the use of the production functions at another location, or under different conditions, is rarely considered in the research. Some researchers have maintained that production functions developed at one site are transferrable to another (Sammis, 1980), but the transferability was not established on more than a statewide basis.

Crop independent production functions are those that may be applied to any crop at any location. (English and Dvoskin, 1977) The drawback with these production functions is that extensive site specific research and testing is required to establish the yield-water use relationship.

Current literature concerning the actual on-farm use of production functions in a cropping operations suggests that these relationships not be used to lower the energy requirements of the irrigation system. (Vaux and Pruitt, 1983)

Alternative Crops for Montana

Some alternative crops have a lower water requirement than the crops commonly grown in Montana. These lower water requirements could translate into an energy savings for producers. Several crops have been suggested as alternative crops for energy and water conservation in Montana. These crops include; fababean, garbanzo bean, and safflower. (Westesen, 1985)

Fababean

Fababean is an Old World crop that has been grown for centuries in Europe, and used as a supplement in both animal and human diets. Fababean is a tall, upright growing, annual legume, which when inoculated with commercial Rhizobium can provide its own nitrogen. The seeds are large (62-70 lbs/bu) and high in protein (28 - 32%) and carbohydrates. (Lockerman et al., 1982) The fababean is well suited to the climate in most regions of Montana.

The yield of fababeans under irrigated conditions ranged from 2000-5000 pounds per acre. (Lockerman et al., 1982) Reports indicate that fababeans are a poor dryland crop but respond well to low and intermediate irrigation levels. A single value irrigation water requirement has not yet been established for the fababean in Montana.

Current commercial market information indicates that the value of fababeans as a bean crop varies from $.12 to $.13 per pound delivered to the dealer. Current seed prices for fababean seed run from $.15 to $.17 per pound, with an additional cent per pound of seed for Rhizobium inoculant. (Bruce, 1986)

There are several on-farm uses for fababeans which hold some promise of making the crop a viable water saving alternative. The crop may be cut as silage or used as a supplement in the diets of swine, poultry, dairy cattle, beef cattle, and sheep. (Lockerman et. al., 1982)

It seems that Fababeans are quite well suited to the agricultural climate and practices in Montana. There is a fairly stable market for the fababean, but this market is largely out-of-state. In addition to the commercial market, there are on-farm uses for fababean. If these on-farm uses could be successfully incorporated into a farming operation fababeans could be considered a feasible water conserving crop for Montana. Unfortunately, fababeans have not yet been commercially tested on a real production basis in Montana, and are therefore not recommended on any large scale or permanent operation.

Garbanzo Bean

The garbanzo bean, commonly called chickpea, was originally a native of Europe. The chickpea is a low growing, bushy, hairy stemmed annual legume. Chickpeas are grown, harvested and handled much in the same way as the field bean. Chickpeas may be used as a protein substitute in the human diet or prepared in the same manner as dried lima beans. (Welty et al., 1982)

It appears that the growing season length and climatological conditions in Montana are quite satisfactory for chickpea production. Research has been done concerning the water use-yield relationships for the chickpea in Montana, the results of which are presented in Table 1. (Welty et al., 1982)

Table 1. Chickpea yields and water use, based on tests in Montana.

Total Water (in)	Grain Yield (lbs/ac)
32.8	2041
28.8	2312
24.5	3032
22.6	2867

The tests were conducted at Bozeman MT during the 1981 growing season on inoculated UC-5 garbanzo bean. It was reported that the two higher irrigation treatments reduced yield because vegetative growth increased, delaying bloom.

The cost of the garbanzo bean seed is the single highest expense in the production of the crop. The seed prices varies from $35 to $80 per hunderedweight. (Baldridge, 1982; Bruce, 1986)

Current information concerning the market potential of garbanzo beans indicates that the harvested crop is worth $.20 to $.50 per pound on the domestic market. This market value varies substantially. There are few reported on-farm uses of the crop. Garbanzo beans may not be harvested as silage for animal feed, as the plant itself is toxic to most farm animals. (Bruce, 1986)

The current farming practices and equipment used in Montana are very applicable to the production of the garbanzo bean. The factors that could limit the feasibility of garbanzo beans as an energy conserving crop are; the lack of a steady commercial market, relatively few on-farm uses of the crop or its residue, and the extremely variable and high cost of the seed. It is not recommended that garbanzo beans be implemented into any large scale or permanent cropping installation in Montana until further research is conducted.

Safflower

Safflower has been an important oil-seed crop in the United States since the 1940's. The safflower is well adapted to semi-arid and irrigated regions. The required frost free season is about 110 days, which makes safflower a suitable crop for most of Eastern Montana. The average yield in Montana is roughly 4000 lbs of seed per acre. (Baldridge, 1986) The safflower is an annual, erect, glabrous herb, 1 to 3 feet high and branched at the top. Safflower seeds weigh roughly 45 lbs per bushel, are smooth and resemble a small sunflower seed in shape. The unhulled seeds contain 18 to 24 percent protein and 32 to 40 percent oil. (Chapman et al., 1976)

Research concerning the seasonal water use by safflower was done at two locations in Montana. The total seasonal water use by safflower ranged from 9.0 inches at Culbertson to 9.8 inches at Fort Benton. These values are total water use for the growing season, and have not been adjusted for precipitation or stored ground water. (Baldridge, 1986)

Seed cost for safflower appears to be roughly $30 per hunderedweight. The current market value of safflower appears to be between $.15 and $.20 per pound of seed. (Baldridge, 1986)

Safflower is promising as a water conserving crop for montana. There is an in-state market for the crop, and the crop is currently grown on a dry-land basis in the state. Currently, safflower as an irrigated crop is not recommended in Montana until the means and effects of safflower irrigation are further evaluated.

Energy Conserving Irrigation Systems

Those systems which have been singled out as being energy saving systems and being potentially applicable to the farming situations in Montana are; drip/trickle, trail tube center pivots, and low pressure sprinkler systems. (Westesen, 1985)

Drip/Trickle Systems

Drip irrigation is the deposition of water directly to or beneath the soil surface utilizing low flowrates. This is accomplished by using individual lines or laterals equipped with emitters for water dispersion. The laterals and emitters themselves are the means by which pressure is reduced to allow low flowrates in drip form. In a drip irrigation system each plant, or small group of plants, is watered individually by its own emitter. (Pair et al., 1983)

Drip irrigation is the most efficient of all irrigation methods. Very little water is wasted because the water is deposited directly onto the soil. This greatly reduces the evaporative and wind induced losses associated with sprinkler systems. Since only small volumes of water are applied there are no deep percolation losses. (Hansen et al., 1979)

Test results have shown that crop yields and irrigation efficiencies are greatly increased with the use of drip irrigation systems. These test results are typical of those found for other field and vegetable crops. (Sammis, 1980)

The major problems encountered with drip irrigation systems are; emitter clogging, salt accumulation, and mechanical damage by farm machinery. (Pair et al., 1983)

Drip irrigation systems are currently used extensively on vineyards and orchard crops. The current trend is towards establishing drip systems as a viable alternative for row crops. This should become more evident as the drip industry grows, thus reducing the purchase price of drip system components. Research has shown that dramatic yield increases result from the conversion to drip irrigation systems from more conventional methods. With more extensive use of drip systems the problems inherent with the systems are being overcome. This energy efficient means of irrigation should become more widespread in the near future. Currently, the purchase costs of drip irrigation systems may limit their use in Montana cropping practices.

Low Pressure Sprinklers

Low pressure sprinklers have the same basic characteristics as any other sprinkler system, with the difference being the operating pressure of the sprinkler. Low pressure sprinkler systems generally operate in the range of 5 to 30 psi. The sprinklers are fitted with low pressure nozzles to help distribute the water more efficiently. The characteristics of a low pressure sprinkler system may be summarized as: a small wetted diameter, relatively high precipitation rates, the water drops are fairly large due to the low pressure, and the moisture distribution pattern is generally only fair at best. (Pair et al., 1983)

Low pressure sprinkler systems are not recommended for use with wind powered irrigation systems until their commercial availability is established, and the full effects of their use is determined. (DeBoerand Beck, 1983)

Trail Tube Center Pivot Sprinklers

Trail tube center pivot systems are center pivots which have been altered so that small tubes emit water slightly above the ground surface. The trail tube system that has received much attention recently is the LEPA (Low Energy Precision Application) system. (Lyle and Bordovsky, 1982)

The LEPA system distributes water directly into a furrow at very low pressures. The drop tubes with emitters are positioned 2 to 4 inches above the furrow. The system was designed to eliminate climatic and soil variables which adversely affect the uniformity and irrigation efficiencies.

The system is designed to be used in conjunction with furrow diking techniques. Furrow diking involves the placing of small dikes at regular intervals along the length of the furrow. With this technique, the water that is placed in the furrow by the LEPA system cannot run off. Using furrow diking also allows better trapping of rainwater. Without the furrow diking, the LEPA would result in excessive runoff losses. This is due to the low pressure and high application rates of the water applied. (Lyle and Bordovsky, 1983)

The LEPA system is only one form of trail tube sprinkler irrigation. Other systems involve dragging tubes suspended from a center pivot, with emitters fitted to the tubes. (Westesen, 1986) Little interest seems to have been generated concerning these systems, due to the high runoff that could occur without the special tillage practices to complement the irrigation system.

These trail tube systems are not yet commercially available, they must be used in conjunction with a labor intensive tillage system, and are thus not recommended for use with wind powered irrigation systems in Montana.

Conservation Farming Techniques

There are some practices which may be incorporated into a farming operation which save water or energy that do not involve altering the irrigation system. These practices are collectively referred to as conservation tillage practices. These are cultural practices that can be incorporated into any farming system. These tillage systems fall into two general categories, those that attempt to conserve water by reducing field runoff, and systems which reduce tillage to conserve the water stored in the soil column. (Bauder, 1986)

The theory behind reducing runoff to conserve water is a simple one. Water that is prohibited from running off the soil surface, whether it is deposited by irrigation or rainfall, can be absorbed by the soil and used to replenish the soil moisture. The two most promising methods of controlling surface erosion involve altering the soil surface characteristics by residue management or tillage practices. (Bauder, 1986)

Residue management is the practice of leaving or incorporating the stubble from the previous crop on or into the soil surface. For example the straw that remains from a wheat crop may be lightly mulched and incorporated into the top two or three inches of the soil. The placing of loose straw in the furrow row of a field bean crop reduced surface runoff by 50%. (Brown, 1985) Increased water storage, fallow efficiency, and grain yield is achieved with the use of a stubble mulch fallow system. (Bauder, 1986) The obvious drawback of a stubble mulch system is that a crop with good residue production must have been grown in the field during the season prior to that in which residue management is desired or straw must be hauled in.

The other method of controlling surface runoff is to simply alter the surface characteristics of the soil by utilizing certain tillage practices. A simple method of reducing surface runoff is through proper land grading techniques. Soils with deep profiles may be graded to decrease slopes that cause high runoff rates.

Another means of increasing the water use efficiency of a farming system is the use of minimum tillage practices. These practices involve the reduction of the number of tillage passes over a field, or the use of tillage implements that decrease the water loss from a soil column. Each tillage pass depletes the soil moisture by an average of 1/2 inch. (Bauder, 1986)

One drawback of minimum or no-till systems is that herbicides must be substituted for tillage in weed control. If weed control is a serious problem, the herbicide cost may offset the resultant savings in water. (Bauder, 1986)

These are only a few of the many tillage and farming practices that may be incorporated into a farming system to conserve water or decrease tillage. This subject area is very broad and cannot be fully covered in the scope of this project. The use of one or several of these conservation farming techniques in a wind powered irrigation system should boost the overall effectiveness of the system. Many of the more feasible and effective conservation farming techniques are already in use in Montana's farming operations.

Off-Season Reservoir Storage

The Soil Conservation Service has published guidelines for the construction and use of irrigation water storage reservoirs. This technology may be easily incorporated into a wind powered irrigation system. The wind powered pumps would provide the water for reservoir storage. Storage reservoirs must be properly sized. There are several major inflows/outflows to a reservoir which must be considered in reservoir sizing. The inflows to the reservoir are; pumped water, precipitation and seepage. The reservoir outflows are: irrigation water, evaporation, and seepage. Seepage is listed as both an inflow and an outflow because in some cases water could be added to the reservoir through groundwater flows. Having identified the major constituents of water movement in a reservoir, a water budget may be constructed (Viessman et al., 1972):

$$S = P + R - E - S_o + S_i$$

where: S = change in storage volume
P = water pumped into reservoir
R = precipitation, E = evaporation
S_o = seepage out of the reservoir
S_i = seepage into the reservoir

The water balance equation may be used to estimate the required reservoir storage volume. The subsequent problem is to accurately estimate the components of the water balance equation. The reservoir should be sized for the period of highest crop water demand and lowest precipitation and pumping capability. If the reservoir can supply sufficient water for the crop in this worst case, excess water will be available for the remainder of the growing season. (Viessman et al., 1972)

The incorporation of an off-stream reservoir into an irrigation system depends largely on the sites topographic and cultural conditions. Conceivably, in some cases a reservoir may decrease the overall water use efficiency of an irrigation system. This would be due to the water losses associated with seepage and evaporation. Even with the lower efficiencies, a reservoir may be required for use with wind powered irrigation systems because of the typical low flow rates inherent with wind powered pumping systems.

Summary of the Applicability of Energy Conserving Concepts

The literature on the topics evaluated provides a basis for the following statements;

1. Crop production functions should not be used to lower the energy requirements of an irrigation pumping system, without substantial on site research concerning the validity of the production function.

2. The alternative crops examined should not be used in a large scale production operation without further research concerning these crops adaptability to Montana's farming situations.

3. The energy conserving irrigation systems examined should not be implemented into a production situation in Montana at this time, with the possible exception of the drip/trickle systems.

4. The conservation tillage practices that are most applicable to production situations in Montana are currently in widespread use.

5. Off-season pumped water reservoirs should be considered for use in wind powered irrigation systems.

With these statements justified, the remaining parameters concerning wind powered irrigation systems may now be considered.

CHAPTER 3

WIND POWERED IRRIGATION SYSTEM DESIGN CONSIDERATIONS

The design procedures for wind powered irrigation systems involves the examination of several critical parameters. Based on these parameters, decisions concerning the design of the system can be made. These parameters must be assessed on a site specific basis.

The parameters that must be assessed in the planning of a wind powered irrigation system are; the soil type, the crop water requirements and irrigation schedule, the irrigation system type, the growing season length, the pumping head, timing considerations, wind powered irrigation system compatibility, and the wind regime. In this section these parameters and the decisions to be made concerning them are individually discussed.

Soil Type

The soil type of the site is always a necessary consideration. The U.S. Soil Conservation Service has developed a system of rating a soils characteristics for agricultural considerations. Under the system the soil and the surrounding topography is ranked and said to be in one of eight classes, numbered I to VIII. Class I land is fit for any agricultural use. The limitations on land use increase with class number. The class number is determined from the soil texture, depth, and structure. Additional factors involved in soil classification are the slope, erodibility, drainage, stoniness and vegetation of the plot and surrounding areas. (Brady, 1974)

When considering a wind powered irrigation system, land classes I,II, and III are considered acceptable. In some cases class IV land may be used, but care in land management and improvement should be taken. (Brady, 1974)

Crop Water Requirements and Irrigation Schedule

A crops water requirements are the basis for establishing the flowrates that are necessary from a pumping system. The pumping system, be it stand alone or in conjunction with some type of water storage system, must be capable of meeting the peak crop water requirement. The timing of monthly and seasonal water requirements are estimated from climatic or lysimeter data. The required flow rate is determined using the water requirement for the acreage irrigated and the period of time considered. (Hulsman, 1985)

The peak flowrate must be within the limits of the wind powered pumping unit. Crops with low water consumption may be chosen as principle crops in order to decrease the water flowrate required of the irrigation system. These crops must be compatible with the site conditions and must show economic potential.

Irrigation System Type

The type of irrigation system type is also a factor in determining the flowrates pumped. If an irrigation system is already in existence at the proposed site, it may be unreasonable to alter the irrigation system for the sake of installing wind power. The factors associated with the irrigation system type that influence design decisions for a wind powered irrigation system are the required pressures and flowrates and the system efficiencies.

Growing Season Length

The growing season at a site is usually considered the period of frost free days. For this period of time the wind regime and pumping parameters are critical in a system with no water storage facility. During this time period the wind powered irrigation unit must be able to supply the irrigation needs of the crop. If the system is to have some type of water storage facility, the months surrounding the growing season should also be considered. During this time water may be pumped and stored for later use. The number of frost free days on a regional basis for particular Montana areas is available from the Soil Conservation Service or the Agricultural Extension Service.

Pumping Head

The head against which the pump is operating is one parameter which determines the amount of power that must be available to the pump. Pumping head includes both the elevation head and the friction head. The friction head is a function of the pipe lengths, diameters, and roughness coefficients, as well as the flowrates required by the irrigation system. The elevation head is a function of the height that the water must be raised to bring it to the level of the irrigation system.

Timing Considerations

In considering a wind powered irrigation system, the matching of timing between irrigation needs and wind power availability must be favorable. If it can be assumed through wind regime evaluations that sufficient winds are available when irrigation is scheduled, then the wind powered pumping system can be designed to supply water directly to the irrigation system. If the wind regime evaluation shows little consistency or predictability in the wind speeds, or that the windy periods do not coincide with the irrigation needs, then a water storage system should be considered in the design.

Wind Power Irrigation System Compatibility

The means by which wind power is incorporated into an irrigation system is important when considering the conversion of an existing conventional irrigation system to a wind powered or wind assisted system. This decision should be based primarily on the way the existing system is powered. Internal combustion engines and electric motors may be fitted with a wind machine via an overrunning clutch.

Electric motors on irrigation pumps may also be assisted electrically with a wind turbine in situations where excess energy is sold back to the utility. (Clark, 1985) It has been determined that mechanical wind assist systems provide about 12% more energy to the pump than do electrical wind assist systems. The electrical wind assist mode will pay for itself much quicker than the mechanical system if utility buy back is considered. (Clark, 1983) It is logical to suggest that if the current irrigation system is electrical, than electrical wind assist should be considered. If the irrigation pump is driven by an internal combustion engine, then mechanical wind assist is appropriate. In either case, alterations to the existing pumping unit should be kept to a minimum.

For new installations it seems logical that stand alone wind systems possibly in conjunction with water storage facilities should be considered. If it were economical to install an electric or internal combustion engine driven pump in conjunction with a wind system, it seems likely that these systems would have been previously installed without the wind assist.

Wind Regime

Wind regime assessments on a site specific basis should be carried out. There are no hard rules concerning the minimum quality of a wind regime acceptable for a wind powered irrigation site. (Barnett, 1985)

Other consideration in the planning of a wind powered irrigation system are (Barnett, 1985):

1. Site accessibility and the quality of roads leading to the site.

2. The possibility that the wind machine may not be usable in extreme weather conditions, due to winter snow or ice buildup.

3. The distance of the wind machine from existing residences or dwellings, for noise and safety considerations.

Site specific conditions may require design decisions not covered in this report. It is expected that the designer will make sound decisions based on logic and good judgment.

CHAPTER 4

WIND ENERGY CONVERSION SYSTEMS

Wind energy systems have been developed in many sizes and configurations. The technology concerning wind energy systems is well developed and has improved greatly over the past decade. (Gipe, 1983) This chapter reviews the basic operating principles and types of systems which make up wind energy technology.

The two basic wind machine configurations are horizontal and vertical axis. The aerodynamic principles in either situation are similar, but the construction and operation of the two differ greatly. (Barnett, 1985)

Horizontal axis machines have a horizontal axis which is parallel to the wind, about which the blades rotate. The horizontal axis machines were the first developed, and date back to the fifteenth century. In 1890 the Danes were generating electricity with a 23 m diameter horizontal axis wind turbine. Horizontal axis technology was used extensively in the Midwest and Western United States during the nineteenth and twentieth centuries to pump domestic and stock water or produce electricity at remote locations. During the late 1970's NASA, in conjunction with Boeing Engineering and Construction Company, built several large wind-electrical conversion turbines. The largest of these turbines was rated at 2.5 MW at a wind speed of 12.4 m/s. This verifies that horizontal axis machines have been well proven over the years. (Johnson, 1985)

There are two configurations of horizontal axis machines, upwind and downwind. The upwind machines are equipped with a tail or a mechanical orientation device so they continuously face the wind. The downwind machines are mounted in a caster situation, and the drag on the blades keeps them positioned such that their axis is parallel to the wind. The upwind machines have been used for more total hours, and are a more proven technology. The downwind machines, although simpler in design, block a small portion of the wind that strikes the tower. (Barnett, 1985) Some researchers still dispute the desirability of each configuration. (Gipe 1983)

Vertical axis machines spin around an axis that is perpendicular to the wind. The most common type of vertical axis is the Darrieus turbine, which was patented by G.J.M. Darrieus in the U.S. in 1931. There are curved and straight bladed Darrieus machines. The curved bladed machines are unique because the blades form troposkien shapes, or the shape formed by swinging a rope. This results in the blades sustaining almost pure tension forces. Since the blades are in pure tension a light, inexpensive blade is adequate. The curved blades are commonly formed from extruded aluminum. (Barnett, 1985)

The vertical axis machines are usually not self-starting. A small motor is used to start rotation when an acceptable wind speed is reached. After start-up is achieved, natural rotation will be sustained until low wind speeds reoccur. The major advantage of vertical axis machines is that the generator or power take off unit is at ground level instead of on a high tower. Installation and maintenance are thus much easier. The vertical axis machine does not have to be oriented to a particular wind direction. Since the axis of rotation is perpendicular to the wind, the wind may come from any direction. (Barnett, 1985)

Extensive research has been done in Texas using vertical axis machines to pump irrigation water. A vertical axis machine was coupled to an irrigation pump to obtain a 65% savings in energy in the wind assist mode. (Clark, 1979) This research proved the system to be technically feasible, but did not consider an actual cropping system served by the water pump. Total economic feasibility was not considered in the research.

The installation of modern wind energy conversion machines is often difficult and sometimes hazardous. A great deal of preparation and planning must go into the installation of a wind machine. Only experienced personnel should undertake the installation of a wind machine. Wind machines are often installed by the dealer from which the machine is purchased. If the dealer does not provide installation, this service should be contracted out to a firm with the proper equipment and facilities. Improper installation of a wind machine could result in a hazardous situation after the wind system is operating. (Gipe, 1983)

The designers of wind energy conversion machines have always attempted to minimize machine maintenance. Maintenance of a wind machine primarily involves keeping lubricating fluids at the proper levels. For a vertical axis machine this is simple because the gears and equipment are at ground level. Some horizontal axis machines are designed to be tipped over to simplify maintenance. Other horizontal axis machines require climbing the tower to check the lubrication fluid levels. Fortunately this need not be done very frequently with a well designed modern machine. (Gipe, 1983)

Other factors to consider when choosing a wind machine type are the cost per unit of power generating or water pumping capability, the service and reliability record of the manufacturer, and the installation and maintenance costs of the system. After all these factors have been considered, a wind machine type may be chosen. (Barnett, 1985)

The decision as to the type of machine most suitable to a wind powered irrigation system depends on several factors. The most important factor to consider is the means by which the wind machine is to be coupled to the irrigation system.

If electricity is to be generated to lessen the amount of power drawn from the utility lines, any electricity producing wind energy configuration will work well as long as the wind turbines power output is well matched to the load being drawn by the pumping plant. If mechanical coupling of a wind machine to an existing irrigation pump is to be used, perhaps a vertical axis machine is more desirable because the power take off is at ground level, making the power transmission system less complicated. For those wind machines which pump water directly, a traditional horizontal axis system is commonly used. Commercially units of this type are available. (Patterson, 1986) Because of the relatively large water volumes involved, wind powered irrigation pumping is new technology. There is room for innovative thinking and new design configurations.

Wind Regime Assessments

Climatological considerations constitute the most crucial factor in the design of a wind powered irrigation system. (Barnett, 1985) The best designed systems and machinery will not function if there is not enough, or too much, wind available. This section covers the methodology followed in assessment of the amount of energy available in a given regime.

The siting of a wind machine must be based on sufficiently accurate wind data. Wind data from nearby monitoring stations such as airports or research stations is normally accurate only for that site. (Gipe, 1983) For the data to be transferrable, the geographic conditions at the site and the monitoring station must be similar. A minimum of two years of data must be available for siting wind machines. Factors that may decrease the accuracy of data from a monitoring site are; obstructions near the monitoring site such as buildings and trees, "sloppy" data recording and gathering techniques, inconsistencies in the time interval at which the data was collected, or sites that have been falsely unobstructed by the clearing of natural vegetation such as runway clearings at airports. (Barnett, 1985)

The height of the anemometer used for recording the data must either be consistent with the height of the wind machine, or the wind data must be adjusted for the difference in height. This adjustment is accomplished by using the following equation (Johnson, 1985):

$$u(z_2)/u(z_1) = (z_2/z_1)^a$$

where: u = the windspeed
z = the elevation
a = a constant at approximately 1/7

The most extensive wind records have been collected by the National Weather Service (NWS), and the Federal Aviation Administration (FAA). A good compilation of wind data for Montana is available through the Energy Division of Montana Department of Natural Resources and Conservation (DNRC). (GeoResearch, 1986)

Once the designer is satisfied that his wind data is accurate and fairly representative of the site being considered, the data must be analyzed to determine if enough wind exists at the site to justify a wind energy conversion system.

There are many ways that the wind data may be analyzed. Wind patterns can be explained but not predicted using some basic mathematical principles. Therefore wind data is analyzed statistically rather than deterministically. The most often used wind statistic is the average or mean wind speed. This statistic is easily computed, and is usually included in any wind data set. The mean is computed as (Johnson, 1985):

$$U = 1/n \{\text{sum } U_i\}$$

where the data set contains wind readings U_i, and n is the number of data points in the set. Although mean wind speeds are frequently used in describing a wind regime this statistic can be misleading. For example, high wind speeds in the spring may increase the mean wind speed but there may be periods during the summer when the wind is almost nonexistent. To help clarify the validity of the mean wind speed, the standard deviation can be calculated. The standard deviation is an indicator of how the individual wind data deviates from the mean wind speed. The standard deviation may be calculated using (Johnson, 1985):

$$\text{eta} = [1/(n-1)\{\text{sum } (U_i - \overline{U})^2\}]^{1/2}$$

A low value of the standard deviation indicates that the wind data is consistently close to the mean speed. Both of these statistics give a good rough estimate of the quality of a wind regime and are easily calculated. (Barnett, 1985)

The most complete method of analyzing wind data is to establish the Weibull parameters for a site. (Barnett, 1985) The Weibull function utilizes recorded data, which is often too erratic to evaluate on a simple histogram, and smooths it to a general shape. The Weibull function is a very good model of real wind conditions. (Johnson, 1985)

The Weibull function is a two-parameter probability distribution function which appears as (Johnson, 1983):

$$f(U) = [(k/c)(U/c)^{k-1} (\exp(-(U/c)^{k})]$$

where k is a shape parameter and c is a scale parameter. The calculation of k and c is a complicated procedure. Commercially available computer software is now commonly used to estimate the Weibull parameters for a site. A computer program for computing these parameters is included in Appendix 1, Figure 20. Much of the wind data currently being generated includes a listing of the Weibull parameters.

The probability distribution function provides the preliminary information necessary to determine the amount of power that can be produced or the water flowrates that can be expected with a given wind powered irrigation system.

The Weibull parameters are those necessary for design considerations that are associated with the wind regime. Determining these parameters is the first step in an overall system design.

Pumping Capabilities of Wind Powered Irrigation Systems in Known Wind Regimes

The conversion of raw wind energy into usable energy is dependent on the type and efficiencies of the system and its components. In this section a method of estimating the water pumping capacity of a wind system is developed. A discussion of the means by which wind energy may be used to pump irrigation water is included.

Conversion of Wind Energy to Usable Energy

Given a wind speed it is possible to assess the total amount of power which is contained in that wind. The power of a given wind speed is given by (Johnson, 1985):

$$Pt = 1/2 \times p \times A \times U^3$$

This equation gives the amount of power that an ideal wind turbine would extract from the wind if the swept area of the turbine were A, the density of air p, and the windspeed at the time of evaluation, U. Of course no wind machine can extract all the power from the wind, and it can be shown that the theoretical maximum that a wind turbine can extract is about 60% of Pt. The actual factor is .593, which is referred to as the Betz coefficient. (Johnson, 1985) Most wind machines are able to extract 20 to 40% of the power in the wind. (Gipe, 1983) Transmission losses must be deducted from this estimated power. The means of determining the available power for water pumping varies with the method by which the wind machine is coupled to the irrigation pump.

A wind system that may be applicable to some conditions in Montana could supply electrical power to an existing irrigation pumping plant. This load would probably be a synchronous one. A synchronous system has a fixed rotational speed. At some low wind speed (cut in speed, Uc) the turbines will begin to rotate. The turbines will rotate at a constant speed (rated speed, Ur) until the wind becomes too strong. At this high wind speed (furling speed, Uf) the blades will furl or a braking device will be engaged. (Johnson, 1985)

The manufacturers of wind turbines should supply the buyer with accurate values of Uc, Ur, Uf and the rated power (Pr). Using these values and the Weibull coefficients determined from the sites raw wind speed data, an estimate can be made of the electrical power expected from a known wind regime. This power (Pe,ave) is expressed as (Johnson, 1985):

$$Pe,ave = CF \times Pr$$

where CF is the capacity factor. The capacity factor is dependent on the characteristics of both the wind regime and the wind turbine. The capacity factor is derived from the integration of the product of the rated power output from a wind machine and the probability density function of wind speeds over the entire theoretical wind speed range. In integral form this appears as (Johnson, 1985):

$$Pe,ave = \int_{0}^{\infty} Pe \times f(U)\, du$$

where f(U) is the Weibull density function of wind speeds. After substitution, integration, and simplification, the capacity factor can be expressed as (Johnson, 1985):

$$CF = \frac{\exp(-(Uc/c)^{k}) - \exp(-(Ur/c)^{k})}{(Ur/c)^{k} - (Uc/c)^{k}} - \exp(-(Uf/c)^{k})$$

where c and k are the Weibull parameters. From this equation it can be seen that given the parameters c and k we would like to choose a machine with values of Uc, Ur, and Uf that maximize CF.

Those systems which pump water using direct mechanical power are often sold as a complete package. (Patterson, 1986) To estimate the volume of water that these systems will pump, the manufacturer will normally supply a graph depicting flowrate vs. windspeed. This type of test data has been compiled by the Drainage Branch, Alberta Agriculture in Lethbridge Alberta, and is available to the public. The flowrates are read for each windspeed and multiplied by the number of hours in the time period and the percent probability of that windspeed occurring as given by the Weibull density function. The sum of these values is the expected volume of water pumped for the given time period.

Some manufacturers provide a table giving values of flowrate for certain pump head values and an average wind speed. The user determines the head which the pump is working against, then locates the flowrate for this value. If the average wind speed at the site is equal to the wind speed at which the manufacturers table was developed, this number is correct. If not, the flowrate must be adjusted to make up for the deviation in average wind speed.

There is no general way to estimate pumping capabilities for wind powered water pumping units. (Paterson, 1986) The pumping capabilities can only be ascertained by actual tests and trial runs of the units in question. Using this actual test data, the pumping capacities may be calculated for any site.

Feasibility Considerations in Assessing Wind Powered Irrigation Systems

In assessing site adaptability for a wind powered irrigation system, there are more factors to consider than wind regime quality. The economics of the system must be accurately predicted. The integration of a wind power system with a particular irrigation system must also be technically feasible.

Economic Considerations

There are two basic scenarios for which the economics of a wind powered irrigation system may be evaluated. The first is the situation where irrigation pumping is currently accomplished using some non-renewable energy source. This fuel would be displaced either partially or fully by wind energy. The second scenario occurs when an irrigation system is not presently installed, and a wind powered system could to be installed to pump irrigation water. Both of these situations could occur in Montana.

The percent of the current energy bill which can be eliminated by adding wind power is a major concern to a producer. This addition could involve the complete conversion of an existing system to wind power or the use of wind energy for supplementary power.

After the wind regime at the proposed site is evaluated, the system economics may be estimated. First the energy consumed by the pumping system should be plotted versus time based on historic data (eg. past electric bills). Expected power from the wind system can then be plotted versus time. Resemblance of the plots indicates that wind power substitution may be desirable. Having the cost of power bought and using the plots of power load and gain versus time, an economic assessment of the wind system can be made. If wind power offsets existing irrigation loads it may be desirable to also have a residential heating load that can be offset during the months when irrigation is not necessary.

A situation where the economics are assessed in a slightly different manner occurs when the wind powered system is used in the initial irrigation system development. In this case the amount of water that will be provided by the wind system is estimated from the quality of the wind regime, the wind machine parameters, and the water availability. The economic considerations then involve a cost-benefit analysis with benefits based on crop yield. If the increased revenue from the crop yields is enough to offset the cost of installing and maintaining the wind system then the wind system may be considered feasible.

The quantity and combinations of variables involved in assessing the economic feasibility of a wind powered irrigation system require that all evaluations be done on a site specific basis.

The most comprehensive assessment of the economics of wind energy for irrigation pumping has been developed and is available through the U.S. Department of Energy. (Lansford et.al., 1980)

Technical Feasibility

The technical feasibility of a wind powered irrigation system must be assessed in the preliminary design of the system. Past research and experience indicates that it is definitely possible to pump water using power generated from the wind. The problem lies in adapting this technology to a complete irrigation system.

Researchers in the field of wind powered water pumping have different opinions as to the state of wind powered pumping. Some researchers are enthusiastic concerning the technology of wind powered irrigation pumping. (Clark, et al., 1980) Others say the technology could stand much improvement in the way of reliability. (Patterson, 1986) It is my feeling that the technology exists and is available at the commercial level. The problem lies in adapting this technology on a site specific basis.

CHAPTER 5

WINDMILL-RESERVOIR SYSTEM MODELS

In this chapter, four site specific scenarios are discussed. The wind powered irrigation systems utilize mechanical windmills to pump water to a storage reservoir. The stored water is then routed into an appropriate irrigation system as needed based on crop irrigation requirements.

Site Selection

The sites for the four scenarios were chosen based on several parameters. These were; topography, applicability to cropping situations, availability of water source, availability of wind data, and land ownership. (Westesen, 1986)

Wind data sites were first chosen to provide a good geographic distribution of sites. The data from the wind site also had to be statistically valid and continuous. This eliminates errors due to poor data recovery.

Having the wind data sites, topographic maps were used to locate the actual field sites. Those sites that had rough and irregular topographies or ground slopes greater than three or four percent were eliminated. From the locations that were of adequate topography, the possible sites were narrowed down to those being on public land, and within one mile from the nearest water source. State or Federal land was used for these site scenarios to eliminate the need for interaction with the owners of private land. (Westesen, 1986)

Having chosen sites according to the above procedures, those with good soil characteristics were selected as the final field sites. The soil types were determined from the Montana Soil Surveys.

Since the sites were chosen based on information taken from maps and surveys which can be vague or misleading, it is possible that the actual sites may not be suitable for a farming operation. These sites are not suggested for actual implementations of wind powered irrigation systems, but are to be used solely for the models presented herein.

Methodology

The methodology used in the site specific scenarios may be broken down into a series of design problems:

1. Irrigation System Design
2. Wind Data Analysis
3. Sizing the Windmills and Reservoir, and Determining the Number of Windmills Needed
4. Earth Moving Calculations
5. Pump Sizing (backup and booster)
6. Bill of Materials
7. Economic Analysis

Irrigation System Design

The design procedures for each site differ with the irrigation system used. In all cases, the design procedures used are those specified by the Soil Conservation Service as outlined in the National Engineering Handbook, Section 15.

The irrigation system that is used on each site is determined by the crops that are appropriate at the site, the soil characteristics and the field slope. Guidelines for irrigation system selection are available in the SCS National Engineering Handbook.

For any given irrigation system there are several parameters that are crucial to the design of the system; the appropriate crops and crop water requirements, the soil type and slope considerations and, the field shape and size. (Hulsman, 1985)

The crops selected are those that have economic potential and are compatible with the climate at the site. (Dalton 1986) Having identified these crops, the irrigation requirements were determined via a computer program that John Dalton developed. The computer program uses the SCS TR-21 (Blaney-Criddle) method with adjustments for elevation differences. The soil type at each site was determined from the Montana Soil Survey maps and data. The ground slopes were determined by measuring the contour lines on the topographic maps. In actual design cases, soil samples should be evaluated for each site and a survey of the field area should be done to more accurately determine the field slopes.

The field size used in these scenarios is 40 acres, and the field shape used was a square to simplify design procedures. These 40 acre blocks may be expanded in a modular fashion to increase the total on-site acreage. (Westesen, 1986)

Sizing mainlines, laterals and manifolds was done either on the Rainbird slide rule, using the energy equation and continuity equation, or the Hazen-Williams equation. The Rainbird slide rule is an engineering aid that uses a nomogram technique to solve the equations relevant to irrigation system design. (Hulsman, 1985)

Wind Data Analysis

The wind data for each site is from the Montana Wind Energy Atlas. If the data in the Wind Energy Atlas included the Weibull parameters for the site, these values were used. For those sites at which the Weibull parameters were not presented, they were determined using the computer program given in Appendix 1, Figure 20.

Sizing the Windmills and Reservoir

The pumping and reservoir system consists of one or more water pumping windmills, a reservoir, and the pipeline connecting the two. The reservoirs must be lined, as the subsoil at each site is assumed unsuitable for use as a reservoir lining.

The methodology used in sizing the reservoir is centered around three basic relationships: the Weibull parameters, the relationship between wind speed and flow from the windmills, and the balance equation for reservoirs. The monthly net irrigation requirements of the crop are also used in the calculations. A computer program was developed for each site to expedite the calculations.

The computer program for each site must contain site specific data. The expected precipitation and evaporation for each site may be found in NOAA Climatological Data reports. The net crop water requirements are the irrigation requirements divided by the irrigation system efficiency. The Weibull parameters for each site are also included in the data statements of each program.

The computer program first prompts for an initial assumption of the rated flow from the windmills, and prompts for an initial reservoir surface area. The program then estimates the total monthly flow volume expected of the windmill. This is accomplished by calculating the expected frequency of each windspeed, f(ui) via the Weibull parameters. The flowrate from the windmill at that windspeed is then calculated. Then the number of hours per month is multiplied by the frequency of each windspeed and the flowrate at each windspeed. These products are then summed to provide an estimate of the total monthly flow volume from the windmills at the assumed rated flowrate.

The program then does a reservoir water balance on a monthly basis. The inflows to the reservoir are the flow from the windmill, and the precipitation at the site. The reservoir outflows are evaporation and the crop irrigation requirements. There are no seepage flows as the reservoir is to be lined. If at any time the resultant reservoir volume is less than zero, the calculations terminate and begin again using a larger rated flow from the windmills. This process is continued until the rated windmill flows are enough to maintain adequate reservoir volume throughout the irrigation season.

The relationship between windspeed and flowrates from the windmills was developed using the information provided by Southern Cross Ltd. of Australia as shown in Appendix 4, Table 27. Using this information, a regression analysis was performed to provide an accurate measure of the percent of rated flow as a function of windspeed. The resultant relationship is shown in Figure 1.

The computer program is first run, (run #1) with a preliminary estimate of the reservoir surface area. The program outputs the required rated flow that will keep the reservoir volume above zero at all times throughout the year. It is assumed that the system will be installed in the summer and is brought on-line in October. Bringing the system on-line in October reduces the pumping requirements of the windmills, because of the additional water storage