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WIND POWERED IRRIGATION IN KANSAS
A SYSTEM DYNAMICS APPROACH

by

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Document WIND POWERED IRRIGATION IN KANSAS
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CHAPTER I - INTRODUCTION

The amount of land area being farmed per person in the United States has been on the decline for the past several years. Yet today the people of America are eating better than ever before. This is due in part to the development of new strains of crops that reach maturity faster and give a higher yield than the old strains. But at the same time the amount of energy required per given area of farm land has increased. Larger, more powerful pieces of farm equipment are being used today than ever before. It is customarily the case that these machines are fueled by an oil product. It is estimated that in 1974 the equivalent of 487 million gallons of gasoline was consumed on the 86,000 farms in the state of Kansas alone (1). This fuel was consumed in the process of tillage and harvesting operations, irrigation, grain drying, marketing, business and management transportation, and poultry and livestock operations. The production of fertilizer, a large consumer of natural gas, is not included in the above estimates. Therefore, it should be clear that the American farm is very dependent on an available supply of oil product fuels.

Common sense indicates that the supply of oil will eventually be exhausted at the rate it is presently being consumed. Estimates of our remaining oil reserves range from 30-50 years (2,3). Many industries are today converting to electricity produced by coal or nuclear powered plants. But there does not appear to be a method available at the present time to allow a conversion from petroleum fuels to electricity for the mobile high energy demands of most farm equipment.

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The conversion from petroleum based fuels to a more plentiful energy supply for even only a few farm operations would help the overall situation. If, for example, irrigation water could be pumped without having to deplete the limited supply of natural gas (the fuel used on the majority of midwestern farms for irrigation pumps) there would be that much natural gas available for other uses. The simple conversion to an electric pump might help, but most of the electrical power generated in the midwest still depends on petroleum fuel supplies. So, an alternative source of energy that could easily be used to pump irrigation water without depleting limited fossil fuels would be a better solution.

The use of methane derived from animal wastes has been proposed as a substitute for the natural gas presently being used. So has hydrogen produced electrolytically at the farm site using electrical energy derived from solar sources (and possibly from conventional coal and nuclear fueled generating stations during off peak periods). This paper is concerned with the evaluation of two alternative energy systems for pumping irrigation water. The first method would utilize wind power coupled mechanically to the pump. The second method would use wind power to generate electricity, electricity to produce hydrogen, and hydrogen to fuel the pumps.

An extension of the second method could eventually lead to production of hydrogen on a large scale and the use of hydrogen as the basic fuel on the farm of the future.

There are many approaches that could be taken in developing an "optimal" system for use on a farm. There are many different

types of windmills currently available at a variety of prices. If hydrogen is going to be included in the system, some sort of storage facility should be considered for the hydrogen produced during low energy demand times. Little actual optimization work has been done on systems similar to those considered in this paper. By considering the system as simply as possible, linear programming could be applied to minimize the total cost involved in establishing such a system. By viewing the problem from different points of view, dynamic programming, stochastic programming, or multi-objective decision problem techniques could be utilized. A "system dynamics" approach is taken in this paper. Rather than attempting to satisfy certain objective functions subject to various constraints, as would be the case with the techniques already mentioned, system dynamics is used here to model a proposed system and to evaluate its performance. From these findings, changes in the model of the proposed system can be made. By continuing in this fashion, a "best" design can be forced to emerge.

CHAPTER 2 - GENERAL CONCEPTS OF SYSTEM DYNAMICS

2.1 BACKGROUND

When Vannevar Bush built his differential analyzer in the 1930's to solve the equations of simple engineering problems, he also laid the ground work for a powerful approach to understanding the dynamics of complex systems. This ground work eventually lead to the development of "system dynamics". The differential analyzer, set up in accordance to the equations that described the system under investigation, became a simulator tracing the dynamic behavior of the system. It was during this same period in time that Norbert Wiener developed his concepts of feedback systems that were later labeled "cybernetics". Some of the first introductory papers in the field of feedback control systems (soon to be coined "servomechanisms") were written by Harold L. Hazen. Gordon S. Grown created the Servomechanisms Laboratory in the 1940's. It was here that the theory of feedback systems was first expanded, taught, recorded, and introduced to the world on a large scale. Digital computers were first used for system simulators in the 1950's at the Digital Computer Laboratory and Division 6 of the Lincoln Laboratory under the direction of Jay W. Forrester. Since 1956 Professor Forrester and a group of associates at the M.I.T. Alfred P. Sloan School of Management have extended the concepts of system dynamics to cope with the great complexity of social systems (2).

For many years the modeling of feedback-loop systems has been known as "industrial dynamics". But with the application to important areas outside of the industrial structure, the name "system dynamics" has come into more general use. Applications

of system dynamics have been made in corporate policy, dynamics of diabetes as a medical system, social forces affecting drug addiction, and the behavior of research and development organizations to list just a few (4,5,6,7).

2.2 SYSTEMS

Almost anything can be thought of as a system. Man lives in a social system. Through his scientific research he has uncovered some of nature's systems structures. Through his technological breakthroughs he has created complex physical systems. But, he still does not fully understand the principles governing the behavior of systems.

As used here, a "system" is a group of parts that operate together with a common goal. A school is a system for education. Panting or shivering in a dog is a system for regulating body temperature. Communication satellites in space provide a system by which communication between almost any two points on earth is instantaneously possible.

With systems being common and easily defined, why is it that man has been so late in grasping the concepts and principles of systems? Jay W. Forrester has pointed out three possible answers to this question (8). First of all, until recently there has really been no need for understanding the nature of systems. The systems that primitive man were exposed to were mostly those of nature and were accepted as being divinely given and beyond comprehension and control. In order to survive, man adapted himself to these natural systems and change came slowly, usually through evolution rather than desire.

Secondly, many systems did not seem to possess any meaning

or general theory. As man's societies emerged and systems of trade, economics, and politics began to evolve, man was unable to distinguish all of the interactions and principles due to the overall complexity of the systems. And finally, even after man began to seek the underlying principles of systems, these principles were so obscure that they were undetected. During the last century it has become clear that the barrier to uncovering the principles of systems was not the absence of general concepts. Rather, it was the difficulty of expressing these principles. Mathematics have only relatively recently reached a level such as to be adequate for handling the essential realities of some of man's more complex systems.

Learning from past experience is difficult without a structure to interrelate facts and observations. Jerome S. Bruner of Harvard (9) has argued well the importance of structure in education.

"Grasping the structure of a subject is understanding it in a way that permits many other things to be related to it meaningfully. To learn structure, in short, is to learn how things are related.....good teaching that emphasizes the structure of a subject is probably even more valuable for the less able student than for the gifted one, for it is the former rather than the latter who is most easily thrown off the track..."

2.3 SYSTEMS - OPEN AND FEEDBACK

All systems can be classified as either open systems or closed systems. Closed systems are also called "feedback"

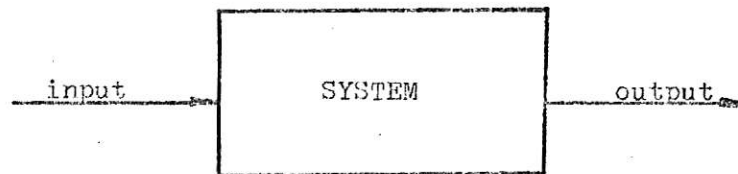
systems. The difference between an open system and a feedback system is that in a feedback system the behavior is influenced by its own past behavior whereas an open system is unaware of its past behavior. A watch, taken by itself, is not aware of its inaccuracies and can not correct itself, thus it may be thought of as an open system. But, if you include the owner of the watch in the system and the owner continuously corrects the inaccuracies in the watch, the system may be thought of as a closed (feedback) system. An open system and a feedback system are skematically illustrated in Figure 2.3.1.

Whether a system is classified as an open system or a feedback system is more dependent on the viewpoint of the observer defining the purpose of the system than the particular assembly of parts. A broad purpose may be seen as a large feedback system consisting of several small subsystems, each with its own purpose. Each subsystem may then in turn be considered an open or a feedback system.

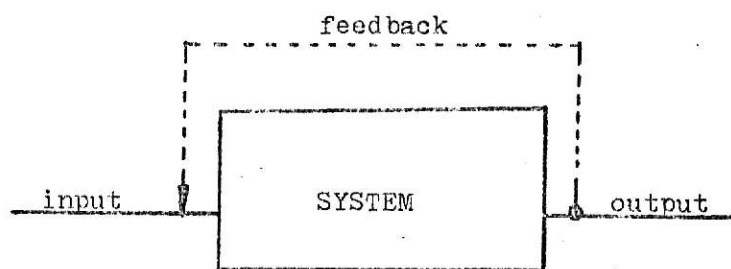
The basic structure of a feedback loop appears in Figure 2.3.2. The feedback loop forms a closed path starting at a decision that controls an action, passing through the level (state or condition) of the system, the information about the level of the system, and terminating at the decision-making point. The available information, at any point in time, is the basis for the current decision that controls the action of the loop. It is this action which alters the level of the system. The level of the system generates information about the system. This information may be delayed or erroneous. It is this information (apparent level) of the system, though, that is used as the basis for the decision process.

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(a) Open System



(b) Feedback System

Figure 2.3.1 - Schematic of (a) Open System
(b) Feedback System

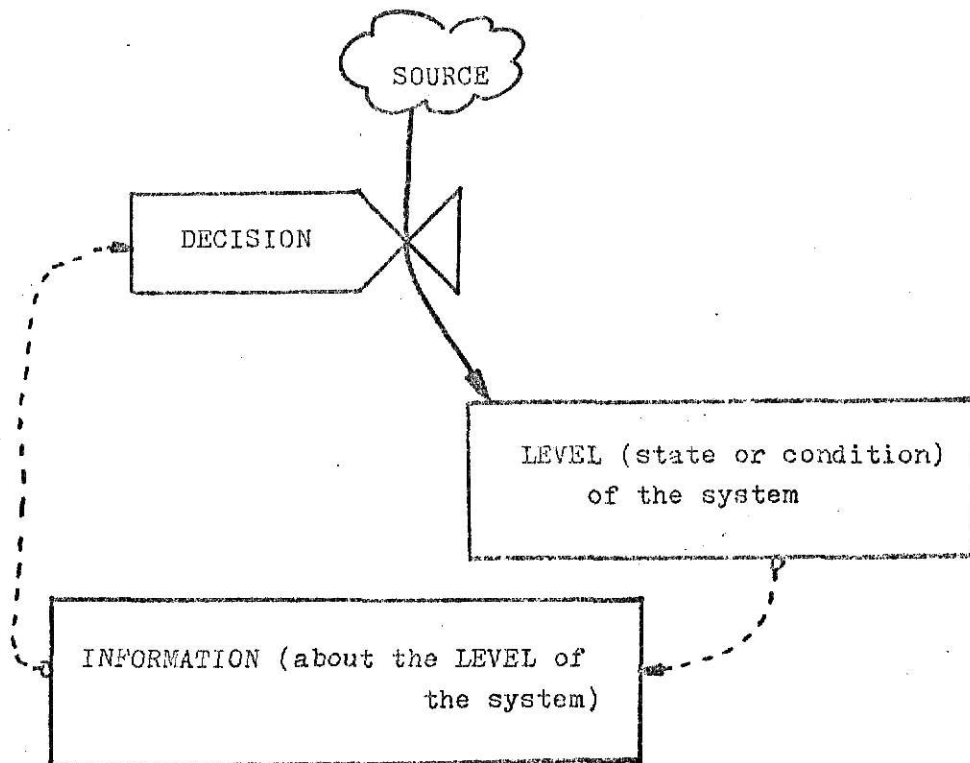


Figure 2.3.2 - Feedback Loop

Feedback loops fall into two categories; positive feedback and negative feedback.

In a positive feedback loop, the result of the action generates still greater action, thus generating a growth process. Positive feedback loops are relatively rare in nature. The compounding of interest on money in a bank account is an example of positive feedback (see Figure 2.3.3). The amount of money in the account at a given point in time determines the amount of interest the account earns; the greater the amount of money, the greater the amount of interest earned. The amount of money is thus increased continuously by the interest paid and the amount of interest paid increases continuously due to the increasing amount of money in the account. Population also generally follows the rules of a positive feedback loop. A single cell splits into two cells. These two cells then each split resulting in a total of four cells. The more cells there are before splitting the more there will be after splitting.

In a negative feedback loop, the action strives to maintain a specific level. A thermostat in a building is an example of a negative feedback loop (see Figure 2.3.4). The specific level is the temperature set on the thermostat. If the room temperature drops below this level, the heater comes on until the room temperature reaches the specified level at which time the heater is shut off. If it should become too warm in the room, the air conditioner is switched on until the temperature is reduced to the specified level. Negative feedback loops are quite common in nature. The thermoregulation of the human body follows closely that of the building thermostat already

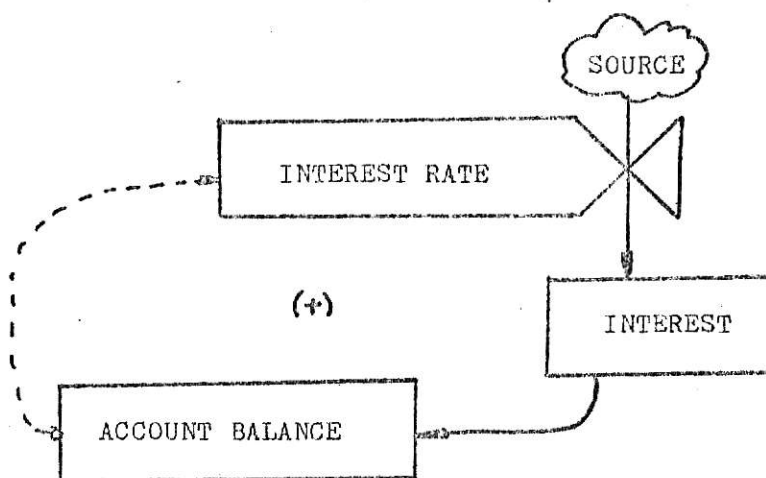


Figure 2.3.3 - Positive Feedback Loop

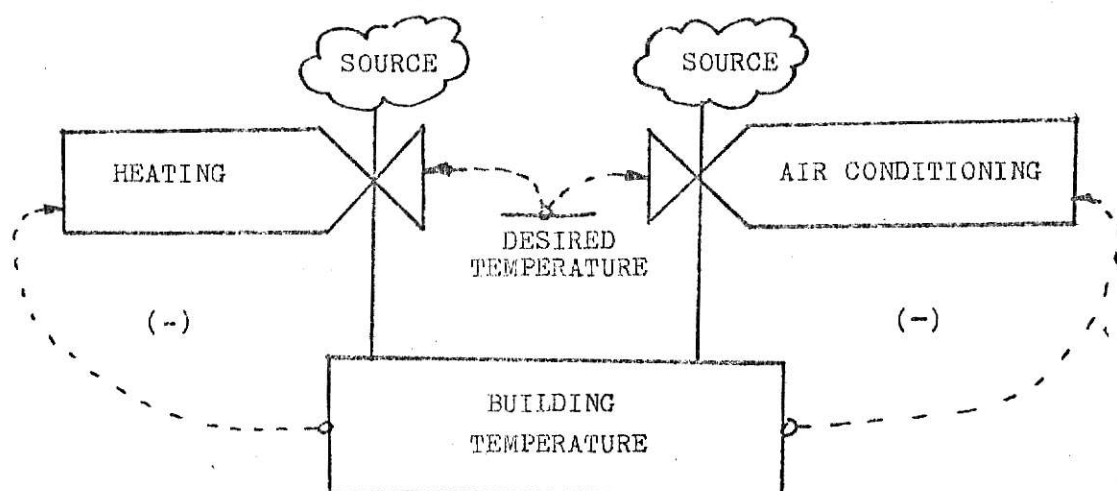


Figure 2.3.4 - Negative Feedback Loop

discussed with perspiration acting to cool the body when over heated and shivering and body metabolism acting to warm the body when it is chilled.

The concept of information-feedback loops, both positive and negative, provides a basis for attempting to understand and interpret the behavior of all systems. Feedback theory has successfully been applied to mechanical and electrical systems over the past 50 years. During the past 15 years these same principles have been applied to social systems as well.

2.4 MODELS

A model is a substitute for an object, situation, or system. It can be expressed in many forms. Concrete models of cars, airplanes, and ships are common toys on which children often focus imaginative adventures. Concrete models of various objects also aid scientists and engineers in wind tunnel tests and in visualizing space and arrangements in architectural designs and in community development. But even more common than concrete models are abstract models. Any set of rules and relationships that describe an object, situation, or system is an abstract model of that object, situation, or system. Our mental processes use concepts of a model which we manipulate into new arrangements. These mental concepts are actually an abstract model of the real system. These abstract mental models are subject to filtering, distortions, and delays as a result of our individual perceptions and experiences. Mathematical simulation models are a special class of abstract models.

The human mind is capable of absorbing, adapting, building, and using fairly complex models of various systems. But the

human mind is subject to certain inherent drawbacks. The effects of these drawbacks are amplified when the system becomes very complex and dynamic (changing with time) behavior is introduced.

(1) Mental models are often ill defined. Interpretations and assumptions about real-life situations are continuously changing resulting in changes in what the models imply and often resulting in internal mental contradictions.

(2) It is often not possible to review how a mental model was formulated. Consequently, assumptions are often not clearly identified.

(3) Formation of a mental model is an individual experience subject to individual prejudices and personal feelings. As a result of this, mental models are not easily communicated to others. Two parties may feel they both have the same mental model of a system but in actuality the two models may differ. These differences may be slight but they can often lead to heated disagreements and false conclusions.

(4) The capacity of the human mind for absorbing and manipulating ideas is extremely vast but it is limited. When one tries to manipulate complex dynamic mental models, confusion is usually the result. The unaided human mind is just not adequate for constructing and manipulating dynamic models.

System dynamics provide a foundation for translating mental models into mathematical models which can, with the aid of a computer, be manipulated with relative ease. By translating mental models into mathematical models most of the problems associated with mental models are alleviated. With all models expressed in the same terminology confusion about terms, assump-

tions, and communication of models is reduced.

Models should not be judged against imaginary perfection. Rather, they should be judged in terms of how well they describe the system compared to existing models. The certainty with which models show the correct time-varying results of the model statements compared to the same conclusion reached in extending mental models is another base on which to judge the mathematical model. Models should then be judged not on an absolute scale that applauds or condemns them but rather on a relative scale that approves them if they satisfactorily clarify the known facts about a system. One model is better than another only if it better communicates the mental and physical statements of the system with a higher degree of reliability.

2.5 SIMULATION TECHNIQUES vs ANALYTICAL SOLUTIONS

Simulation is an experimental attempt to represent the behavior of systems. It consists of a step-by-step approach to "simulate" the dynamic (time varying) behavior of the real system the model represents. An analytic solution expresses the system's condition in terms of any future time, not just in terms of short time intervals between computations as in a simulation approach. In addition, the form of an analytic solution can tell much about the general nature of the response of the system without having to carry out any numeric computations.

For example, consider a simplified inventory control system (assuming no delay between ordering of goods and their receipt into inventory). Figure 2.5.1 shows the simple first-order negative feedback loop that models the system. The "goal" of the system modeled is to maintain the desired inventory DI which is a constant. Assume that merchandise can be either ordered or returned to the manufacturer; that is, the order rate OR can be either positive or negative. In attempting to bring the actual inventory toward the desired inventory, the order rate must increase positively as inventory falls and negatively as inventory increases beyond the desired inventory.

Assuming a linear relationship for the ordering rate, the system could be described in equation form as:

$$OR = \frac{1}{AT} (DI - I)$$

where OR - order rate (units/week)

AT - adjustment time (weeks)

DI - desired inventory (units)

I - inventory (units)

The adjustment time AT factor is included to make the equation dimensionally balanced and by being a constant establishes the linearity of the system. Assume that the desired inventory DI is 6000 units and that the adjustment time (the time that any current order rate would require to correct the inventory) is 5 weeks. The equation describing the system then becomes:

$$OR = \frac{1}{5} (6000 - I)$$

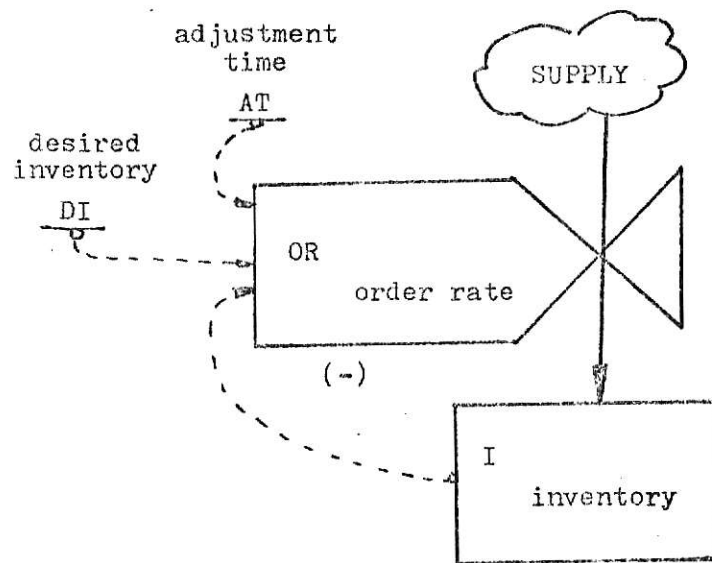


Figure 2.5.1 - Simple Inventory System

Assuming also that the initial inventory is 1000 units, the initial order rate becomes 1000. Now, if this order rate is in effect for 2 weeks before a new order rate is calculated, there will be 2000 units added to inventory which then becomes 3000 units. This new value of I results in a new order rate of 600 units per week. By continuing in this fashion it is possible to simulate the dynamic behavior of the system through time. Proceeding with these calculations yields the results shown in Table 2.5.1. These results are shown plotted in Figure 2.5.2. This demonstrates the simulation approach to a solution. Now consider the analytical approach to the same problem.

Due to the relatively simple structure of this system, it is possible to arrive at an analytic solution.

$$OR_n = \frac{1}{AT} (DI - I_n) \quad \text{EQ(2-1)}$$

$$I_{n+1} = I_n + \frac{1}{AT} (DI - I_n)(\text{time interval}) \quad \text{EQ(2-2)}$$

where the subscripts n and $n+1$ denote the present and next time interval values respectively. Assuming that the time interval between successive simulation computations has become vanishingly small;

$$I_{n+1} - I_n = dI = \frac{1}{AT} (DI - I_n) dt \quad \text{EQ(2-3)}$$

$$\frac{dI}{dt} = \frac{1}{AT} (DI - I) \quad \text{EQ(2-4)}$$

$$\frac{dI}{dt} + \frac{1}{AT} (I) = \frac{1}{AT} (DI) \quad \text{EQ(2-5)}$$

Equation 2-5 is a first order differential equation whose solution yields:

Table 2.5.1
Computation of Inventory

<u>Time (weeks)</u>	<u>Inventory (units)</u>	<u>Order Rate (units/week)</u>
0	1000	1000
2	3000	600
4	4200	360
6	4920	216
8	5352	130
10	5611	78
12	5767	47
14	5860	28
16	5916	17
18	5950	10
20	5970	6
22	5982	4
24	5989	2

$$I(t) = A_0 e^{-t/AT} + DI \quad \text{EQ(2-6)}$$

Assuming an initial inventory of I_0 it is possible to determine the value of the constant A_0 .

$$I(0) = I_0 = A_0 + DI \quad \text{EQ(2-7)}$$

$$A_0 = I_0 - DI \quad \text{EQ(2-8)}$$

Therefore,

$$I(t) = (I_0 - DI)e^{-t/AT} + DI \quad \text{EQ(2-9)}$$

Substituting in the constant values assumed in the simulation solution:

$$I = 6000 - 5000 e^{-t/5}$$

By substituting any time (in weeks) for t , the inventory at that time can be computed directly without going through the step-by-step calculations required in the simulation procedure. The negative exponential nature of the system shown in the plot of the simulation solution (Figure 2.5.2) is obvious from the form of the analytical solution.

Since the analytic solution of a system's behavior contains so much information and since it allows direct computation of the condition of a system at any specified time, it might be presumed that an analytic solution should always be obtained for every system under study. However, this is not possible. Present mathematical procedures do not permit formulation of an analytical solution for many complex systems. When an analytical solution is beyond the scope of today's mathematics, simulation techniques are used to model the dynamic behavior of

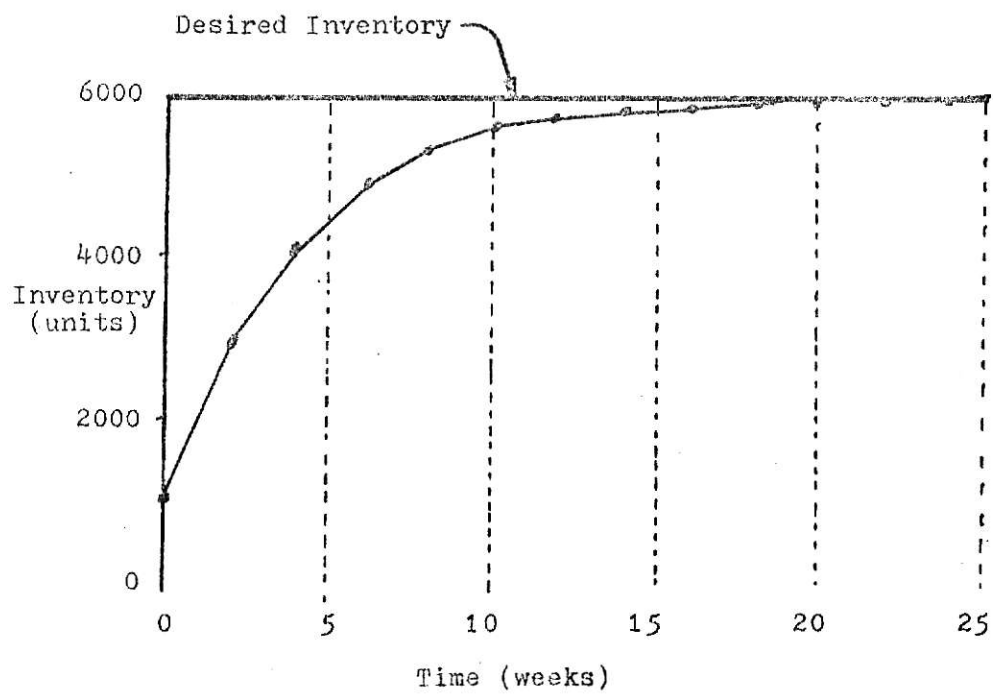


Figure 2.5.2 - Inventory System Response

the system.

The use of simulation has been limited in the past due to the costs and time involved. Navigation tables dating from the 1600's that were computed using simulation techniques show the relatively long history of the simulation technique (8). It was not until about 1955, when computation could first be carried out on digital computers, that the time and costs associated with simulation techniques were reduced to the point where simulation solutions were not only more easily reached than analytic solutions but were inexpensive as well. Today, with the aid of high speed electronic computers, a lengthy simulation of a complex system takes only a few seconds and costs only a few cents.

2.6 FLOW DIAGRAMS, COMPUTATIONS, AND EQUATIONS

Flow Diagrams. "A picture is worth a thousand words", or equations as the case may be. Often it is easier to grasp the idea of the workings of a system if that system can be diagrammed effectively. That is the goal of flow diagramming. Whereas the equations of a system focus on the composition of the elements that make up the system, the flow diagram should show how these elements are interrelated to include feedback loops and how they effect the system.

The Industrial Dynamics Research Group at the M.I.T. Sloan School of Management has developed a set of standard flow diagram symbols for dynamic models (10).

LEVELS - Levels are represented by a rectangle. Calculation of all levels involves integration of incoming and outgoing data that are controlled by rates. The letter group of the represented

portion of the system, the full name of the represented portion of the system, and the equation number as a cross reference to the formal definition of the system model are included in the rectangle (see Figure 2.6.1).

RATES - Rate equations of a system model are the policy statements and define the flow streams in the system. The only input to a rate is information and the only output is in the form of controlling flows. A symbolic valve is used to represent a rate due to this type of "controlling" output. The letter group of the represented portion of the system, the full name of the represented portion of the system, the equation number as a cross reference to the formal system model, and the information inputs on which the rate depends should be shown with the rate symbol (see Figure 2.6.2).

AUXILIARY VARIABLES - Auxiliary variables lie in the flow channels between levels and rates. They are actually parts of the rates but are subdivided separately because they represent independently meaning concepts of interest or because they make the computation of rates less complex. A circle is the symbol for an auxiliary variable and should include the abbreviation of the variable name, the variable name, the equation number as a cross reference to the formal model of the system, and the input and output flows (see Figure 2.6.3).

FLOW LINES - Six types of flows are shown in Figure 2.6.4.

Use of the appropriate flow will eliminate the need to label individual flows (with respect to type) within the flow diagram of the system.

INFORMATION TAKE-OFF - A small circle at the information source



Figure 2.6.1 - Flow Diagram for a Level

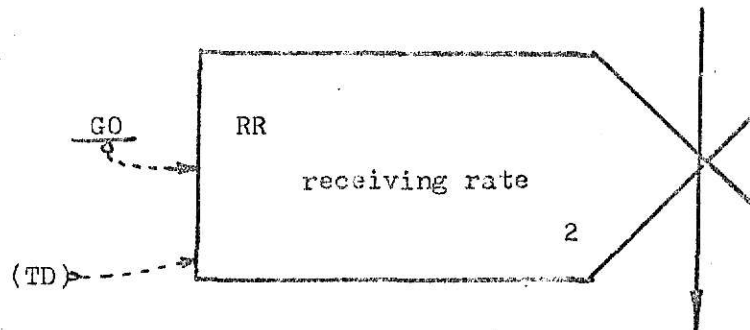


Figure 2.6.2 - Flow Diagram for a Rate

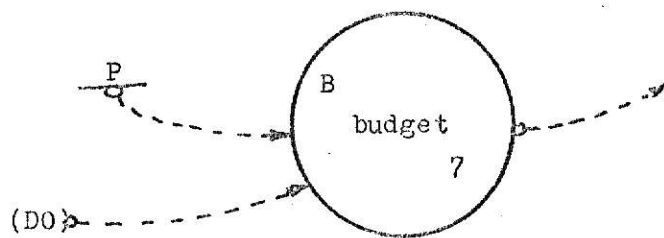


Figure 2.6.3 - Flow Diagram for an Auxiliary

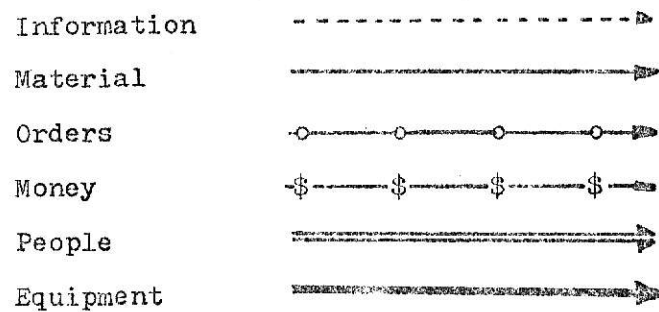


Figure 2.6.4 - Flow Lines

and the information flow line represents information take-off. This represents the removal of information about an element of the system without affecting that element. In some instances, though, the information taken from a flow, rate, level, or auxiliary will be used to change that flow, rate, level, or auxiliary (see Figure 2.6.5).

SYSTEM PARAMETERS AND CONSTANTS - System parameters and other constants do not change within a given simulation but may change between successive simulations. Figure 2.6.6 shows the symbol for a constant.

SOURCES AND SINKS - In some cases, the source or termination of a flow has no influence on the system itself. In this case it is assumed that the source or sink is "infinite". Such a source can never be exhausted and such a sink can never become full. Figure 2.6.7 shows the symbol for a source and a sink. Such symbols have no dynamic characteristics.

OTHER SYMBOLS - Logic functions, delays, table functions, and other special functions have special flow diagram symbols. These are explained in further detail in Appendix 2 as well as in (8,10,11,12).

Computations. Simulation is a step-by-step computation based on a set of equations describing a given system. This step-by-step procedure calls for some sort of definite computing sequence. System dynamics models contain only two basic types of equations; levels and rates. Other types of equations include auxiliary and supplementary equations, constants, and initial value

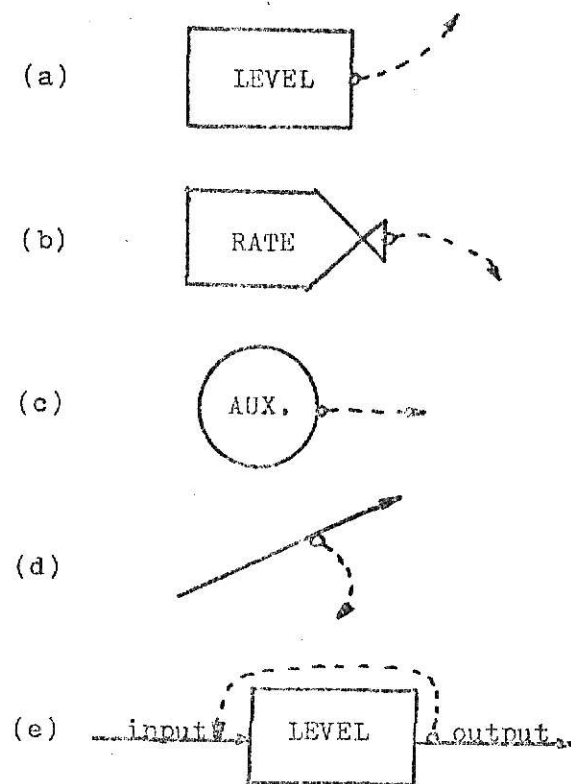


Figure 2.6.5 - Information Take-Off from

- (a) level
- (b) rate
- (c) auxiliary
- (d) material flow
- (e) information about the output of a level affecting the input to the same level

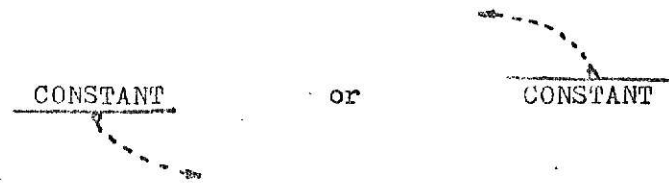


Figure 2.6.6 - Flow Diagram for a System Parameter or a Constant



Figure 2.6.7 - Flow Diagram for a Source and a Sink

equations. The time step size DT used in carrying out the step-by-step calculations of a simulation is also very important.

Time can be broken into three distinct sectors; past, present, and future. The time notation convention utilized in system dynamics is illustrated in Figure 2.6.9. The "present" instant in time is designated by 'K', an instant one DT time interval in the past by 'J', and an instant one DT time interval in the future by 'L'. Values for levels at 'K' can be calculated from their values at 'J' (from previous calculations) and from the value of the rates involved during the interval 'JK'. Given this information, the values of the rates during the next time period 'KL' can be calculated. This is the situation shown in Figure 2.6.8.

The sequence of calculations may now be repeated by advancing the time indicators, J, K, and L, by one DT . This is shown in Figure 2.6.9. All calculations are carried out exactly the same as before. The time interval that was previously 'KL' is now 'JK'. This process is continued until the simulation has been carried as far as desired.

Equations. The variables and constants of a system are represented in equation form by symbols (or abbreviations). A standardized style of establishing these abbreviations is essential for practical purposes. A symbol (or abbreviation) for a variable or constant in a system consists of up to seven characters, the first being alphabetic. All variables are followed by a period and a time postscript. Levels and auxiliary variables carry a single letter postscript indicating the

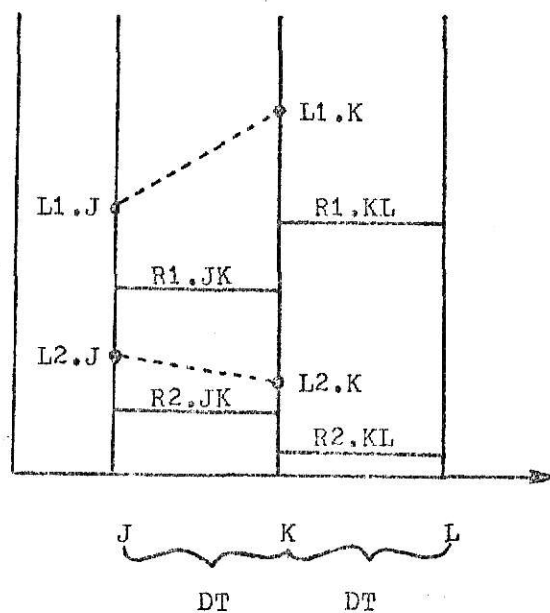


Figure 2.6.8 - Computation Sequence

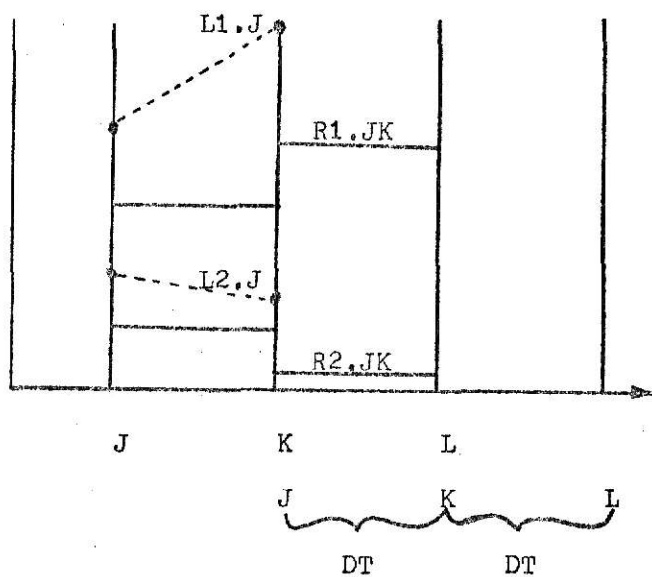


Figure 2.6.9 - Computation Sequence Extended

point in time for which the value applies. Rates carry a two letter postscript indicating the time interval over which they apply. Constants are characterized by no postscript.

LEVEL EQUATIONS - A level equation represents a reservoir (or accumulator) that accumulates the rates of flow that flow into and out of the reservoir. A new value is calculated by adding to or subtracting from the previous value the flows that have occurred during the DT time interval. The level equation format is given below.

$$L \quad L.K=L.J+(DT)(RIN.JK-ROUT.JK)$$

where

L - level equation

L.K - value of L computed at K (units)

L.J - value of L from previous time period J (units)

DT - length of time interval

RIN.JK - rate into L during interval JK (units/time)

ROUT.JK - rate out of L during interval JK (units/time)

The level equation is the only equation type that contains the time interval DT notation. Any number of rates may be added or subtracted from the level at one time.

The level equation performs the process of integration. The above equation could be written in the notation of calculus and differential equations as

$$L = L_0 + \int_0^t (RIN - ROUT) dt$$

Level equations are represented by the letter "L".

RATE EQUATIONS -- Rate equations define how flows within a system are controlled. System levels and constants provide the input to rates and rates in turn control the flows to, from, or between levels. The format of the rate equation is:

$$R \quad R.KL = f(\text{levels and constants of the system})$$

Rate equations are denoted by the letter "R".

AUXILIARY EQUATIONS -- Often a rate equation will be subdivided to enhance its meaning or to separate an intermediate value of interest. This is accomplished by the use of auxiliary equations. Since auxiliary equations express the value of a particular quantity at a point in time, they are followed by either "J" or "K" time subscripts. The use of auxiliary equations is illustrated below:

$$R \quad OR.KL = \frac{1}{AT}(DI-I.K)$$

$$A \quad I.K = Q.K/CC$$

$$A \quad Q.K = SAP/RP.K$$

Auxiliary equations are designated by the letter "A".

SUPPLEMENTARY EQUATIONS -- Supplementary equations define variables that are not actually variables in the system, but which contain information which it is desired to have printed or plotted. These variables are then used only in printing and plotting instructions.

INITIAL VALUE EQUATIONS -- All levels must have their initial values specified before a simulation can begin. These values are necessary for determining the flow rates over the first time interval (0 - DT). These equations are designated by the letter "N".

CONSTANTS - Constant equations are designated by the letter "C".
A constant contains no time postscript since it does not change
with time.

CHAPTER 3 - THE IRRIGATION SYSTEMS - STRUCTURE AND REQUIREMENTS

3.1 A GENERAL OVERVIEW

The energy of the wind has been harnessed for hundreds of years in Europe. Since the late 1800's the wind has been used to pump water for livestock throughout the plains states of America. It is a coincidence that the areas that seem in the most need of power for crop irrigation are also the areas richest in wind power. Therefore, it is often asked; Why not drive irrigation systems with wind power? (13). It is generally accepted that it can be done. But no one has yet devised and tested successfully a system that will solve the economic and technical problems which must be solved before widespread use of wind power for irrigation can become a reality. There seems to be almost a feeling of impatience centering around this problem. If the Dutch could pump the polders dry with wind power 400 years ago, why can't we irrigate with wind power today? The problem of cost-benefit seems to be of major concern today. We must be careful not to spend more for irrigation than a crop is worth. The use of system dynamics as a tool for evaluating various proposed systems has not been explored as far as the author can determine.

The midwest is the bread basket of the United States, and the United States is the bread basket of the world. The western plains of the midwest are also rich in available wind energy. It is in this area, then, that the proposed wind powered irrigation systems (WPI) are considered.

1965 wind data from the U.S. Weather Bureau Office in Dodge City, Kansas, is used in the simulation of the two proposed

systems. 1965 wind data is used because it tends to be a "typical" year. The summer months during which irrigation will be taking place have average wind velocities within one half a standard deviation of a 25 year average for the area. The other nine months each have average wind velocities within two standard deviations of a 25 year average. Wind data were recorded every 3 hours. The data was obtained at a height of 6 meters above the terrain.

The WPI systems are designed to provide energy to irrigate 160 acres with 6 to 8 acre-inches of water per month during June, July, and August. The water table is assumed to be at 200 feet.

3.2 MODEL STRUCTURE - OPTION 1

Introduction. A schematic of Option 1 appears in Figure 3.2.1.

In this system, the wind turns a wind turbine (windmill) which is coupled to a flywheel through a gear box. The energy in the wind is directly related to the velocity of the wind. But the wind does not blow at a steady speed for more than a few seconds at a time. So the flywheel acts as a buffer to even out the high and low wind periods and it also serves to store a certain amount of energy for use when the wind is not blowing.

The energy in the flywheel is passed through a transmission to a mechanical pump where it does the work of pumping the irrigation water. A farm tractor provides a back up for those periods when the wind is not blowing and the flywheel's stored energy is low. Each component in the system has its own efficiency, η_i .

A casual loop diagram of Option 1 is shown in Figure 3.2.2 and the DYNAMO flow diagram of the model is shown in Figure 3.2.3.

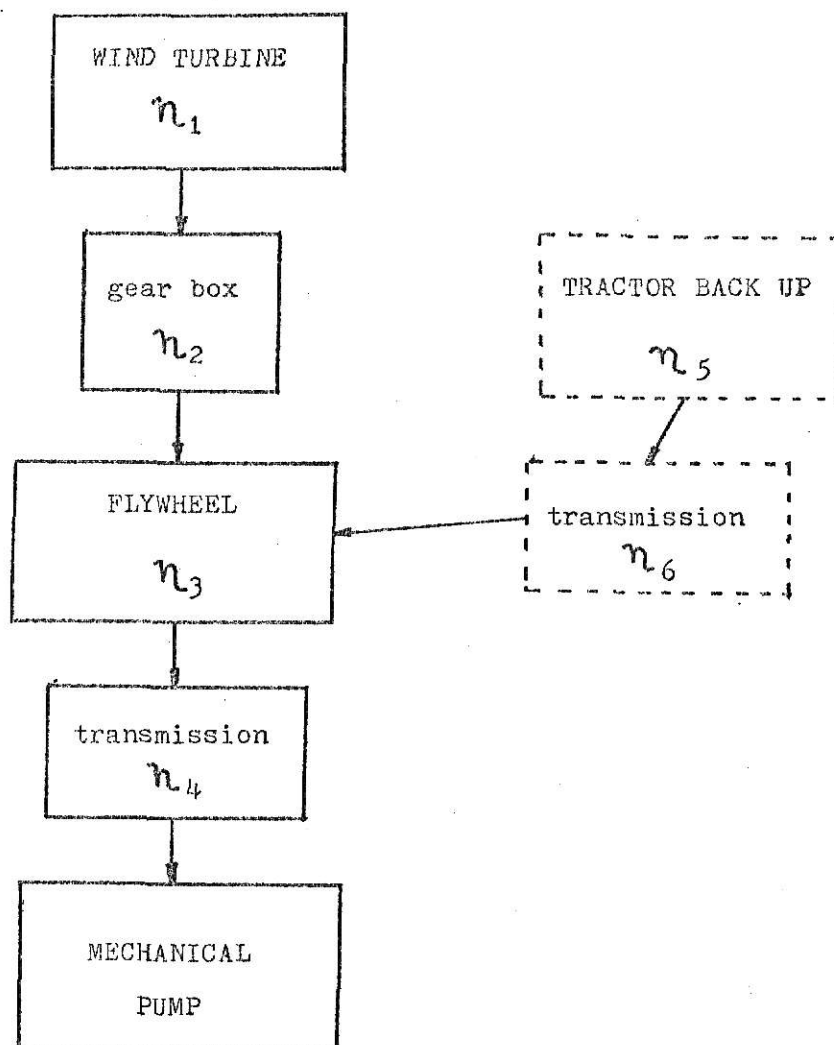


Figure 3.2.1 - Schematic of Option 1

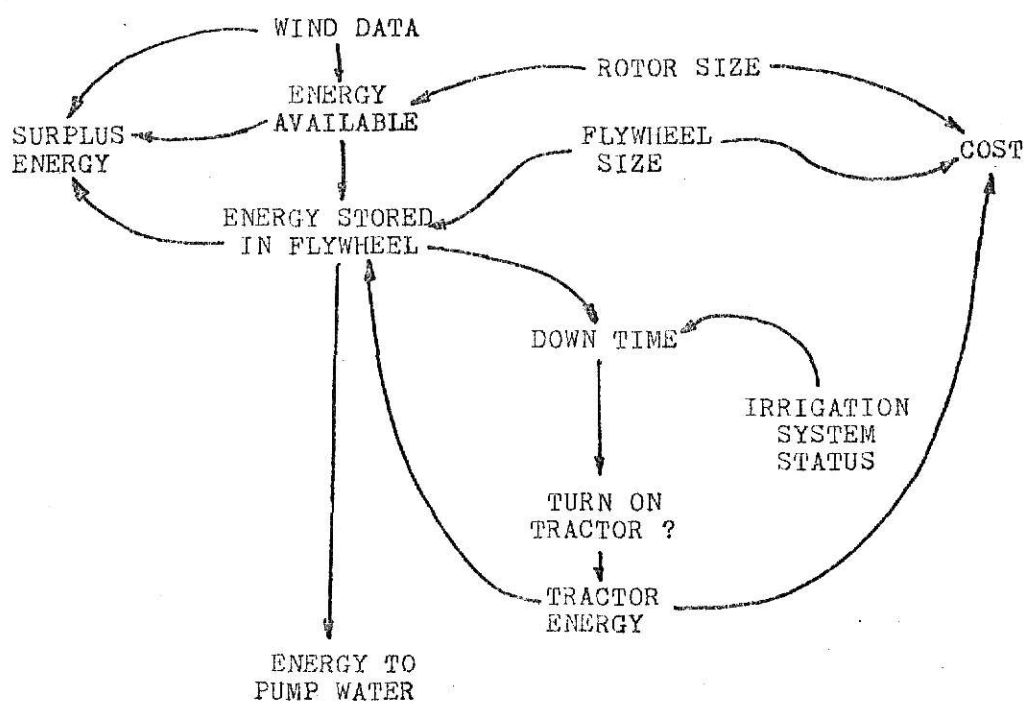


Figure 3.2.2 - Casual Loop Diagram of Option 1

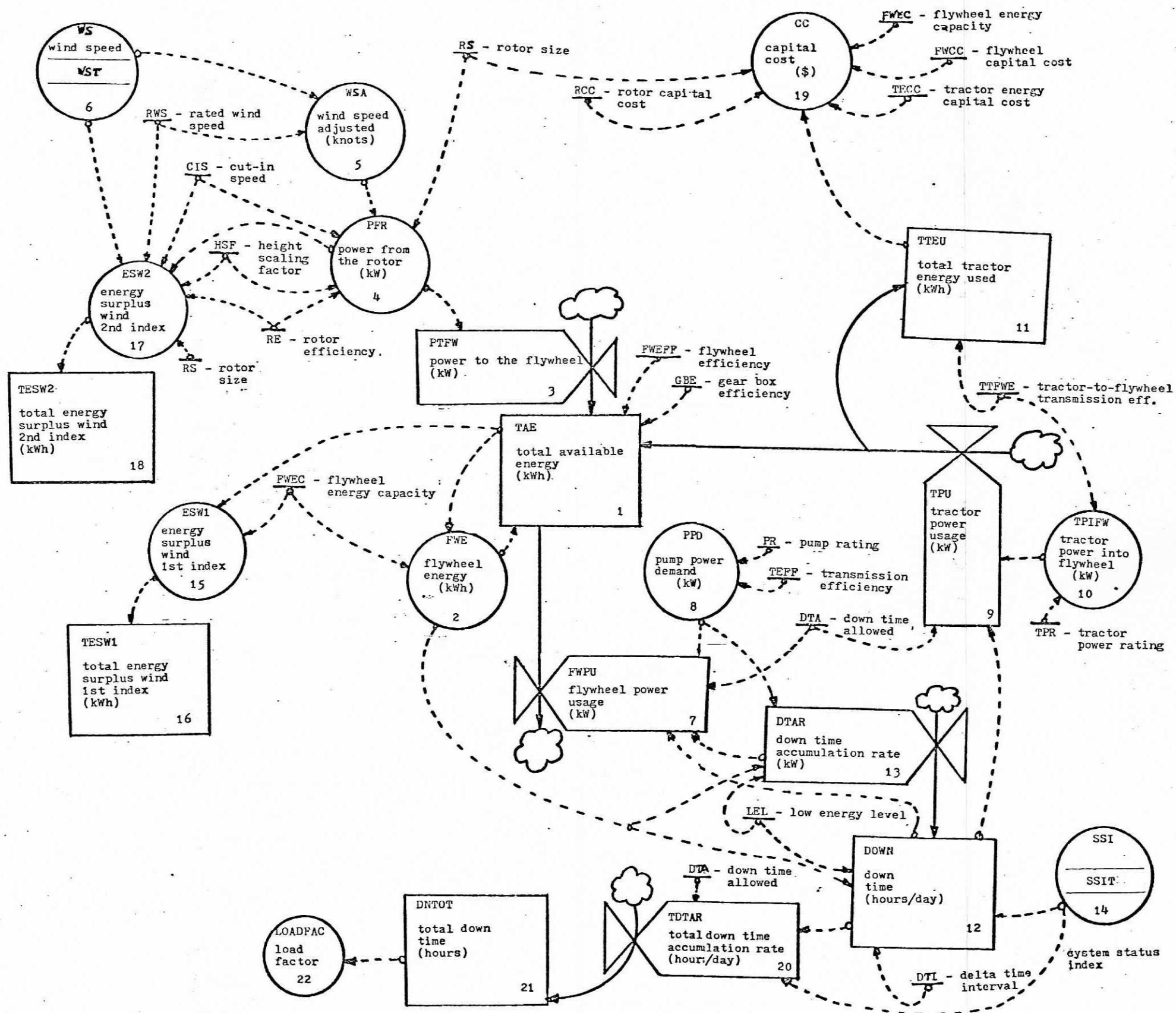


Figure 3.2.3 - Flow Diagram of Option 1

System Levels. There are six levels in Option 1. Total available energy TAE is the total amount of energy available at any point in time.

Total energy surplus (wind) 1st index TESW1 is a level which accumulates and keeps track of wind energy that is available from the rotor but can not be put to use immediately or stored in the flywheel for future use. This surplus energy occurs when the flywheel storage is full but the wind is still blowing. TESW1 is used in evaluating the rotor and flywheel combination. A large TESW1 would indicate that the rotor is too large or that the flywheel is too small.

Total energy surplus (wind) 2nd index TESW2 is a level which accumulates and keeps track of wind energy that can not be generated due to the rated wind speed RWS of the system. Suppose, for example, that the rated wind speed of the system is 10 knots. The energy available from the wind is directly proportional to the cube of the wind speed. So as the wind speed increases from 5 knots to 7 knots to 10 knots the system will be able to extract more and more energy from the wind. But for any wind speed greater than 10 knots the energy extracted by the system will be the same as at 10 knots. Thus, with the wind blowing at 12 knots, only 10 knots worth of energy can be extracted. TESW2 keeps track of the difference between this amount of energy and the amount of energy available were the system able to extract all 12 knots worth of energy. If simulation of a system results in a large TESW2 then the rated wind speed RWS should be increased. There is a limit to how large RWS may become depending on the system. Suppose the system has a mechanical device coupled directly to the mechanical

output of the rotor and that the rotor is rated at 10 knots. Assume also that the rotor will begin to extract energy from the wind at about 4 knots. Then, at 4.64 knots the mechanical device coupled to the rotor will be operating at only 10% of its rating. If RWS is increased to 21.54 knots then the device would be operating at only 1% of its rating at 4.64 knots. This is why RWS must be limited. A range of 10 to 15 knots between the speed at which the rotor begins to extract energy and the rated wind speed is approximately as large as most mechanical devices will tolerate and still operate.

The system described by Option 1 could theoretically pump irrigation water 24 hours a day, every day, for the three summer months; June, July, and August. But such a constraint would not correctly describe the physical situation and would cost a considerable amount. If the system were to be pumping 24 hours everyday, more water would be available than would be needed. More realistically, the pump would be shut off during times when the wind were not blowing. These times when the pump is shut off are referred to as "down" time. And the daily amounts of down time are stored in the DOWN accumulator. The amount of down time allowed per day is specified in the program as down time allowed DTA. DNTOT accumulates the total amount of down time occurring in the complete simulation run.

When the system has already been "down" for the allowed amount of time and the wind is not providing enough energy for the system, the farm tractor is attached to the system as a back up. Running the tractor cost additional money. Therefore, the total amount of tractor energy used in the complete simulation

run is recorded in the total tractor energy used TTEU accumulator.

All "ENERGY'S" are expressed in kilowatt-hours (kWh) and all "POWER'S" are expressed in kilowatts (kW).

Structure and Assumptions. The 22 equations that describe Option 1 and the assumptions underlying them are explained below.

1 TOTAL AVAILABLE ENERGY TAE

The total available energy TAE is a level and is expressed in kilowatt-hours (kWh). This is the total amount of energy that exists in the system at a given point in time. TAE at any point in time is calculated as the flywheel energy at the preceding point in time plus the power to the flywheel since the last period minus the flywheel power used since the last period plus the tractor power used since the last period. Mechanical energy into and out of the flywheel must pass through a gear box or transmission with an associated efficiency. These energies are also affected by the efficiency of the flywheel itself. Initial values must be provided for all levels. In the case of TAE it is assumed that the initial level is 75% of the flywheel's energy capacity. A factor of 24 is included to convert the time units from days to hours.

```

L   TAE,K=FWE,J+(DT)*(PTFW,JK-FWPU,JK+TPU,JK)*24*GBE*FWEFF  1
N   TAE=.75*FWEC      INITIAL CONDIOIONS                    1.1
C   GBE=.95                                                    1.2
C   FWEFF=.95                                                 1.3
      TAE - TOTAL AVAILABLE ENERGY (KWH)
      FWE - FLYWHEEL ENERGY (KWH)
      DT - TIME INTERVAL (DAYS)
      PTFW - POWER TO FLYWHEEL (KW)
      FWPU - FLYWHEEL POWER USAGE (KW)
      TPU - TRACTOR POWER USAGE (KW)
      GBE - GEAR BOX EFFICIENCY (DECIMAL FRACTION)
      FWEFF - FLYWHEEL EFFICIENCY (DECIMAL FRACTION)

```

2 FLYWHEEL ENERGY FWE

If it were possible to store an infinite amount of energy in the flywheel, the flywheel energy FWE and the total available energy TAE would always be equal. But the flywheel can only store a finite amount of energy. This amount of storage is referred to as the flywheel energy capacity FWEC and is expressed in kWh's. So, in order to assume a maximum energy storage capacity, FWE is the same as TAE until TAE becomes larger than FWEC. Whenever TAE is greater than FWEC, the flywheel is assumed to be filled with energy to its capacity.

```

A   FWE.K=MIN(FWEC,TAE.K)      2
C   FWEC=1000                  2.1
      FWE - FLYWHEEL ENERGY (KWH)
      MIN - DYNAMO FUNCTION FOR 'MINIMUM'
      FWEC - FLYWHEEL ENERGY CAPACITY (KWH)
      TAE - TOTAL AVAILABLE ENERGY (KWH)

```

3 POWER TO THE FLYWHEEL PTFW

The power to the flywheel PTFW is a rate that controls the wind energy input to the flywheel. For the next period in time PTFW is assumed to be equal to the power from the rotor PFR during the present period if PFR is positive. If PFR is negative, PTFW is set to zero.

```

R   PTFW.KL=CLIP(PFR.K,0,PFR.K,0)  3
      PTFW - POWER TO FLYWHEEL (KW)
      CLIP - DYNAMO LOGIC FUNCTION
            (SEE APPENDIX 2)
      PFR - POWER FROM ROTOR (KW)

```

4 POWER FROM THE ROTOR PFR

Wind power, P_w , is calculated from the kinetic energy, KE, per unit time, t ,

$$P_w = \frac{KE}{t} = \frac{mV^2}{2t} = \frac{1}{2}mV^2 = \frac{1}{2}\rho AV^3$$

where m is mass and \dot{m} its flow rate, V is wind speed, ρ is air density, and A is cross-sectional area perpendicular to the flow. For the examination of wind turbine performance, these factors combine to give a function of the form:

$$\frac{P}{A} = 8.355 \times 10^{-5} V^3 \text{ kilowatts/square meter}$$

where V is in knots. However, this assumes that the rotor is 100% efficient and that it will perform over an infinite range of wind speeds. A more realistic form would be:

$$P_w(kW) = 8.355 \times 10^{-5} \times \text{rotor size}(m^2) \times \text{rotor efficiency (decimal fraction)} \times (V^3 - V_s^3)$$

where V_s (in knots) is the wind speed at which the rotor will overcome friction and begin to turn. V_s is sometimes referred to as the cut-in wind speed. In addition there is a rated wind speed V_R of the system, beyond which no increase in power will result due to an increase in wind speed. The Betz theorem (14) indicates that the rotor efficiency has a theoretical maximum of 16/27ths (=0.5926). Measured values range from 0.45 to 0.10 (15).

Another factor that should be considered when examining the power in the wind is the height of the windmill. Near the ground the wind is slowed by friction. The amount of this friction depends on the roughness of the surface and obstacles in the wind's path. Studies have shown that a power law increase of speed with height is adequately descriptive for practical purposes (18). Over flat terrain similar to that which we are considering for

irrigation, this power relation can be expressed as:

$$\frac{P}{P_0} = \left(\frac{z}{z_0}\right)^{3/7}$$

where P is the power available, z is the height above ground, and the subscripted values are those at the anemometer height at which the wind data was gathered. Thus, as the height of the wind turbine is increased, the power available from the wind increases.

All of these principles are considered in the equations for power from the rotor.

```

A   PFR.K=RE*8.36E-5*RS*(WSA.K*WSA.K*WSA.K*(EXP(.42857*LOGN(HSF))))-
X   CIS*CIS*CIS)
C   RE=.30      4.1
C   RS=1100     4.2
C   HSF=5       4.3
C   CIS=3       4.4
      PFR - POWER FROM ROTOR (KW)
      RE - ROTOR EFFICIENCY (DECIMAL FRACTION)
      8.36E-5 - CONSTANT COEFFICIENT TO CONVERT TO DESIRED UNITS
      RS - ROTOR SIZE (SQUARE METERS)
      WSA - WIND SPEED (ADJUSTED) (KNOTS)
      EXP(.42857)*LOGN(HSF) - HEIGHT POWER FUNCTION
      HSF - HEIGHT SCALING FACTOR = WINDMILL HEIGHT
              (IN METERS) DIVIDED BY ANEMOMETER HEIGHT.
              ANEMOMETER HEIGHT = 6 METERS IN 1965.
      CIS - CUT-IN-SPEED (KNOTS)

```

5 ADJUSTED WIND SPEED WSA

As has already been mentioned, there exists a wind speed above which an increase in wind speed will not result in an increase in power from the rotor. This is referred to as the rated wind speed RWS of the system. The adjusted wind speed WSA is actual wind data that has been adjusted so that any wind data that is recorded as being higher than RWS is set equal to RWS. This adjustment is made here in a separate auxiliary equation in

order to simplify the equation for power from the rotor.

```

A   WSA.K=CLIP(RWS,WS.K,WS.K,RWS)      5
C   RWS=22      5.1
      WSA - WIND SPEED (ADJUSTED) (KNOTS)
      CLIP - DYNAMO LOGIC FUNCTION
      RWS - RATED WIND SPEED (KNOTS)
      WS - WIND SPEED DATA (KNOTS)

```

6 WIND SPEED WS

The wind speed data used for this program was recorded by the National Weather Bureau in Dodge City, Kansas. Long term Weather Bureau wind data is recorded as a one minute visual average as observed on a wind speed meter. This is typically recorded every three hours. The standard height for recording is 10 meters. However, the anemometer at Dodge City is only 6.6 meters high.

The cubic response to wind speed of the power in the wind makes predictions very sensitive to averaging. The actual energy output of a system will always be higher than the output predicted by using average wind speeds (16). This discrepancy can be reduced by using as short an averaging time period as possible. The Weather Bureau's 3 hour interval is used here.

The wind data is represented in table form.

ACTUAL WIND DATA FROM JUN, JUL, AND AUG 1965

```

A   WS.K=TABLE(WST,TIME.K,0,90,.125)    6
T   WST=0
X   /09/09/11/10/14/16/16/12/15/09/07/05/01/08/16/14
X   /12/12/07/14/10/12/07/08/06/05/01/03/12/13/15/10
      .
      .
      .
X   /05/04/03/10/17/18/09/07/09/10/11/14/16/12/08/10
X   /09/10/13/15/16/09/10/06/10/07/08/15/11/15/14/14
      WS - WIND SPEED (KNOTS)

```


7 FLYWHEEL POWER USAGE FWPU

The mechanical irrigation pump draws its needed power from the flywheel. The flywheel power usage FWPU will be equal to the pump power demand PPD as long as there is energy available in the flywheel. When the energy in the flywheel drops below a specified low energy level LEL, the pump will stop drawing power. Whenever the pump is shut off, "down" time is accumulating. The system can only tolerate a certain amount of down time, down time allowed per day DTA. If this amount of down time has already accumulated and the flywheel energy is still low, the tractor back up will be switched on and the pump will begin to draw power from the flywheel again.

Thus, in determining FWPU for the next interval of time, one first examines the system to determine if the system was accumulating down time in the previous time interval by looking at the down time accumulation rate DTAR. If no down time was accumulating, then FWPU will equal PPD. If down time was accumulating and DTA has not been exceeded, the system will shut down for the next time interval. And if down time was accumulating and DTA has been exceeded, FWPU will equal PPD.

```
R   FWPU,KI=CLIP(CLIP(PPD,K,0,DOWN,K,DTA+1),PPD,K,DTAR,JK,2)
C   DTA=15      7.1
```

```
FWPU - FLYWHEEL POWER USAGE (KW)
CLIP - DYNAMO LOGIC FUNCTION
PPD - PUMP POWER DEMAND (KW)
DOWN - DOWN TIME (HOURS/DAY)
DTA - DOWN TIME ALLOWED (HOURS/DAY)
DTAR - DOWN TIME ACCUMULATION RATE (KW)
```

8 PUMP POWER DEMAND PPD

The pump power demand referred to the input side of the flywheel is equal to the pump rating PR divided by the combined flywheel and the flywheel-to-pump transmission efficiencies. The pump rating depends on the demand that will be placed on the irrigation system. The type of irrigation, the amount of area to be irrigated, and the depth of the water table are all important and need to be considered. Sprinkler irrigation requires more power than does flood irrigation, for example. Assuming a 200 foot water table and sprinkler irrigation, a 100 kW (approximately 134 HP) pump is assumed to be adequate to meet the farmer's needs.

```

A      PPD.K=PR/TEFF      8
C      PR=100      8.1
C      TEFF=.90      8.2
      PPD - PUMP POWER DEMAND (KW)
      PR - PUMP RATING (KW)
      TEFF - COMBINED FLYWHEEL-TO-PUMP AND FLYWHEEL
              EFFICIENCIES (DECIMAL FRACTION)

```

9 TRACTOR POWER USAGE TPU

Tractor power serves as a back up for the irrigation system when the wind is not blowing. This back up is activated when the flywheel energy level FWE is low and the system has already accumulated the allowed amount of down time DTA. Therefore, at any point in time, tractor power usage is equal to zero or the tractor power into the flywheel TPIFW.

```

R      TPU.KL=CLIP(TPIFW.K,0,DOWN.K,DTA+1)      9
      TPU - TRACTOR POWER USAGE (KW)
      CLIP - DYNAMO LOGIC FUNCTION
      TPIFW - TRACTOR POWER INTO THE FLYWHEEL (KW)
      DOWN - DOWN TIME (HOURS/DAY)
      DTA - DOWN TIME ALLOWED (HOURS/DAY)

```

10 TRACTOR POWER INTO THE FLYWHEEL TPIFW

Tractor power into the flywheel is defined as the product of the tractor power rating TPR and the tractor-to-flywheel transmission efficiency. Farm tractors have become more powerful each year as the equipment that the farmer uses has grown in size and power requirements. Today, tractors with 100 to 200 HP ratings are not uncommon. A tractor rating of 100 kW (approximately 134 HP) is assumed for this system.

```

A      TPIFW.K=TPR*TTFWE      10
C      TPR=100      10.1
C      TTFWE=.95      10.2
      TPIFW - TRACTOR POWER INTO FLYWHEEL (KW)
      TPR - TRACTOR POWER RATING (KW)
      TTFWE - TRACTOR-TO-FLYWHEEL TRANSMISSION EFFICIENCY
              (DECIMAL FRACTION)

```

11 TOTAL TRACTOR ENERGY USED TTEU

Total tractor energy used TTEU is a level. Every hour that the tractor is operating and putting energy into the irrigation system costs money. It is, therefore, necessary to keep a running total of how much time the tractor is turned on in order to examine the economic aspects of the irrigation system. At any point in time the total tractor energy used is equal to the total tractor energy used up to the previous period in time plus the tractor energy used in the previous period of time. One must pay for all the energy put out by the tractor, not just that energy that is put into the flywheel after passing through the tractor-to-flywheel transmission. Therefore, the tractor-to-flywheel transmission efficiency must be divided out of the tractor power used in the previous time interval. Zero initial conditions are assumed.

```

L   TTEU.K=TTEU.J+(DT)*(TPU.JK)*24/TTFWE      11
N   TTEU=0      INITIAL CONDITIONS      11.1
      TTEU - TOTAL TRACTOR ENERGY USED (KWH)
      DT  - TIME INTERVAL (DAYS)
      TPU - TRACTOR POWER USAGE (KW)
      TTFWE - TRACTOR-TO-FLYWHEEL TRANSMISSION
              EFFICIENCY (DECIMAL FRACTION)

```

12 DOWN TIME DOWN

Down time DOWN is a level and is the amount of time, in hours, that the irrigation system would be down each day, one day at a time, if there were no back up. DOWN at any point in time is equal to the amount of down time accumulated since the previous midnight plus the amount of down time that will occur in the next interval. If the flywheel energy level FWE is below the specified low energy level LEL at a point in time, then additional down time will be accumulated during the next time interval. At the end of the day, the down time accumulator is set equal to zero. This is accomplished by multiplying the entire function for DOWN by a system status index SSI. Zero down time is assumed as the initial value of DOWN.

```

L   DOWN.K=SSI.J*(DOWN.J+CLIP(0,DTI,FWE.J,LEL))  12
N   DOWN=0      INITIAL CONDITIONS      12.1
C   LEL=600      12.2
C   DTI=3        12.3
      DOWN - DOWN TIME (HOURS/DAY)
      SSI - SYSTEM STATUS INDEX (DIMENSIONLESS)
      CLIP - DYNAMO LOGIC FUNCTION
      DTI - DELTA TIME INTERVAL = (DT)*24 (HOURS)
      FWE - FLYWHEEL ENERGY (KWH)
      LEL - LOW ENERGY LEVEL (KWH)

```

13 DOWN TIME ACCUMULATION RATE DTAR

The down time accumulation rate DTAR is an index of whether the system is accumulating down time or not. If the flywheel energy level FWE is below the specified low energy level LEL,

then down time will be accumulated at a rate related to the pump power demand PPD. DTAR does not directly influence the level of DOWN. Instead, it acts as an index as to the immediate future accumulation of down time.

```
R      DTAR.KL=CLIP(1,PPD.K,FWE.K,LEL)      13
      DTAR - DOWN TIME ACCUMULATION RATE (KW)
      CLIP - DYNAMO LOGIC FUNCTION
      PPD - PUMP POWER DEMAND (KW)
      FWE - FLYWHEEL ENERGY (KWH)
      LEL - LOW ENERGY LEVEL (KWH)
```

14 SYSTEM STATUS INDEX SSI

The system status index SSI resets the DOWN accumulator to zero every 24 hours at midnight. It is also used in the calculation of the total down time accumulation rate TDTAR. It has the value of 1 at every point in time except at midnight each day when it has the value 0. These values are stored in table form. Figure 3.2.4 shows one section of this table as the computer interprets the system.

```
A      SSI.K=TABLE(SSIT,TIME.K,0,90,.125)      14
T      SSIT=0/
X      1/1/1/1/1/1/1/0/1/1/1/1/1/1/1/0/1/1/1/1/1/1/0/
X      1/1/1/1/1/1/1/0/1/1/1/1/1/1/1/0/1/1/1/1/1/1/0/
      .
      .
      .
X      1/1/1/1/1/1/1/0/1/1/1/1/1/1/1/0/1/1/1/1/1/1/0/
X      1/1/1/1/1/1/1/0/1/1/1/1/1/1/1/0/1/1/1/1/1/1/0/
      SSI - SYSTEM STATUS INDEX (DIMENSIONLESS)
      SSIT - SYSTEM STATUS INDEX TABLE
```

15 ENERGY SURPLUS (WIND) 1st INDEX ESW1

In a given interval in time it is very possible that the energy available from the wind exceeds the available storage remaining in the flywheel. In such a case the excess energy

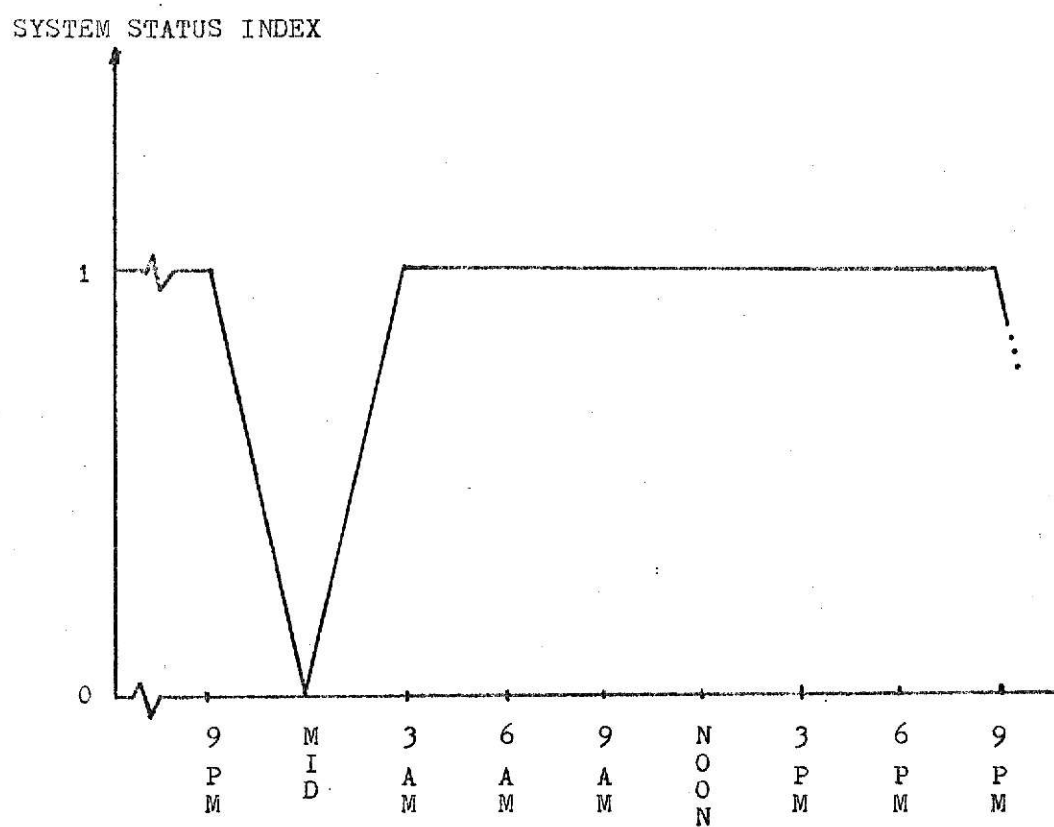


Figure 3.2.4 - System Status Index

can not be put to use. This surplus wind energy is noted by the auxiliary register ESW1. It is simply any positive difference between the total available energy TAE and the flywheel energy capacity FWEC. Thus, once the flywheel is filled to capacity, any excess wind energy is noted.

```

A      ESW1.K=MAX(TAE.K-FWEC,0)      15
      ESW1 IS USED TO EVALUATE THE ROTOR SIZE -
      FLYWHEEL SIZE COMBINATION
      ESW1 - ENERGY SURPLUS WIND (1ST INDEX) (KWH)
      MAX - DYNAMO FUNCTION FOR 'MAXIMUM'
      TAE - TOTAL AVAILABLE ENERGY (KWH)
      FWEC - FLYWHEEL ENERGY CAPACITY (KWH)

```

16 TOTAL ENERGY SURPLUS (WIND) 1st INDEX TESW1

Total energy surplus TESW1 accumulates a running total of ESW1 while the system is operating. This level is equal to TESW1 up to the previous point in time plus the surplus wind energy (1st index) of the previous period. The units are kilowatt-hours and zero initial conditions are assumed.

By examining the total energy surplus (wind) 1st index and the total tractor energy used TTEU at the end of a simulated summer, a logical decision can be made concerning possible modifications in the system. If TESW1 and TTEU are about equal, one would know that over the summer there is enough power in the wind to meet the power demands of the irrigation system but that possibly a larger flywheel is needed to even out periods of low and periods of high wind. Likewise, if TTEU is much larger than TESW1, then a larger rotor is needed to make the system less dependent on back up energy.

```

L   TESW1.K=TESW1.J+(DT)(ESW1.J)*8      16
N   TESW1=0      INITIAL CONDITIONS      10.1
      TESW1 - TOTAL ENERGY SURPLUS WIND (1ST INDEX) (KWH)
      DT - TIME INTERVAL (DAYS)
      ESW1 - ENERGY SURPLUS WIND (1ST INDEX) (KWH)

```

17 ENERGY SURPLUS (WIND) 2nd INDEX ESW2

A wind power system of any kind will have a wind speed at which the system will operate at its peak. This wind speed is referred to as the rated wind speed RWS since this is the speed at which the system will perform at its maximum rating. The energy available from the wind is directly proportional to the cube of the wind speed. Thus, as the wind speed increases, more and more energy can be extracted by the wind power system. But, as has been explained already, beyond the rated wind speed of the system, no additional energy can be derived from an increase in wind speed. This 2nd index of surplus wind energy keeps track of the amount of energy in the wind that can not be extracted due to the rated wind speed of the system.

```

A   ESW2.K=CLIP(RE*8.36E-5*RS*(WS.K*WS.K*WS.K*(EXP(.42357*LOGN(HSF)))
X   -CIS*CIS*CIS)-PFR.K,0,WS.K,RWS)      17
      ESW2 IS USED TO EVALUATE THE RATED WIND SPEED OF THE SYSTEM
      ESW2 - ENERGY SURPLUS WIND (2ND INDEX) (KWH)
      CLIP - DYNAMO LOGIC FUNCTION
      RE - ROTOR EFFICIENCY (DECIMAL FRACTION)
      8.36E-5 - CONSTANT COEFFICIENT TO CONVERT TO DESIRED UNITS
      RS - ROTOR SIZE (SQUARE METERS)
      WS - WIND SPEED DATA (KNOTS)
      EXP(.42357)*LOGN(HSF) - HEIGHT POWER FUNCTION
      HSF - HEIGHT SCALING FACTOR = WINDMILL HEIGHT
              (IN METERS) DIVIDED BY ANEMOMETER HEIGHT
      CIS - CUT-IN-SPEED (KNOTS)
      PFR - POWER FROM THE ROTOR (KW)
      RWS - RATED WIND SPEED (KNOTS)

```

18 TOTAL ENERGY SURPLUS (WIND) 2nd INDEX TESW2

Total energy surplus TESW2 accumulates a running total of ESW2 throughout the simulation of the system. This level is equal to TESW2 up to the previous point in time plus the surplus wind energy (2nd index) of the previous period. The units are kilowatt-hours and zero initial conditions are assumed. As has already been explained, there is a limit as to how large the rated wind speed of a system may practically be considered. Therefore, it may never be possible to change RWS enough to reduce TESW2 to zero.

```

L      TESW2.K=TESW2.J+(DT)(ESW2.J)*8      18
N      TESW2=0      18.1
      TESW2 - TOTAL ENERGY SURPLUS WIND (2ND INDEX) (KWH)
      DT - TIME INTERVAL (DAYS)
      ESW2 - ENERGY SURPLUS WIND (2ND INDEX) (KWH)

```

19 (TOTAL) CAPITAL COST CC

Capital cost CC is expressed in dollars. CC includes the cost of the flywheel and rotor system. In addition, each time the tractor is turned on as a back up, the cost of this energy is assessed.

The rotor cost is assumed to be \$100 per square meter and includes the cost of a 30 meter tower. This figure is based on cost information provided by various manufacturers. It assumes the rotor will be a Darrieus design with a Savonius self-starting capability.

The flywheel capital cost is assumed to be \$35 per kWh of storage capacity. Such a flywheel would be approximately 8 - 10 feet in diameter and weigh between 50 and 75 tons for a storage capacity up to 5000 kWh's (19).

The other cost considered is that of operating the back up, the tractor energy. Assuming a tractor rating of 100 kW, each kWh of energy costs between \$0.10 and \$0.20. \$0.20 is assumed for the purposes of this model.

It is not the author's intention to slight any of the other costs associated with a system such as is proposed here. It is assumed, though, that the cost of the transmissions and the gear box are minor and they are therefore not considered. The rotor capital cost and the flywheel capital cost can be assumed to equal zero if just the cost of maintaining the back up system is desired.

```

A      CC.K=TTEU.K*TECC+RS*RCC+FWEC*FWCC      19
C      TECC=.20      19.1
C      RCC=100      19.2
C      FWCC=35      19.3
      CC - (TOTAL) CAPITAL COST ($)
      TTEU - TOTAL TRACTOR ENERGY USED (KWH)
      TECC - TRACTOR ENERGY CAPITAL COST ($/KWH)
      RS - ROTOR SIZE (SQUARE METERS)
      RCC - ROTOR CAPITAL COST ($/SQUARE METER)
      FWEC - FLYWHEEL ENERGY CAPACITY (KWH)
      FWCC - FLYWHEEL CAPITAL COST ($/KWH)

```

20 TOTAL DOWN TIME ACCUMULATION RATE TDTAR

This rate controls the accumulation of the total number of hours the system is actually "down" during a simulation run. As the system has been defined, there is a maximum number of hours of down time allowed per day DTA. At the end of each day, TDTAR looks at the DOWN accumulator. If DOWN is less than DTA, TDTAR assumes the value of DOWN. If DOWN is greater than DTA, TDTAR assumes the value of DTA. In the calculation of the total down time DNTOT, TDTAR is multiplied by the time interval DT. DT is defined as being equal to .125 days, or 1/8th of a day.

To cancel the effect of this, the entire function for TDTAR is multiplied by 8.

```
R      TDTAR.KL=SWITCH(MIN(DTA,DOWN.K),0,SSI.K)*8      20
      TDTAR - TOTAL DOWN TIME ACCUMULATION RATE (HOURS)
      SWITCH - DYNAMO LOGIC FUNCTION
              (SEE APPENDIX 2)
      MIN - DYNAMO FUNCTION FOR 'MINIMUM'
      DTA - DOWN TIME ALLOWED (HOURS/DAY)
      DOWN - DOWN TIME (HOURS/DAY)
      SSI - SYSTEM STATUS INDEX (DIMENSIONLESS)
```

21 TOTAL DOWN TIME ACCUMULATED DNTOT

This level accumulates the total number of hours the system is "down" during a simulation run. DNTOT can be used to determine the load factor (percent of time the system is operating) during a simulation run. Zero initial conditions are assumed.

```
L      DNTOT.K=DNTOT.J+(DT)*(TDTAR.JK)      21
N      DNTOT=0      INITIAL CONDITIONS      21.1
      DNTOT - TOTAL DOWN TIME ACCUMULATED (HOURS)
      DT - TIME INTERVAL (DAYS)
      TDTAR - TOTAL DOWN TIME ACCUMULATION RATE (HOURS)
```

22 LOAD FACTOR LOADFAC

The load factor, as calculated by this auxiliary equation, is the percent of time the irrigation system is operating during the summer months of June, July, and August. At any point in time, LOADFAC is the percent of the elapsed time that the system has been operating.

Using a pump rated at 100 kW, it would be necessary to operate the pump 50 - 60% of the time in order to provide 6 to 8 acre-inches of irrigation per month. The down time allowed per day DTA can be adjusted until, at the end of the summer, the overall load factor is between 50 and 60%.

A $LOADFAC.K = 1 - DNTOT.K / (24 * TIME.K)$ 22
 $LOADFAC$ - LOAD FACTOR (DIMENSIONLESS)
 THE LOAD FACTOR IS THE PERCENT OF THE
 TIME THE SYSTEM IS TURNED ON DURING
 JUNE, JULY, AND AUGUST.
 $DNTOT$ - TOTAL DOWN TIME ACCUMULATED (HOURS)

3.3 MODEL STRUCTURE - OPTION 2

Introduction. A schematic of Option 2 appears in Figure 3.3.1. In this system the wind turns a wind turbine (windmill) which is coupled to an electrical alternator. The electricity generated is then rectified and fed into an electrolysis cell. The electrolysis cell produces hydrogen and oxygen from water (H_2O). The hydrogen gas produced is then piped off and stored in an exhausted natural gas well. When it becomes necessary to provide energy for irrigation, the hydrogen is piped to an internal combustion engine which drives the irrigation pump. Propane provides a back up for operation of the system when no hydrogen is available.

Option 2 involves three energy conversions, wind power to electrical, electrical to production of hydrogen, and burning the hydrogen to provide mechanical energy, compared to the simple conversion of wind power into mechanical power as in Option 1. Thus, Option 2 is inherently less efficient. However, Option 2 provides a means for storing much more energy at a lower cost than Option 1. Therefore, the system could easily operate during the entire year, storing the hydrogen produced during the months of September through May for use during June, July, and August. Thus, it is possible to provide the same amount of total energy as Option 1 at a lower total cost.

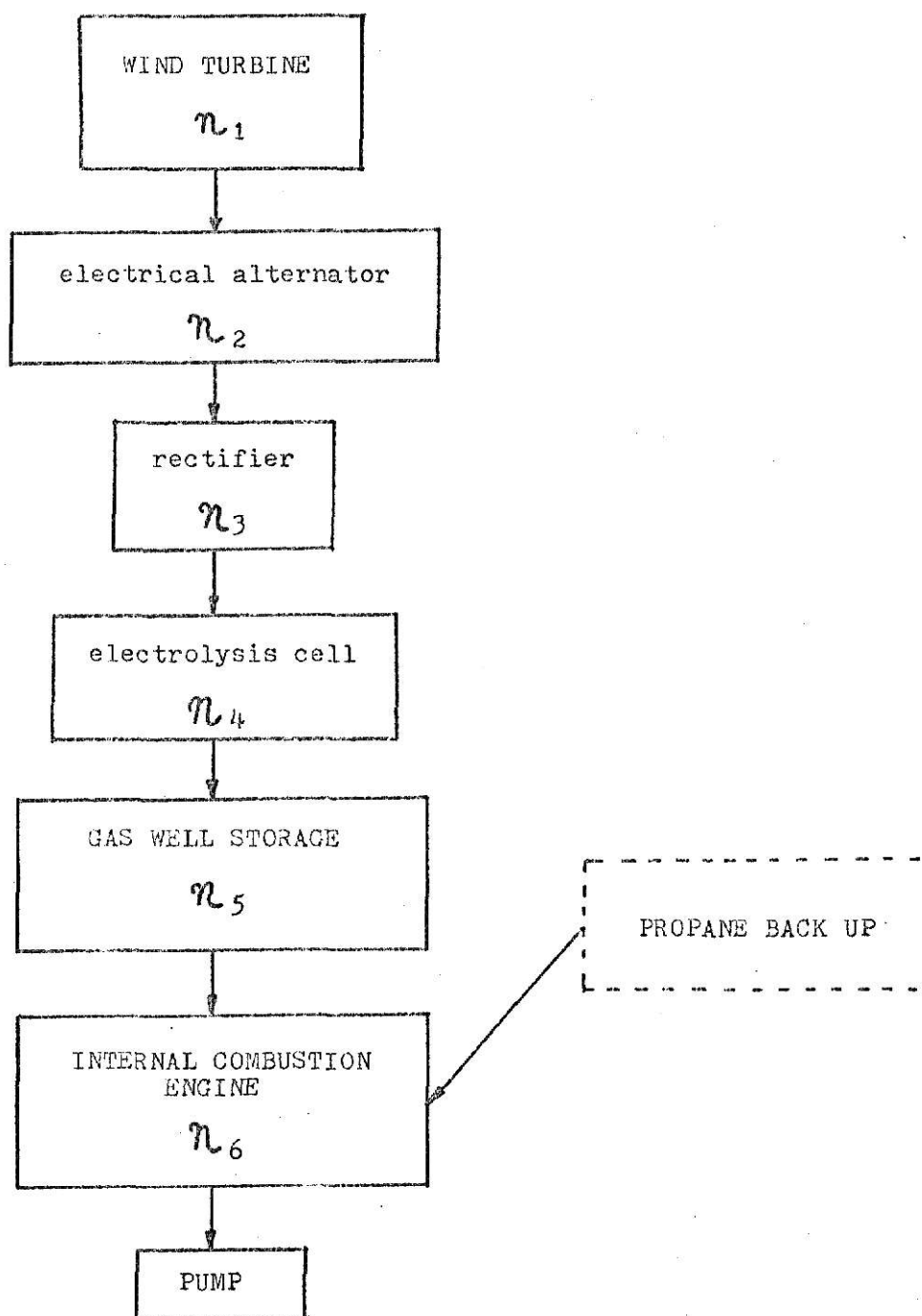


Figure 3.3.1 - Schematic of Option 2

A casual loop diagram of Option 2 is shown in Figure 3.3.2 and the DYNAMO flow diagram for the model is shown in Figure 3.3.3.

System Levels. There are four levels in Option 2. Hydrogen storage level H2SL is the number of kilowatt-hours of hydrogen energy that are in the natural gas well at any given point in time.

Total energy surplus (wind) 2nd index TESW2 serves the same function as TESW2 in Option 1. Similarly, down time DOWN serves the same function as DOWN in Option 1.

The propane used PU is similar to the total tractor energy used in Option 1. When the system has been "down" for the allowed amount of time and there is not enough hydrogen to power the system, propane is used to power the irrigation pump. PU is the total amount of propane used up to any point in time.

Due to the large capacity for energy storage of Option 2, it is no longer critical to be pumping water whenever the wind is blowing. Therefore, the approach to establishing the load factor of the system is different than in Option 1. These differences are explained below.

All "ENERGY'S" are expressed in kilowatt-hours (kWh) and all "POWER'S" are expressed in kilowatts (kW).

Structure and Assumptions. The 18 equations that describe Option 2 and their underlying assumptions are explained below.

1 HYDROGEN STORAGE LEVEL H2SL

The hydrogen storage level H2SL contains the number of kilowatt-hours of hydrogen that are available for use in the

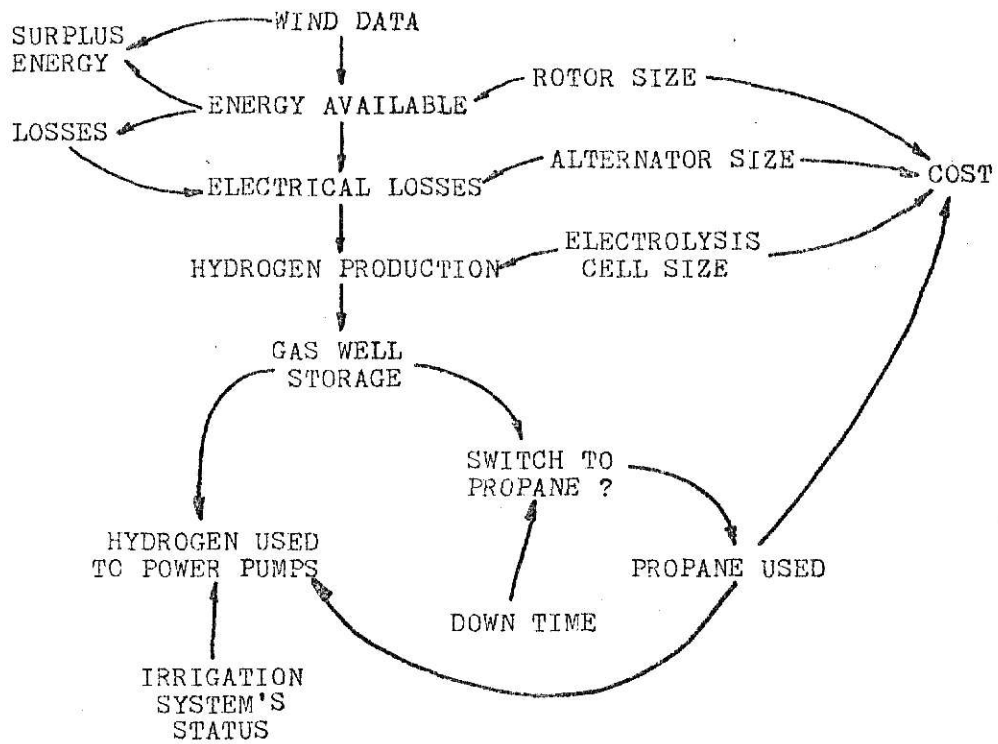


Figure 3.3.2 - Casual Loop Diagram of Option 2

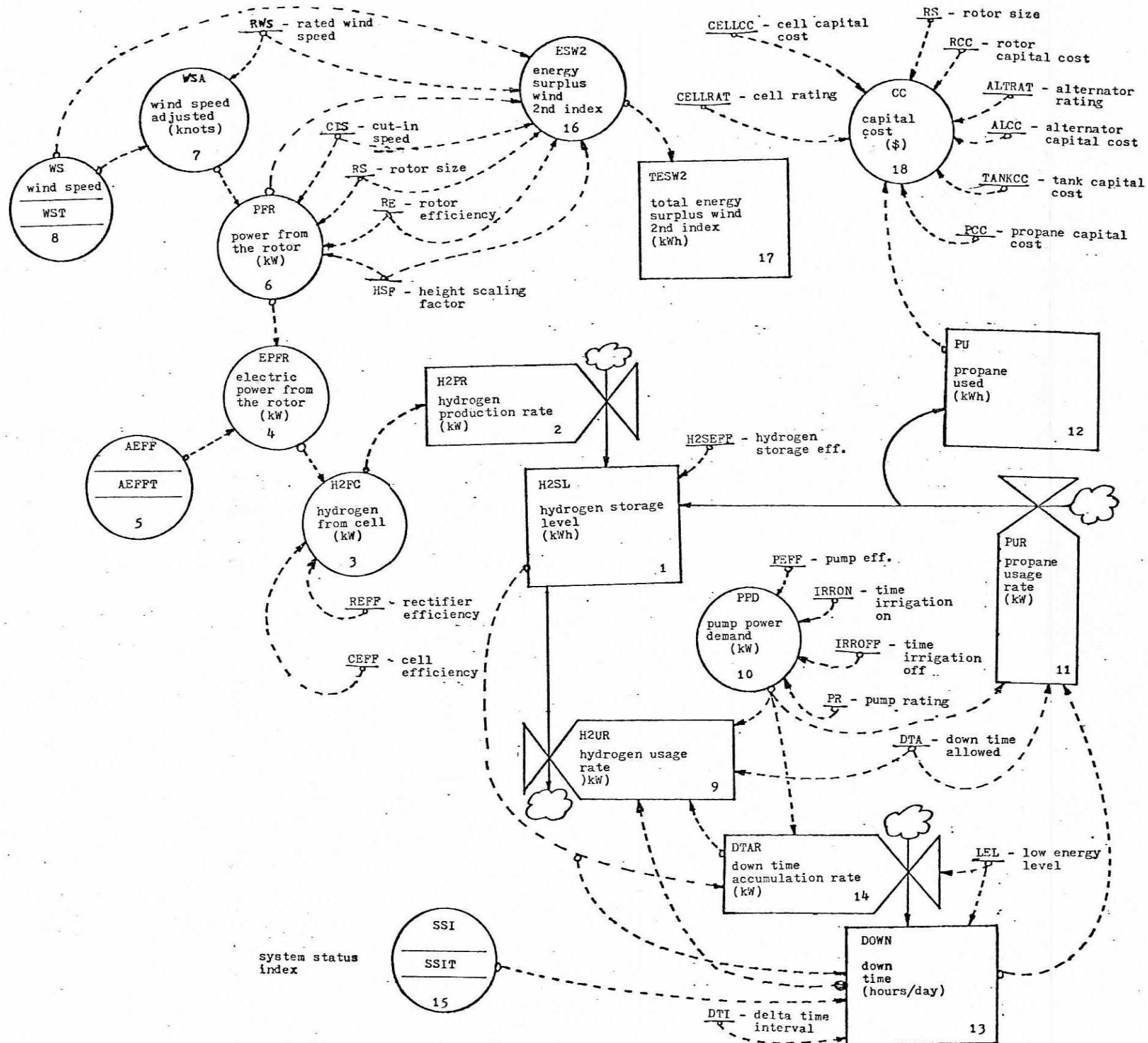


Figure 3.3.3 - Flow Diagram of Option 2

hydrogen internal combustion engine. H2SL at any point in time is equal to the H2SL value at the previous point in time plus the hydrogen produced during the last time interval minus the hydrogen used during the last time interval. In addition, any propane used as back up fuel must be considered. The amount of hydrogen into and out of the gas well storage is also effected by the hydrogen storage efficiency H2SEFF. The calculated value of H2SL at each point in time is first compared with zero and the larger of the two is assigned as the actual H2SL. This is to insure that there is never any "negative energy" stored in the gas well. Zero initial constitions are assumed for this level.

```

L      H2SL.K=MAX(0,H2SL.J+(DT)*(H2PR.JK-H2UR.JK+PUR.JK)*24*H2SEFF)  1
N      H2SL=H2L0      INITIAL CONDITIONS      1.1
C      H2L0=0          1.2
C      H2SEFF=.95      1.3
      H2SL - HYDROGEN STORAGE LEVEL (KWH)
      MAX - DYNAMO FUNCTION FOR 'MAXIMUM'
      DT - TIME INTERVAL (DAYS)
      H2PR - HYDROGEN PRODUCTION RATE (KW)
      H2UR - HYDROGEN USAGE RATE (KW)
      PUR - PROPANE USAGE RATE (KW)
      H2SEFF - HYDROGEN STORAGE EFFICIENCY
              (DECIMAL FRACTION)

```

2 HYDROGEN PRODUCTION RATE H2PR

The rate of production of hydrogen over an interval of time is assumed to be equal to the amount of hydrogen produced by the electrolysis cell during the same time period.

```

R      H2PR.KL=H2FC.K      2
      H2PR - HYDROGEN PRODUCTION RATE (KW)
      H2FC - HYDROGEN FROM (ELECTROLYSIS) CELL (KW)

```

3 HYDROGEN FROM (ELECTROLYSIS) CELL H2FC

The amount of hydrogen produced by the electrolysis cell

H2FC is equal to the amount of electrical power produced by the rotor EPFR times the rectifier efficiency REFF (the rectifier converts the alternating current power produced by the alternator to direct current power for the production of hydrogen) times the electrolysis cell efficiency CEFF. The rectifier is a solid state device with an efficiency easily approaching 95%. There presently does not exist an electrolysis cell of the size needed for this system. However, General Electric projects a cost of \$50/kW at 93% efficiency for this size of cell by 1985 (20). For this simulation, an efficiency of 90% is assumed.

```

A      H2FC.K=EPFR.K*REFF*CEFF      3
C      REFF=.95      3.1
C      CEFF=.9      3.2
      H2FC - HYDROGEN FROM (ELECTROLYSIS) CELL (KW)
      EPFR - ELECTRICAL POWER FROM ROTOR (KW)
      REFF - RECTIFIER EFFICIENCY (DECIMAL FRACTION)
      CEFF - (ELECTROLYSIS) CELL EFFICIENCY
              (DECIMAL FRACTION)

```

4 ELECTRICAL POWER FROM THE ROTOR EPFR

The mechanical output from the rotor is used to turn the alternator to produce electrical power. The electrical power being generated by the rotor EPFR will equal the mechanical power from the rotor times the alternator efficiency AEFF.

```

A      EPFR.K=CLIP(PFR.K*AEFF.K,0,PFR.K,0)      4
      EPFR - ELECTRICAL POWER FROM ROTOR (KW)
      CLIP - DYNAMO LOGIC FUNCTION
      PFR - POWER FROM ROTOR (KW)
      AEFF - ALTERNATOR EFFICIENCY (DECIMAL FRACTION)

```

5 ALTERNATOR EFFICIENCY AEFF

The alternator efficiency is load dependent. A typical efficiency-load curve for an alternator is shown in Figure 3.3.4.

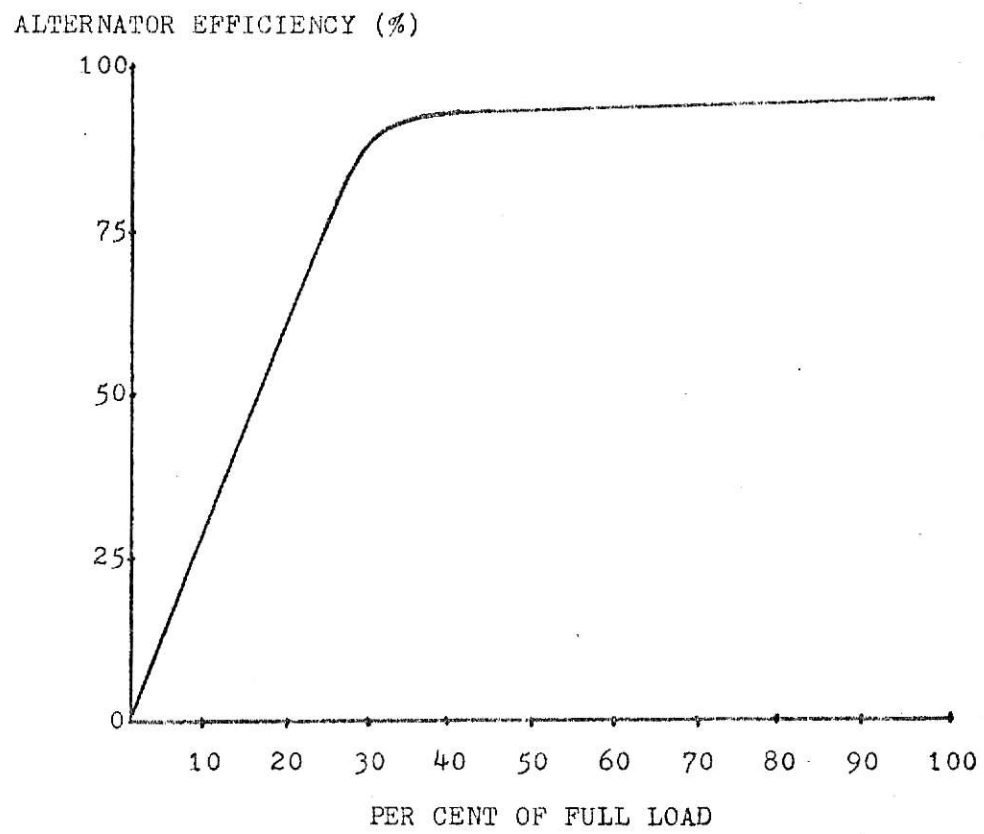


Figure 3.3.4 - Typical Alternator Efficiency

In this system the alternator will be operating under full load at the rated wind speed RWS. Thus, the input rating of the alternator ALTRAT can be calculated by computing how much power will be available from the rotor at the rated wind speed. The efficiency of the alternator at a given point in time may then be calculated based on PFR at that same point in time. AEF is represented in table form as shown in Figure 3.3.5.

```

A      AEF.K=TABLE(AEFT,PFR.K,0,.5*ALTRAT,.05*ALTRAT)      5
N      ALTRAT=RE*8.36E-5*RS*(RWS*RWS*RWS*(EXP(.42857*LOGN(HSF))) -
X      CIS*CIS*CIS)                                           5.1
C      HSF=5                                                  5.2
T      AEFT=0/.15/.33/.50/.63/.75/.86/.93/.94/.945/.95    5.3
      AEF - ALTERNATOR EFFICIENCY (DECIMAL FRACTION)
      TABL - TABLE (HIGH - LOW) FUNCTION
      AEFT - ALTERNATOR EFFICIENCY TABLE
      PFR - POWER FROM ROTOR (KW)
      ALTRAT - ALTERNATOR RATING (KW)
      RE - ROTOR EFFICIENCY (DECIMAL FRACTION)
      8.36E-5 - CONSTANT COEFFICIENT TO CONVERT TO DESIRED UNITS
      RS - ROTOR SIZE (SQUARE METERS)
      RWS - RATED WIND SPEED (KNOTS)
      EXP(.42857)*LOGN(HSF) - HEIGHT POWER FUNCTION
      HSF - HEIGHT SCALING FACTOR = WINDMILL HEIGHT
              (IN METERS) DIVIDED BY ANEMOMETER HEIGHT
      CIS - CUT-IN-SPEED (KNOTS)

```

6 POWER FROM THE ROTOR PFR

PFR in Option 2 is the same as in Option 1. The effects of rotor size and efficiency, rated wind speed, tower height, and cut-in-speed are all considered.

```

A      PFR.K=RE*8.36E-5*RS*(WSA.K*WSA.K*WSA.K*(EXP(.42857*LOGN(HSF))) -
X      CIS*CIS*CIS)                                           6
C      RE=.30        6.1
C      RS=700        6.2
C      CIS=8         6.3
      PFR - POWER FROM ROTOR (KW)
      RE - ROTOR EFFICIENCY (DECIMAL FRACTION)
      8.36E-5 - CONSTANT COEFFICIENT TO CONVERT TO DESIRED UNITS
      RS - ROTOR SIZE (SQUARE METERS)
      WSA - WIND SPEED (ADJUSTED) (KNOTS)
      EXP(.42857)*LOGN(HSF) - HEIGHT POWER FUNCTION

```

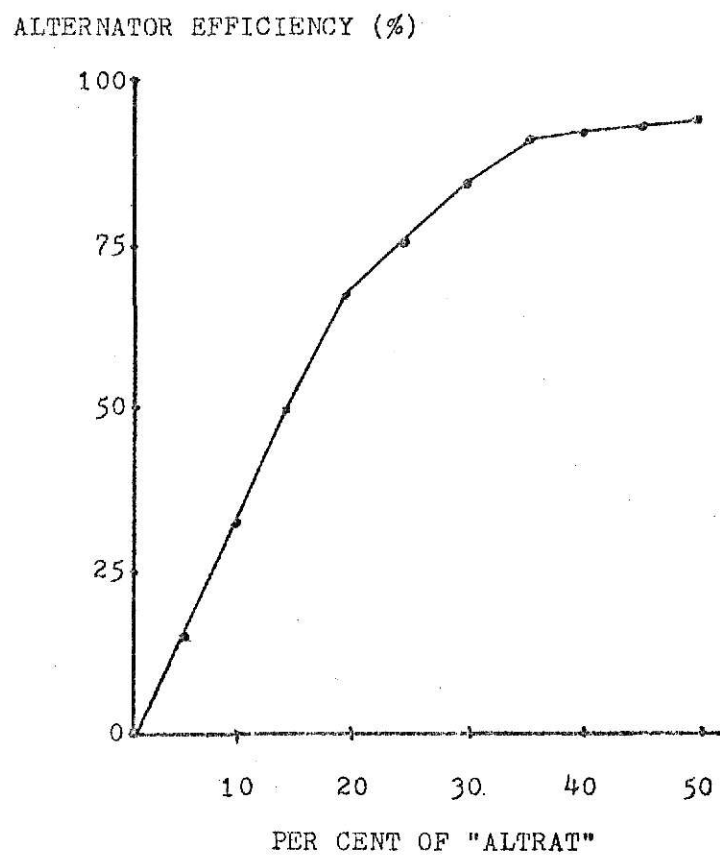


Figure 3.3.5 - Alternator Efficiency Table

HSF - HEIGHT SCALING FACTOR = WINDMILL HEIGHT
 (IN METERS) DIVIDED BY ANEMOMETER HEIGHT
 CIS - CUT-IN-SPEED (KNOTS)

7 ADJUSTED WIND SPEED WSA

WSA in Option 2 is the same as in Option 1. The effect of the rated wind speed RWS of the system is considered.

```
A WSA.K=CLIP(RWS,WS.K,WS.K,RWS) 7
C RWS=22 7.1
  WSA - WIND SPEED (ADJUSTED) (KNOTS)
  CLIP - DYNAMO LOGIC FUNCTION
  RWS - RATED WIND SPEED (KNOTS)
  WS - WIND SPEED DATA (KNOTS)
```

8 WIND SPEED WS

The wind speed data used in Option 2 is the same as that used in Option 1 with one exception. Option 1 is only concerned with June, July, and August. But the system modeled in Option 2 would operate year round and thus uses wind data from all 12 months. To prevent an overflow of the computer memory, wind data is used in 3 month blocks beginning with September, October, and November and ending with June, July, and August. Thus, the system is able to produce and store hydrogen for 9 months before the irrigation pump is turned on.

```
A WS.K=TABLE(WST,TIME.K,DS,DF,.125) 3
C DS=0 8.1
C DF=94 8.2
  DS - (WIND) DATA STARTING TIME
  DF - (WIND) DATA FINAL TIME
```

ACTUAL WIND DATA FROM 1965. DATA FOR SEPT, OCT, NOV.

```
T WST=0
X /17/16/15/14/20/22/19/15/11/10/03/10/14/10/12/16
X /13/11/10/07/14/07/14/07/01/03/06/06/07/09/14/09
```

X /10/07/07/09/16/03/03/06/10/13/12/14/21/16/07/08
 X /08/07/10/09/07/08/03/07/07/08/09/13/13/16/06/16

WS - WIND SPEED (KNCTS)
 WST - ACTUAL WIND SPEED DATA (KNOTS)

9 HYDROGEN USAGE RATE H2UR

The hydrogen usage rate H2UR is similar to the flywheel power usage FWPU of Option 1. H2UR will be equal to the pump power demand PPD as long as the amount of hydrogen in storage is greater than a specified low energy level LEL. When the hydrogen storage level H2SL drops below LEL, the pump will cease burning hydrogen. Whenever the pump is turned off, "down" time is accumulating. The system can only tolerate a set amount of down time per day DTA. If the amount of down time accumulated is equal to or greater than DTA, the system will begin to burn propane as a back up.

Therefore, in determining H2UR for the next interval of time, one first examines the system to determine if the system was accumulating down time in the previous time interval. If no down time was accumulating, then H2UR will equal PPD. If down time was accumulating and DTA has not been exceeded, the system will shut down for the next time interval. And if down time was accumulating and DTA has been exceeded, H2UR will equal PPD.

R H2UR.KL=CLIP(CLIP(PPD.K,0,DOWN.K,DTA+1),PPD.K,DTA+1,2) 9
 C DTA=0 9.1
 H2UR - HYDROGEN USAGE RATE (KW)

CLIP - DYNAMO LOGIC FUNCTION
 PPD - PUMP POWER DEMAND (KW)
 DOWN - DOWN TIME (HOURS/DAY)
 DTA - DOWN TIME ALLOWED (HOURS/DAY)
 DTAR - DOWN TIME ACCUMULATION RATE (KW)

10 PUMP POWER DEMAND PPD

The pump power demand of Option 2 differs from that of Option 1. In Option 1 it was desirous to have the system pumping whenever the wind was blowing. Due to the very large (assumed infinite for purposes here) storage capacity of Option 2, this is no longer important. Whenever the wind is blowing, hydrogen will be being produced. And whenever the system is pumping, hydrogen will be being consumed.

As has already been mentioned, with a 100 kW pump, the system would need to be operating approximately 60% of the time (load factor = .60) in order to meet the irrigation requirements. Since it is assumed here that it makes no difference when the pump is on, as long as it is on 60% of the time, the pump rating is reduced to 60 kW and DTA is set equal to zero. So instead of having a 100 kW pump operating 60% of the time as in Option 1, this system assumes a 60 kW pump operating 100% of the time.

```
A  PPD.K=CLIP(CLIP(0,PR/PEFF,TIME.K,IRROFF),0,TIME.K,IRON) 10.
C  PR=60          10.1
C  PEFF=.3        10.2
C  IRRON=276      10.3
C  IRROFF=366     10.4
      PPD - PUMP POWER DEMAND (KW)
      CLIP - DYNAMO LOGIC FUNCTION
      PR - PUMP RATING (KW)
      PEFF - PUMP EFFICIENCY (DECIMAL FRACTION)
      IRROFF - TIME IRRIGATION IS TURNED OFF
      IRRON - TIME IRRIGATION IS TURNED ON
```


11 PROPANE USAGE RATE PUR

The propane usage rate PUR corresponds to the tractor power usage in Option 1. Propane serves as the back up for Option 2. This back up is activated when the hydrogen storage level H2SL falls below a specified low energy level LEL. Therefore, at any point in time, PUR is equal to zero or PPD.

```
R    PUR.KL=CLIP(PPD.K,0,DOWN.K,DTA+1)    11
      PUR - PROPANE USAGE RATE (KW)
      CLIP - DYNAMO LOGIC FUNCTION
      PPD - PUMP POWER DEMAND (KW)
      DOWN - DOWN TIME (HOURS/DAY)
      DTA - DOWN TIME ALLOWED (HOURS/DAY)
```

12 PROPANE USED PU

Propane used is a level and accumulates the total amount of propane used during the simulation run. Each kilowatt-hour of propane used costs money and must thus be considered in the total cost of the system. PU at a point in time is equal to the value of PU at the previous point in time plus the amount of propane used during the last time interval. Zero initial conditions are assumed.

```
L    PU.K=PU.J+(DT){PUR.JK}*24    12
N    PU=0    INITIAL CONDITIONS    12.1
      PU - PROPANE USED (KWH)
      DT - TIME INTERVAL (DAYS)
      PUR - PROPANE USAGE RATE (KW)
```

13 DOWN TIME DOWN

DOWN is defined the same as in Option 1. However, since Option 2 is designed to operate continuously during June, July, and August, no actual down time will accumulate. The DOWN level

is kept in the program to make the model more flexible and to have Option 2 parallel Option 1.

```

L   DCWN.K=SSI.J*(DCWN.J+CLIP(0,DTI,H2SL.J,LEL))    13
N   DOWN=0      INITIAL CONDITIONS                 13.1
C   DTI=3                                13.2
C   LEL=225                                13.3
      DOWN - DOWN TIME (HOURS/DAY)
      SSI - SYSTEM STATUS INDEX (DIMENSIONLESS)
      CLIP - DYNAMO LOGIC FUNCTION
      DTI - DELTA TIME INTERVAL = (DT)*24 (HOURS)
      H2SL - HYDROGEN STORAGE LEVEL (KWH)
      LEL - LOW ENERGY LEVEL (KWH)

```

14 DOWN TIME ACCUMULATION RATE DTAR

DTAR is the same in Option 2 as in Option 1. Again it serves as an index of whether or not the system is accumulating down time while not actually directly influencing the level of DOWN.

```

R   DTAR.KL=CLIP(1,PPD.K,H2SL.K,LEL)    14
      DTAR - DOWN TIME ACCUMULATION RATE (KW)
      CLIP - DYNAMO LOGIC FUNCTION
      PPD - PUMP POWER DEMAND (KW)
      H2SL - HYDROGEN STORAGE LEVEL (KWH)
      LEL - LOW ENERGY LEVEL (KWH)

```

15 SYSTEM STATUS INDEX SSI

SSI resets the DOWN accumulator to zero every 24 hours at midnight the same as in Option 1. Figure 3.2.4 shows one 24 hour period as the computer interprets the table format.

```

A   SSI.K=TABHL(SSIT,TIME.K,IRRCN,IRROFF,.125)    15
T   SSIT=0/
X   1/1/1/1/1/1/1/0/1/1/1/1/1/1/1/0/1/1/1/1/1/1/0/
X   1/1/1/1/1/1/1/0/1/1/1/1/1/1/1/0/1/1/1/1/1/1/0/
      :
      :
X   1/1/1/1/1/1/1/0/1/1/1/1/1/1/1/0/1/1/1/1/1/1/0/
X   1/1/1/1/1/1/1/0/1/1/1/1/1/1/1/0/
      SSI - SYSTEM STATUS INDEX (DIMENSIONLESS)

```

TABHL - DYNAMO TABLE (HIGH - LOW) FUNCTION
 SSIT - SYSTEM STATUS INDEX TABLE
 IRROFF - TIME IRRIGATION IS TURNED OFF
 IRRON - TIME IRRIGATION IS TURNED ON

16 ENERGY SURPLUS (WIND) 2nd INDEX ESW2

ESW2 is the same as in Option 1, noting the amount of energy in the wind that can not be extracted due to the rated wind speed of the system.

Since infinite storage capacity is assumed, there is no need for an ESW1 as in Option 1.

```
A ESW2.K=CLIP(PE*8.36E-5*RS*(WS.K*WS.K*WS.K*(EXP(.42857*
X LOGN(HSF))))-CIS*CIS*CIS)-PER.K,0,WS.K,RWS) 16
  ESW2 IS USED TO EVALUATE THE RATED WIND SPEED OF THE SYSTEM
  ESW2 - ENERGY SURPLUS WIND (2ND INDEX) (KWH)
  CLIP - DYNAMO LOGIC FUNCTION
  PE - ROTOR EFFICIENCY (DECIMAL FRACTION)
  8.36E-5 - CONSTANT COEFFICIENT TO CONVERT TO DESIRED UNITS
  RS - ROTOR SIZE (SQUARE METERS)
  WS - WIND SPEED DATA (KNOTS)
  EXP(.42857)*LOGN(HSF) - HEIGHT POWER FUNCTION
  HSF - HEIGHT SCALING FACTOR = WINDMILL HEIGHT
      (IN METERS) DIVIDED BY ANEMOMETER HEIGHT
  CIS - CUT-IN-SPEED (KNOTS)
  RWS - RATED WIND SPEED (KNOTS)
```

17 TOTAL ENERGY SURPLUS (WIND) 2nd INDEX TESW2

TESW2 keeps a running total of ESW2 through the simulation run as in Option 1. This level is equal to TESW2 up to the previous point in time plus the surplus wind energy (2nd index) of the previous period. The units are kilowatt-hours and zero initial conditions are assumed.

```
L TESW2.K=TESW2.J+(DT)*(ESW2.J)*8 17
N TESW2=0 17.1
  TESW2 - TOTAL ENERGY SURPLUS WIND (2ND INDEX) (KWH)
  DT - TIME INTERVAL (DAYS)
  ESW2 - ENERGY SURPLUS WIND (2ND INDEX) (KWH)
```

18 (TOTAL) CAPITAL COST CC

Capital cost CC is expressed in dollars. CC includes the costs of the rotor, alternator, electrolysis cell, and the propane used and propane tank. The rotor capital cost is the same as in Option 1. Alternator costs in the neighborhood of \$50/kW rated output are common today for alternators in the size range represented by ALTRAT. The electrolysis cell capital cost (\$60/kW) is a projected figure from General Electric for the year 1985 (20). Operating costs include the cost of the back up. Propane tanks in the neighborhood of 500 gallon capacity (15,400 kWh) lease for around \$3/month (\$36/year). Propane is presently available at a cost of \$0.27/gallon (31 kWh). This cost will surely rise in coming years causing the cost of the back up to rise. Therefore, the system should be designed so as to require as little back up as possible during a "typical" year. It is assumed that there exists an exhausted gas well and piping already, thus their costs are not considered.

```

A  CC.K=RS*FCC+ALTRAT*ALCC+CELLRAT*CELLCC+TANKCC+PU.K*PCC  19
C  RCC=100  18.1
C  ALCC=50  18.2
N  CELLRAT=ALTRAT*REFF  18.3
C  CELLCC=60  18.4
C  TANKCC=36  18.5
C  PCC=8.7753E-3  18.6

```

```

CC - (TOTAL) CAPITAL COST ($)
RS - ROTOR SIZE (SQUARE METERS)
RCC - ROTOR CAPITAL COST ($/SQUARE METER)
ALTRAT - ALTERNATOR RATING (KW)
ALCC - ALTERNATOR CAPITAL COST (INCLUDING
      INSTALLATION AND RECTIFIER COSTS) ($/KW)
CELLRAT - CELL RATING (KW)
CELLCC - CELL CAPITAL COST ($/KW)
TANKCC - TANK CAPITAL COST ($/YEAR)
PU - PROPANE USED (KWH)
PCC - PROPANE CAPITAL COST ($/KWH)

```

CHAPTER 4 - RESULTS

4.1 A LOOK AT THE OUTPUT

When DYNAMO is used with system dynamics to model a system, two types of output are available; tabular and graphical. The results are plotted verses TIME with the graphical output.

The tabulated results of the last 30 days of simulation are shown in Table 4.1.1 for Option 1 and Table 4.1.2 for Option 2. These tables show the values of each quantity at the end of each 24 hour period. When examining these tables, it should be kept in mind that the calculations defined by the model are carried out every 3 hours, or 8 times between table entries.

Figures 4.1.1 and 4.1.2 show the graphical output from a 2 week period in Option 1. Here, a data point is calculated and plotted every .125 days (3 hours). By examining the graphical output, the operation of the system can easily be followed.

Figure 4.1.1 shows how the back up operates and in turn affects the total cost of the system. Whenever the wind is blowing faster than the cut-in speed, power is being generated by the system. This power is fed into the flywheel. The bottom two curves in Figure 4.1.1 show that when the wind is blowing well, the flywheel energy is increasing, and when the wind is not blowing well, the flywheel energy decreases (due to the fact that the pump is drawing energy from the flywheel).

Whenever the flywheel energy drops below the low energy level, the pump shuts down and ceases to draw energy from the flywheel until the wind has brought the flywheel energy back up above the low energy level. But, if the pump is shut down more

Table 4.1.1.1 - Tabulated Last 30 Days - Option 1

TIME E+00	WS E+00	PTFW E+00	FWE E+00	ESW1 E+00	TESW1 E+00	ESW2 E+00	TESW2 E+00	DTAR E+00	DOWN E+00	FWPU E+00	TPU E+00	TTEU E+00	CC LOADFAC E+00
60.	5.000	.00	110.3	.0	39.398	0.	978.81	111.11	18.000	111.11	95.000	3600.0	145.72
61.	10.000	40.86	1000.0	228.4	39.573	0.	978.81	1.00	12.000	111.11	.000	3900.0	145.79
62.	4.000	.00	1000.0	163.4	40.020	0.	978.81	1.00	12.000	111.11	.000	3900.0	145.78
63.	4.000	.00	604.1	.0	40.184	0.	978.81	1.00	18.000	111.11	95.000	3500.0	145.78
64.	6.000	.00	266.8	.0	40.184	0.	978.81	111.11	21.000	111.11	95.000	4500.0	145.90
65.	5.000	.00	809.8	.0	40.260	0.	978.81	1.00	15.000	111.11	.000	4800.0	145.95
66.	13.000	106.69	1000.0	163.4	41.150	0.	978.81	111.11	12.000	111.11	.000	4800.0	145.96
67.	18.000	306.57	988.0	.0	41.096	0.	978.81	1.00	.000	111.11	.000	4800.0	145.96
68.	5.000	.00	135.5	.0	43.002	0.	978.81	111.11	9.000	.00	.000	4800.0	145.96
69.	7.000	4.74	318.8	.0	43.472	0.	978.81	111.11	12.000	.00	.000	4800.0	145.96
70.	19.000	363.05	376.8	.0	43.472	0.	978.81	111.11	21.000	111.11	95.000	5100.0	146.02
71.	14.000	136.77	246.1	.0	43.788	0.	978.81	111.11	12.000	.00	.000	5400.0	146.03
72.	7.000	4.74	733.4	.0	43.788	0.	978.81	1.00	12.000	111.11	.000	5400.0	146.03
73.	8.000	14.03	558.3	.0	43.982	0.	978.81	111.11	12.000	111.11	.000	5400.0	146.03
74.	5.000	.00	506.6	.0	44.199	0.	978.81	111.11	6.000	111.11	.000	5400.0	146.03
75.	6.000	.00	482.6	.0	44.199	0.	978.81	111.11	12.000	111.11	.000	5400.0	146.03
76.	8.000	14.03	1000.0	682.1	44.333	0.	978.81	1.00	15.000	111.11	.000	5400.0	146.03
77.	6.000	.00	1000.0	163.4	45.407	0.	978.81	1.00	9.000	111.11	.000	5400.0	146.03
78.	6.000	.00	918.2	.0	45.965	0.	978.81	1.00	9.000	111.11	.000	5400.0	146.03
79.	14.000	136.77	1000.0	35.4	45.965	0.	978.81	1.00	15.000	111.11	.000	5400.0	146.03
80.	8.000	14.03	873.3	.0	46.139	0.	978.81	1.00	12.000	.00	.000	5400.0	146.03
81.	11.000	59.07	668.9	.0	46.257	0.	978.81	1.00	6.000	111.11	.000	5400.0	146.03
82.	7.000	4.74	687.2	.0	46.344	0.	978.81	1.00	12.000	111.11	.000	5400.0	146.03
83.	13.000	106.69	425.9	.0	46.344	0.	978.81	111.11	21.000	111.11	95.000	5700.0	146.14
84.	6.000	.00	296.4	.0	46.344	0.	978.81	111.11	9.000	.00	.000	6000.0	146.20
85.	13.000	106.69	414.2	.0	46.344	0.	978.81	111.11	21.000	111.11	95.000	6300.0	146.26
86.	1.000	.00	639.0	.0	46.344	0.	978.81	1.00	3.000	111.11	.000	6600.0	146.32
87.	7.000	4.74	769.5	.0	47.015	0.	978.81	1.00	15.000	111.11	.000	6600.0	146.32
88.	10.000	40.86	655.3	.0	47.478	0.	978.81	1.00	12.000	111.11	.000	6600.0	146.32
89.	6.000	.00	579.3	.0	47.847	0.	978.81	111.11	9.000	111.11	.000	6600.0	146.32
90.	14.000	136.77	1000.0	69.5	48.074	0.	978.81	1.00	12.000	111.11	.000	6600.0	146.32

Table 4.1.2 - Tabulated Last 30 Days - Option 2

TIME	WS	PFR	EPFR	H2FC	ESW2	IESW2	H2SL	H2UR	PPD	PUR	PJ	DOWN	DIAR	CC
E+00	E+00	E+00	E+00	E+00	E+00	E+00	E+00	E+00	E+00	E+00	E+00	E+00	E+00	E+00
335.	5.000	-4.61	.00	.00	0.	622.88	113.17	200.00	200.00	.00	.0	.0000	1.0000	109.26
337.	10.000	26.00	5.91	5.06	0.	622.88	109.56	200.00	200.00	.00	.0	.0000	1.0000	109.26
339.	4.000	-6.75	.00	.00	0.	622.88	105.70	200.00	200.00	.00	.0	.0000	1.0000	109.26
339.	4.000	-6.75	.00	.00	0.	622.88	101.31	200.00	200.00	.00	.0	.0000	1.0000	109.26
340.	6.000	-1.43	.00	.00	0.	622.88	96.76	200.00	200.00	.00	.0	.0000	1.0000	109.26
341.	5.000	-4.61	.00	.00	0.	622.88	92.45	200.00	200.00	.00	.0	.0000	1.0000	109.26
342.	13.000	67.89	42.92	36.69	0.	622.88	89.00	200.00	200.00	.00	.0	.0000	1.0000	109.26
343.	18.000	195.09	185.34	158.46	0.	622.88	85.76	200.00	200.00	.00	.0	.0000	1.0000	109.26
344.	5.000	-4.61	.00	.00	0.	622.88	82.28	200.00	200.00	.00	.0	.0000	1.0000	109.26
345.	7.000	3.01	.07	.06	0.	622.88	78.32	200.00	200.00	.00	.0	.0000	1.0000	109.26
346.	19.000	231.03	219.48	187.65	0.	622.88	73.77	200.00	200.00	.00	.0	.0000	1.0000	109.26
347.	14.000	87.03	63.98	54.70	0.	622.88	69.76	200.00	200.00	.00	.0	.0000	1.0000	109.26
348.	7.000	3.01	.07	.06	0.	622.88	65.55	200.00	200.00	.00	.0	.0000	1.0000	109.26
349.	8.000	8.93	.66	.56	0.	622.88	61.49	200.00	200.00	.00	.0	.0000	1.0000	109.26
350.	5.000	-4.61	.00	.00	0.	622.88	57.54	200.00	200.00	.00	.0	.0000	1.0000	109.26
351.	6.000	-1.43	.00	.00	0.	622.88	53.22	200.00	200.00	.00	.0	.0000	1.0000	109.26
352.	8.000	8.93	.66	.56	0.	622.88	49.58	200.00	200.00	.00	.0	.0000	1.0000	109.26
353.	6.000	-1.43	.00	.00	0.	622.88	45.95	200.00	200.00	.00	.0	.0000	1.0000	109.26
354.	6.000	-1.43	.00	.00	0.	622.88	42.09	200.00	200.00	.00	.0	.0000	1.0000	109.26
355.	14.000	87.03	63.98	54.70	0.	622.88	37.79	200.00	200.00	.00	.0	.0000	1.0000	109.26
356.	8.000	8.93	.66	.56	0.	622.88	33.86	200.00	200.00	.00	.0	.0000	1.0000	109.26
357.	11.000	37.59	12.83	10.97	0.	622.88	29.90	200.00	200.00	.00	.0	.0000	1.0000	109.26
358.	7.000	3.01	.07	.06	0.	622.88	25.73	200.00	200.00	.00	.0	.0000	1.0000	109.26
359.	13.000	67.89	42.92	36.69	0.	622.88	21.22	200.00	200.00	.00	.0	.0000	1.0000	109.26
360.	6.000	-1.43	.00	.00	0.	622.88	16.95	200.00	200.00	.00	.0	.0000	1.0000	109.26
361.	13.000	67.89	42.92	36.69	0.	622.88	12.40	200.00	200.00	.00	.0	.0000	1.0000	109.26
362.	1.000	-5.95	.00	.00	0.	622.88	8.54	200.00	200.00	.00	.0	.0000	1.0000	109.26
363.	7.000	3.01	.07	.06	0.	622.88	4.83	200.00	200.00	.00	.0	.0000	1.0000	109.26
364.	10.000	26.00	5.91	5.06	0.	622.88	.84	200.00	200.00	.00	.0	.0000	1.0000	109.26
365.	6.000	-1.43	.00	.00	0.	622.88	.66	200.00	200.00	.00	.0	.0000	1.0000	109.26
366.	14.000	87.03	63.98	54.70	0.	622.88	.65	200.00	200.00	.00	.0	.0000	1.0000	109.31
										200.00	3000.0	9.0000	1.0000	109.28
										.00	6600.0	9.0000	1.0000	109.31

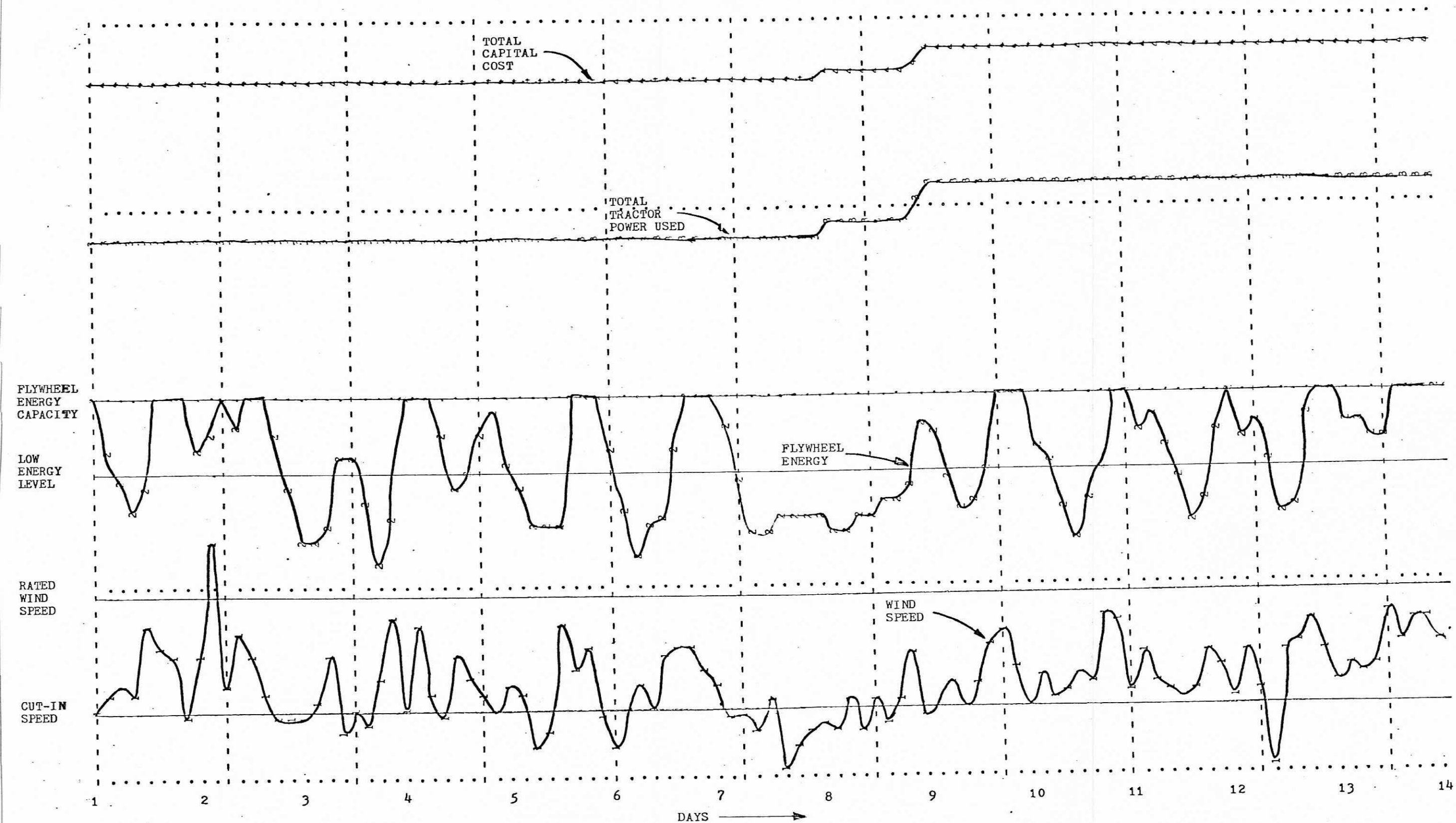


Figure 4.1.1 - Graphical Output - Option 1

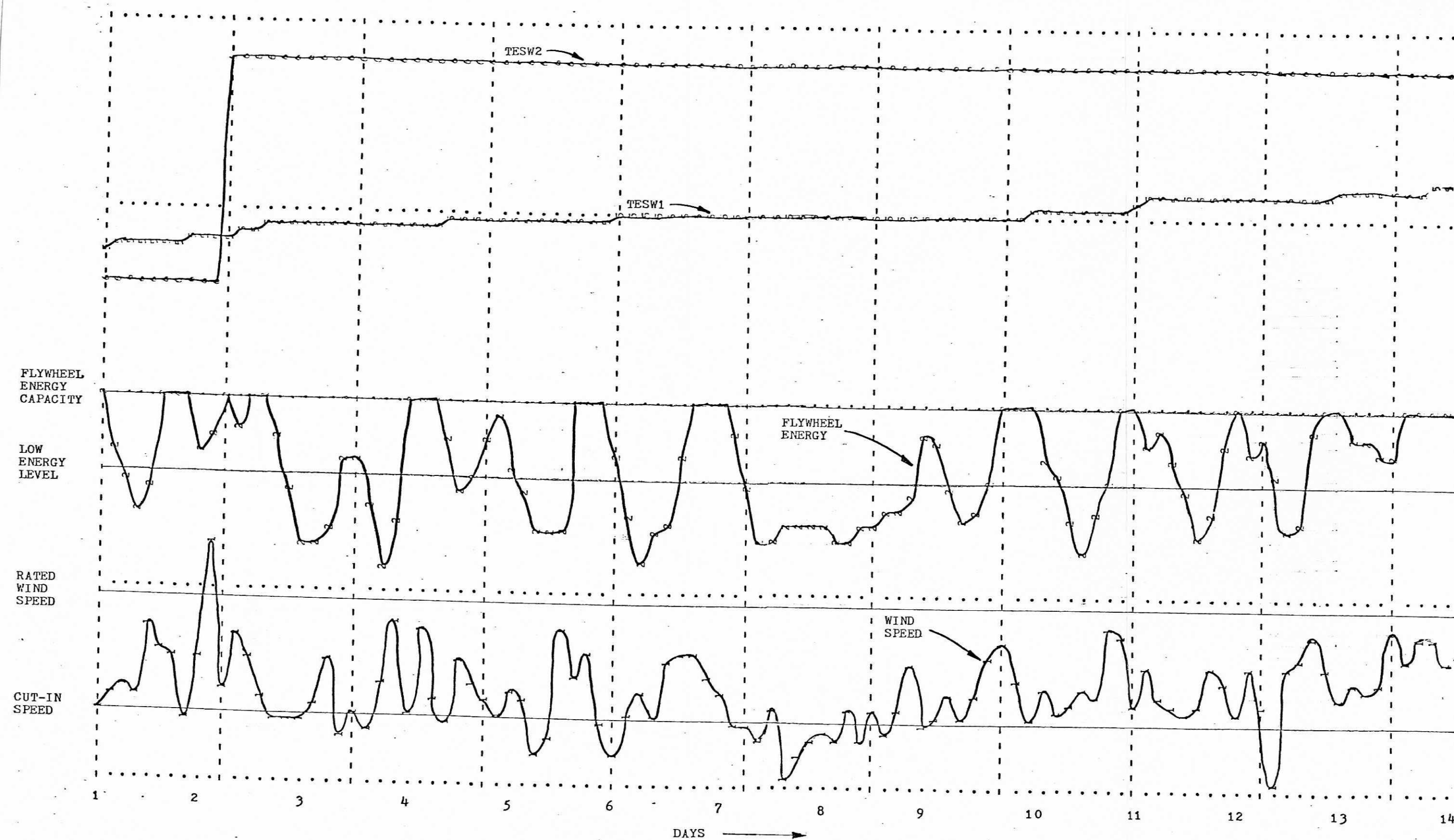


Figure 4.1.2 - Graphical Output - Option 1

than the allowed amount of time per day, the back up (tractor energy in this case) is activated. This is shown between the 7th and 8th days in Figure 4.1.1. This use of tractor energy costs money, which is reflected in the increase in the total capital cost of the system.

Figure 4.1.2 shows the accumulation of "surplus" energy. Whenever the flywheel is filled to capacity with energy and the wind is generating additional energy, this surplus energy is noted by TESW1. This is shown between days 1 and 2 in Figure 4.1.2. Whenever the wind is blowing faster than the rated wind speed of the system, the energy available, but not extracted by the system, is noted by TESW2 (see Figure 4.1.2).

Figures 4.1.3 and 4.1.4 show the graphical output of two 2 week periods in Option 2. Figure 4.1.3 shows a period from the 2nd quarter of the year (December, January, February). During this period, no irrigation is taking place. Therefore, all the energy extracted from the wind is going into the production of hydrogen. Whenever the wind is blowing faster than the rated wind speed of the system, the energy available, but not extracted by the system, is noted by TESW2.

Figure 4.1.4 shows the same 2 week period of time as Figures 4.1.1 and 4.1.2. Irrigation is taking place during this period, therefore, hydrogen is being used at a steady rate. If the hydrogen storage level were to drop below the low energy level, the back up (propane) would be activated. Use of propane causes an increase in the total cost of the system. Since the hydrogen storage level is well above the low energy level, no propane is

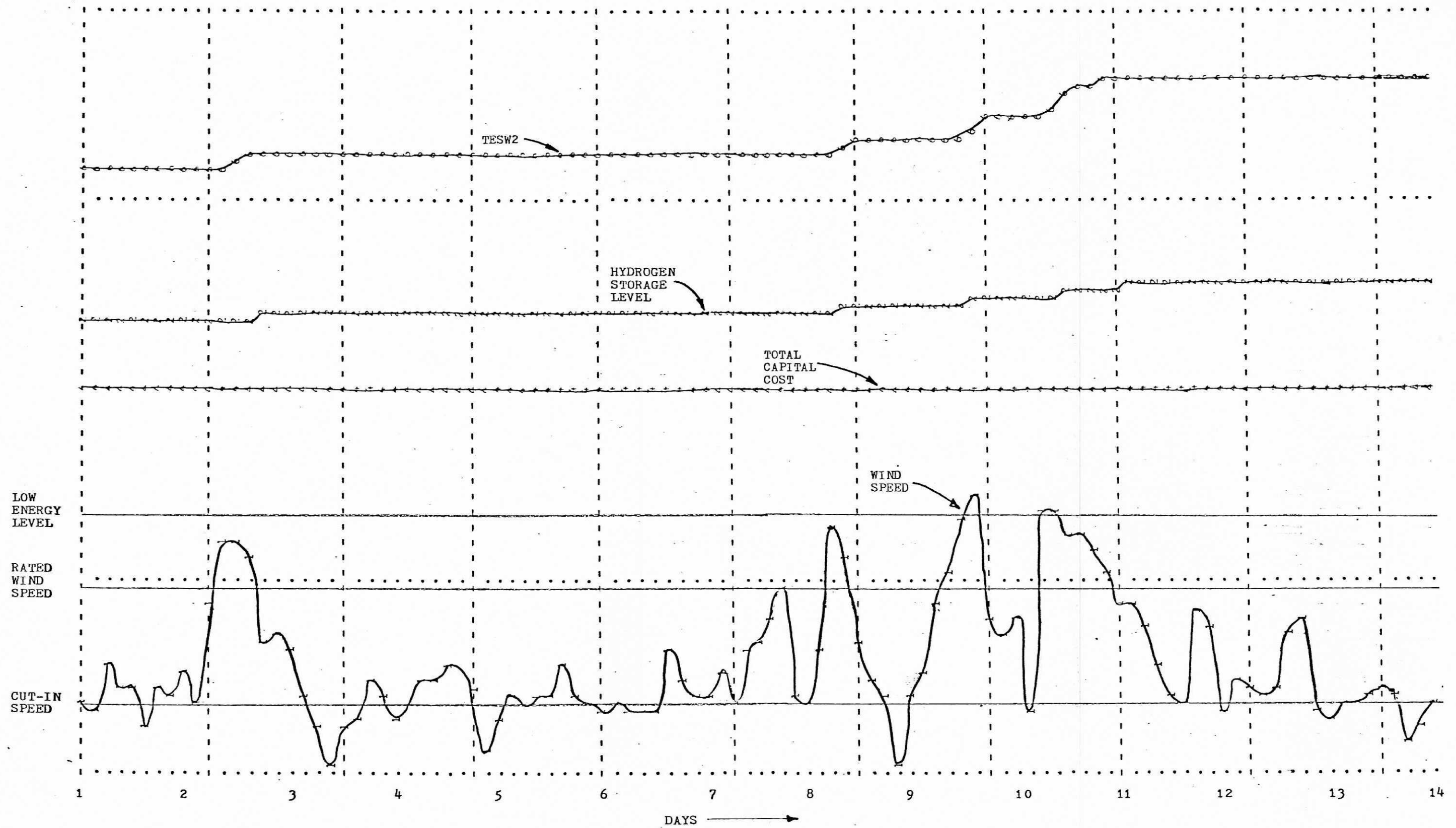


Figure 4.1.3 - Graphical Output - Option 2

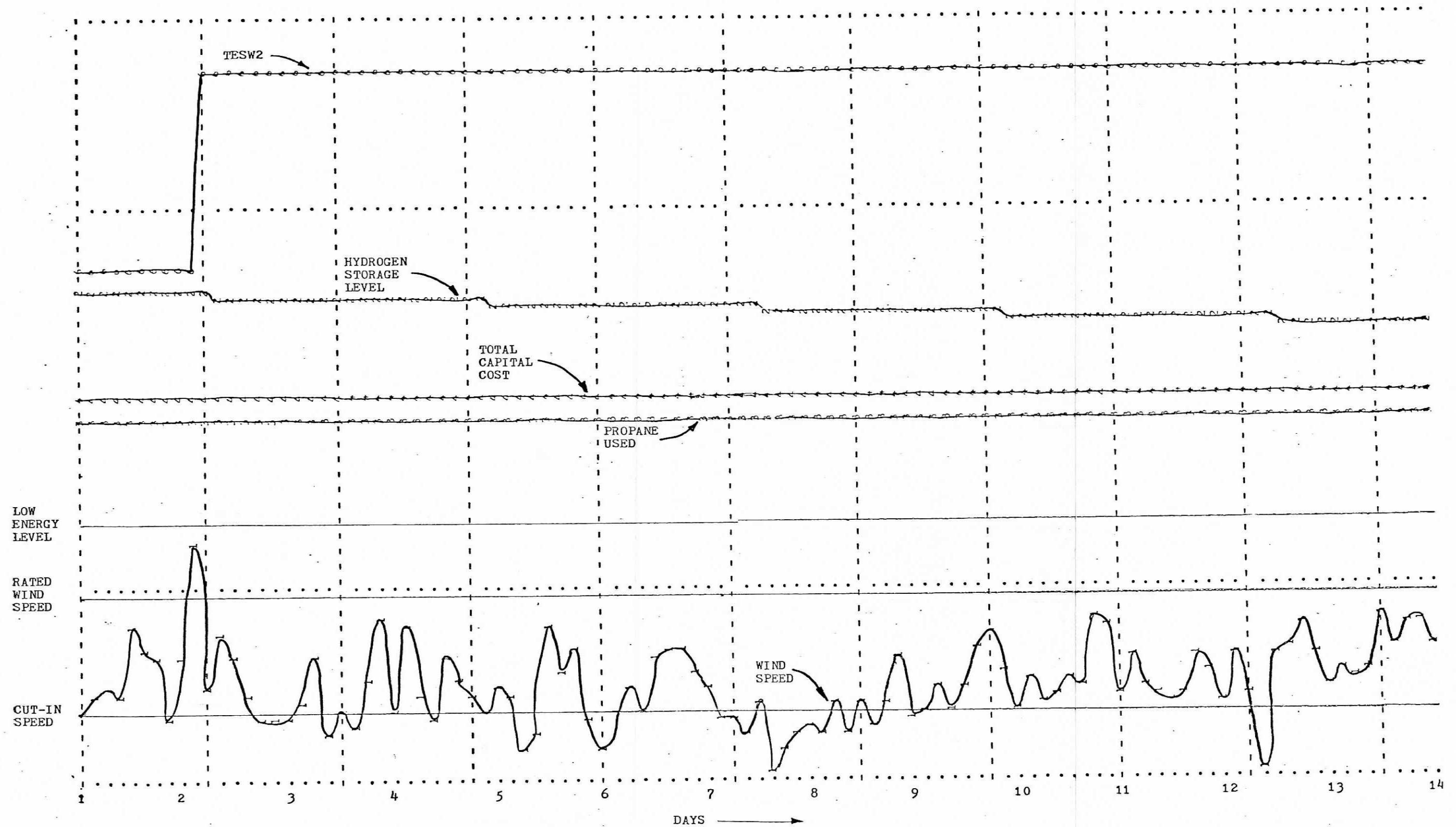


Figure 4.1.4 - Graphical Output - Option 2

used during the 2 week period shown in Figure 4.1.4.

4.2 BASIC ECONOMICS OF THE SYSTEMS

The final total capital cost at the end of a simulation run contains two costs, the cost of the system itself and the cost of operating the system for one year. The cost of the back up systems constitute the operating cost for one year, while the rest of the total capital cost is the cost of the system itself. Maintenance costs are assumed to be negligible and are not considered. Taxes are also not considered here. These cost are summarized in Table 4.2.1.

OPTION 1. The construction of the system modeled by Option 1 requires \$145,000. It is assumed that a farmer wishing to install such a system could borrow the necessary capital at 10% annual interest.

Case 1. In case 1 the lifetime of the system is assumed to be 10 years with zero salvage value at the end of that time. It is also assumed that the farmer will make 12 monthly payments each year to the bank against his loan for the system installation. The amount of each monthly payment is calculated making use of the formula for the Capital Recovery Factor (21) given in EQN 4.2.1.

$$A = P \frac{i(1+i)^N}{(1+i)^N - 1} \quad \text{EQN 4.2.1}$$

where A = end-of-period cash flows in a series continuing for a specified number of periods;

P = present sum of money. The equivalent worth of one or more cash flows at a relative point in time called the present;

Table 4.2.1
Costs From 1965 Wind Data

	<u>Option 1</u>	<u>Option 2</u>
Total CC (\$)	146,680	109,286
System Cost (\$)	145,000	109,260
Operating Cost (\$)	1,320	26

i = the effective interest rate per period;
 N = the number of compounding periods.

With $P = \$145,000$

$i = 10\%$ per year/12 months per year,

$N = 20$ years * 12 months per year,

then $A = \$1,916/\text{month} = \$22,994/\text{year}$

The total cost of the system for one year, then, is:

$$\begin{array}{r} \$ 22,994 - \text{capital recovery cost} \\ + \$ 1,320 - \text{operating cost} \\ \hline \$ 24,314 \end{array}$$

The number of kilowatt-hours of energy produced during this same period is:

$$100 \text{ kW rating} * 90 \text{ days} * 24 \text{ hours/day} * \text{LOADFAC} = 131,695 \text{ kWh}$$

Dividing the total cost of the system for one year by the number of kilowatt-hours produced in one year yields:

$$\$24,314/131,695 \text{ kWh} = \$0.18/\text{kWh}$$

Case 2. In case 2 the lifetime of the system is assumed to be 20 years. The windmill and flywheel system should actually have a lifetime of more than this, but the well and pump may have a lifetime of only 10 to 15 years.

Using EQN 4.2.1 yields:

$$A = \$1,399/\text{month} = \$16,791/\text{year}$$

Therefore, the total cost of the system for one year is:

$$\begin{array}{r} \$ 16,791 - \text{capital recovery cost} \\ + \$ 1,320 - \text{operating cost} \\ \hline \$ 18,111 \end{array}$$

which comes to a cost of $\$0.14/\text{kWh}$.

OPTION 2. The construction of the system modeled by Option 2 requires \$109,260. Again, 10% annual interest is assumed.

Case 1. In case 1 a 10 year lifetime with zero salvage value is assumed. Using EQN 4.2.1 yields:

$$A = \$1,444/\text{month} = \$17,327/\text{year}$$

The total cost of the system for one year comes to:

$$\begin{array}{r} \$ 17,327 - \text{capital recovery cost} \\ + \$ \quad 26 - \text{operating cost} \\ \hline \$ 17,353 \end{array}$$

The total number of kilowatt-hours produced during the same period of time is:

$$60 \text{ kW} * 90 \text{ days} * 24 \text{ hours/day} = 129,600 \text{ kWh}$$

This results in an energy cost of \$0.13/kWh.

Case 2. In case 2 a 20 year lifetime with zero salvage value is assumed. Using EQN 4.2.1 yields:

$$A = \$1,054/\text{month} = \$12,658/\text{year}$$

The total cost of the system for one year equals:

$$\begin{array}{r} \$ 12,658 - \text{capital recovery cost} \\ + \$ \quad 26 - \text{operating cost} \\ \hline \$ 12,684 \end{array}$$

which comes to an energy cost of \$0.10/kWh.

CHAPTER 5 - DISCUSSION AND COMMENTS

5.1 WHY THESE MODELS?

Only two system models are presented in this paper. There are a number of system models that can be formulated in attempting to design a system that would harness the wind. Option 1 was formulated to be as simple a design as possible, converting the wind power to mechanical power and using this mechanical power directly to accomplish the task of pumping irrigation water. Starting with this basic system, many modifications are possible. The flywheel storage could be eliminated and replaced with a large water tank or reservoir. The system could then pump water year round whenever the wind was blowing, storing surplus for periods of low wind. Or add an alternator to the system and you can drive the irrigation pump with an electric motor. During the non-summer months the electricity produced could be used for grain drying, space heating, and other demands presented on the farm. Electric utility off peak power could serve as back up. Add an electrolysis unit to the system and the system would be essentially that presented by Option 2.

Option 1 was chosen as a system to be modeled due to its relative simplicity. The balancing of the rotor size and flywheel (for energy storage) size deserves a more systematic approach than is presented here.

Using electricity produced by the wind to power irrigation pumps has some advantages. However, in order to provide the necessary back up, the irrigated field must be located near a

three phase transmission line to minimize the cost of distribution lines. For the same reason the field must also be located close to other farm buildings if the electricity produced during non-irrigation periods is to be used. The possibility of using existing power company networks as an "infinite" storage device does exist. This would probably require government intervention on the state or federal level, however, before the utility companies and other parties involved could reach an agreement.

Option 2 has several advantages over the other possibilities discussed. The midwest, where it is proposed to install such wind powered irrigation systems, is blessed with many natural gas fields. Natural gas is presently used to power approximately 80% of the irrigation pumps in western Kansas. In years to come, more and more of these gas fields will begin to run out of natural gas. There are already numerous depleted wells in the area. Existing gas engines and pipelines could be used in Option 2. Depleted wells are available at nominal cost, and the turbine could be used year round. By expanding the system, hydrogen could be produced in large enough quantity to be used as the primary energy source on the farm. The idea of a hydrogen economy is not new. (22,23).

When examining Option 2 it should be pointed out that this system could not be built today for the cost cited in the model. The primary obstacle to this is the large electrolysis cell required. The specifications used in this paper reflect 1985 projected cells.

5.2 WHY THESE NUMBERS?

It has already been pointed out that the selection of the

rotor size - flywheel size combination in Option 1 deserves a more sophisticated approach than DYNAMO can give. However, several different combinations were considered. None of these combinations placed "too large" a dependency on the back up system. "Too large" is fairly arbitrary. It was felt that the farmer should not have to use the back up more than once or twice a week. From Figure 5.2.1 it can be seen that rotor size of 1100 square meters with a flywheel energy capacity of 1000 kilowatt-hours is about in the middle of the combinations that provide a load factor of approximately 60%. It was, therefore, decided to use a rotor size of 1100 m² and a flywheel with 1000 kWh of storage capacity in the simulation of Option 1.

In both Option 1 and Option 2, the cost of the back up is actually less than the cost of operating the system itself. This enforced the desire to use as little back up as possible. A 'noneconomic' decision must be made to use as little back up as possible since an attempt to simply minimize the cost would result in the size of the rotor increases, the cost of the system increases linearly. Therefore, it is desired to have the rotor as small as possible while still using as little back up as possible. Figure 5.2.3 shows that a rotor size of 700 square meters requires very little propane be used as back up in Option 2. Therefore, a rotor size of 700 square meters was used in the simulation of Option 2. Figure 5.2.3 is based on 1965 wind data. This data was determined to be "typical" compared to averages over 25 years.

5.3 WHY A SYSTEM DYNAMICS APPROACH?

System dynamics has been criticized by many (24) on the

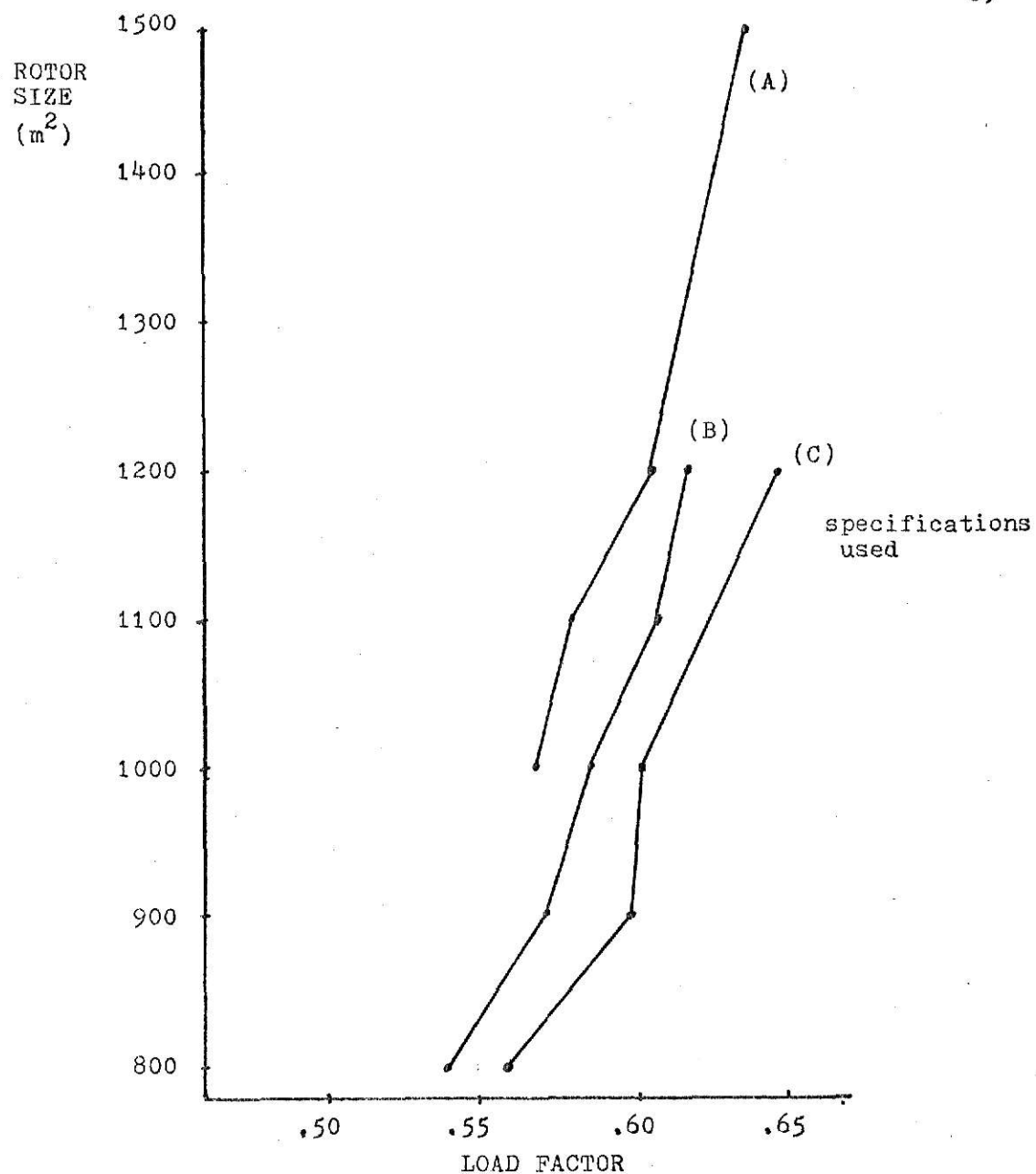


Figure 5.2.1 - Rotor Size -vs- Load Factor for Option 1

- (A) Flywheel Energy Capacity = 800 kWh (LEL=400, DTA=15)
- (B) Flywheel Energy Capacity = 1000 kWh (LEL=500, DTA=15)
- (C) Flywheel Energy Capacity = 1200 kWh (LEL=600, DTA=15)

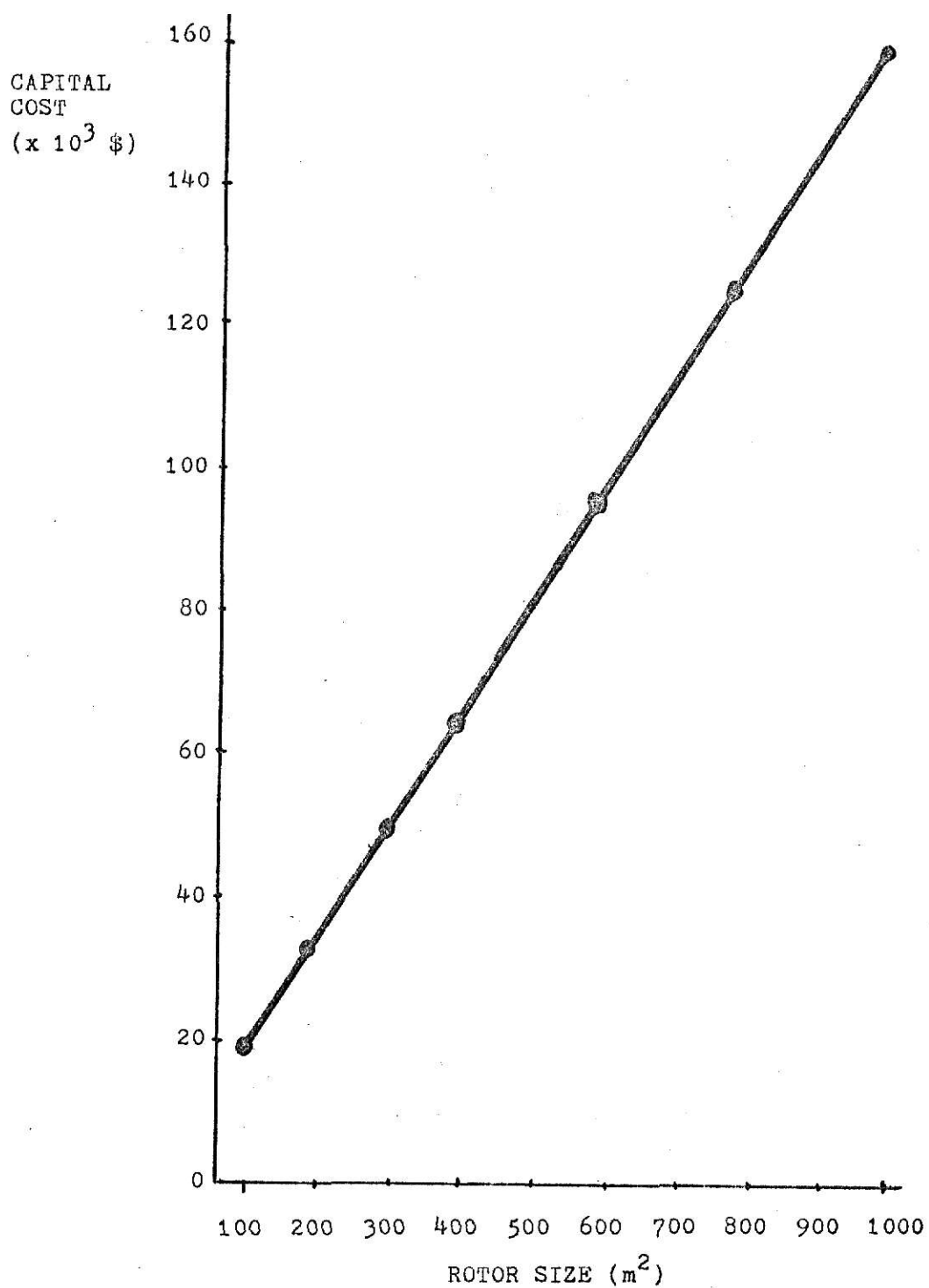


Figure 5.2.2 - Capital Cost -vs- Rotor Size for Option 2

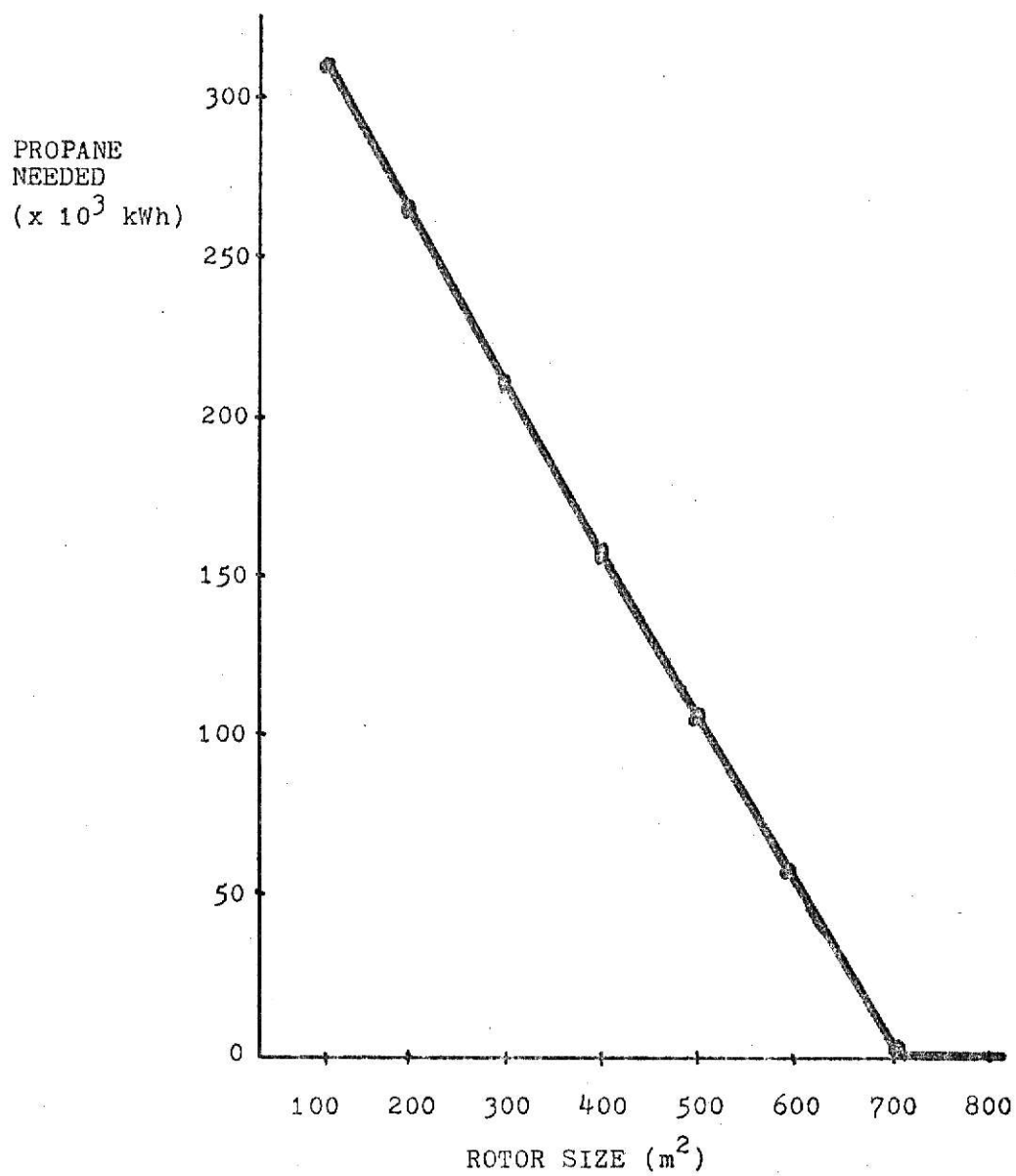


Figure 5.2.3 - Propane Needed -vs- Rotor Size for Option 2*

*1965 wind data

grounds that the assumptions used in many models have not been relevant to economic theory and that the absence of proper estimation techniques result in considerable abstraction from reality (25). But, as has been stated already, the models presented here bear no claim of being "the" correct models. They merely represent the best models available at the time given the available knowledge.

It has been said that increased promotion adds to awareness of a product (26). Such is the case with system dynamics and the use of DYNAMO. Originally developed as a tool for use in solving industrial management problems, system dynamics have now been used to model a wide variety of topics (4,5,6,7).

The author feels, that by using system dynamics in an area that in the past has been ignorant of the subject, he can expose its existence. It might be argued that DYNAMO does not present the best approach to attacking the problem of modeling wind powered irrigation systems. But it is an approach that can be taken, And it is the author's hope that other people working in these areas will become aware of the potential of system dynamics as a method for problem solving.

5.4 A LOOK TO THE FUTURE

The energy costs of Option 1 and Option 2 compared with present energy costs are shown in Table 5.4.1. As can be seen, even the lowest cost associated with the proposed systems is $2\frac{1}{2}$ times as high as the higher of the two present energy costs. But, look to the future.

By the year 1985 construction of Option 2 should be possible. Natural gas prices will have surely risen considerable by then

Table 5.4.1 - Energy Costs

		<u>cost (\$/kWh)</u>
Option 1	(10 year loan)	0.18
	(20 year loan)	0.14
Option 2	(10 year loan)	0.13
	(20 year loan)	0.10
Present	electricity	0.04
	natural gas	0.01

due to, if nothing else, the relative scarcity of the commodity. The cost of fuel to utility companies will likewise have risen resulting in a higher cost to the consumer for electric energy. The cost of constructing the systems modeled will similarly rise. But since these systems use the free wind as their primary source of energy, the rise in energy costs for Option 1 and Option 2 should not be as great as the rise in price of present forms of energy. It is not unlikely, then, that within the next 10 to 15 years systems such as those presented here will produce energy at a lower cost than present utilities. Add to that the fact that our natural resources such as gas and oil will not last forever , but the wind should continue to blow always. Therefore, it would not be unreasonable to expect these types of energy producing devices to become wide spread in the future.

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APPENDIX 1

PROGRAM LISTINGS FOR OPTION 1 AND OPTION 2

OPTION 1

OPTION 1 WPI

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*      OPTION 1 WPI
L      TAE.K=FWE.J+(DT)*(PTFW.JK-FWPU.JK+TPU.JK)*24*GBE*FWEFF  1
N      TAE=.75*FWEC      INITIAL CONDITIONS      1.1
C      GBE=.95           1.2
C      FWEFF=.95        1.3
NOTE    TAE - TOTAL AVAILABLE ENERGY (KWH)
NOTE    FWE - FLYWHEEL ENERGY (KWH)
NOTE    DT - TIME INTERVAL (DAYS)
NOTE    PTFW - POWER TO FLYWHEEL (KW)
NOTE    FWPU - FLYWHEEL POWER USAGE (KW)
NOTE    TPU - TRACTOR POWER USAGE (KW)
NOTE    GBE - GEAR BOX EFFICIENCY (DECIMAL FRACTION)
NOTE    FWEFF - FLYWHEEL EFFICIENCY (DECIMAL FRACTION)
A      FWE.K=MIN(FWEC,TAE.K)      2
C      FWEC=1000      2.1
NOTE    FWE - FLYWHEEL ENERGY (KWH)
NOTE    MIN - DYNAMO FUNCTION FOR 'MINIMUM'
NOTE    FWEC - FLYWHEEL ENERGY CAPACITY (KWH)
NOTE    TAE - TOTAL AVAILABLE ENERGY (KWH)
R      PTFW.KL=CLIP(PFR.K,0,PFR.K,0)      3
NOTE    PTFW - POWER TO FLYWHEEL (KW)
NOTE    CLIP - DYNAMO LOGIC FUNCTION
NOTE          (SEE APPENDIX 2)
NOTE    PFR - POWER FROM ROTOR (KW)
A      PFR.K=RE*8.36E-5*RS*(WSA.K*WSA.K*WSA.K*(EXP(.42857*LOGN(HSF))))-
X      CIS*CIS*CIS)      4
C      RE=.30      4.1
C      RS=1100      4.2
C      HSF=5      4.3
C      CIS=8      4.4
NOTE    PFR - POWER FROM ROTOR (KW)
NOTE    RE - ROTOR EFFICIENCY (DECIMAL FRACTION)
NOTE    8.36E-5 - CONSTANT COEFFICIENT TO CONVERT TO DESIRED UNITS
NOTE    RS - ROTOR SIZE (SQUARE METERS)
NOTE    WSA - WIND SPEED (ADJUSTED) (KNOTS)
NOTE    EXP(.42857)*LOGN(HSF) - HEIGHT POWER FUNCTION
NOTE    HSF - HEIGHT SCALING FACTOR = WINDMILL HEIGHT
NOTE          (IN METERS) DIVIDED BY ANEMOMETER HEIGHT.
NOTE          ANEMOMETER HEIGHT = 6 METERS IN 1965.
NOTE    CIS - CUT-IN-SPEED (KNOTS)
A      WSA.K=CLIP(RWS,WS.K,WS.K,RWS)      5
C      RWS=22      5.1
NOTE    WSA - WIND SPEED (ADJUSTED) (KNOTS)
NOTE    CLIP - DYNAMO LOGIC FUNCTION
NOTE    RWS - RATED WIND SPEED (KNOTS)
NOTE    WS - WIND SPEED DATA (KNOTS)
NOTE
NOTE    ACTUAL WIND DATA FROM JUN, JUL, AND AUG 1965
A      WS.K=TABLE(WST,TIME.K,0,90,.125)      6
T      WST=0
X      /09/09/11/10/14/16/16/12/15/09/09/06/01/08/16/14
X      /12/12/07/14/10/12/07/08/06/05/01/05/12/13/15/10
X      /04/10/04/14/09/13/09/12/20/06/07/05/06/06/08/15
X      /09/07/06/01/10/19/15/08/10/11/10/18/15/14/07/14
X      /28/11/17/14/10/07/07/07/09/14/05/03/06/12/19/08
X      /18/10/07/14/12/10/08/11/10/04/05/18/13/15/07/04

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X      /08/11/08/14/15/15/13/11/07/07/05/09/01/04/05/06
X      /05/09/05/09/06/09/14/07/08/11/08/11/15/17/13/08
X      /12/09/10/12/11/19/18/10/14/11/10/09/10/14/13/09
X      /14/10/01/14/15/18/14/11/13/12/13/19/15/18/18/15
X      /16/18/10/07/04/11/15/08/10/09/06/05/09/10/14/15
X      /18/06/10/15/15/14/13/10/08/07/06/10/04/09/14/05
X      /08/03/13/10/20/15/08/07/13/15/13/10/12/13/12/13
X      /14/09/11/20/18/20/20/15/20/21/12/15/14/17/22/08
X      /07/05/08/15/15/17/22/16/15/12/13/18/14/18/20/10
X      /08/07/13/15/14/18/12/06/09/12/12/18/15/18/16/11
X      /13/07/07/13/10/10/14/13/08/11/05/10/11/07/10/07
X      /10/18/09/09/04/05/03/06/07/09/18/11/12/15/10/13
X      /09/15/15/09/11/13/09/05/04/04/05/05/01/05/11/07
X      /08/04/11/13/11/01/01/07/07/03/07/08/04/08/07/07
X      /08/07/04/11/11/11/11/09/17/06/09/16/16/12/10/10
X      /14/10/14/16/23/18/21/10/11/13/09/09/10/16/15/15
X      /18/06/14/10/09/07/06/01/06/06/07/11/10/09/09/07
X      /10/07/08/09/10/08/03/07/08/07/08/06/10/12/12/09
X      /09/08/11/15/17/20/15/07/15/10/12/18/19/13/17/15
X      /08/05/05/07/10/15/10/15/10/10/14/16/16/14/10
X      /16/08/07/10/15/16/13/10/12/08/08/15/15/09/13/08
X      /08/03/17/21/17/12/13/12/12/06/05/10/10/04/08/12
X      /11/06/04/08/12/14/16/12/12/25/06/05/14/14/11/08
X      /08/07/10/10/10/11/14/04/05/03/03/04/05/07/04/05
X      /07/10/11/18/05/04/18/10/08/04/07/07/16/14/15/04
X      /03/07/05/07/14/06/10/04/05/06/06/06/03/08/07/06
X      /09/10/07/09/12/14/10/05/10/10/03/14/14/19/15/13
X      /15/10/11/18/14/15/13/18/03/20/05/05/08/04/04/05
X      /11/10/14/17/03/10/10/07/03/04/07/03/03/08/08/19
X      /06/06/05/05/03/10/03/14/05/07/06/12/13/11/08/07
X      /08/09/07/15/15/06/11/08/13/13/10/15/14/09/08/05
X      /06/09/10/14/12/08/09/06/07/08/06/10/16/12/19/08
X      /10/06/07/14/14/17/15/06/08/10/13/12/16/14/12/06
X      /11/11/08/10/09/14/10/14/14/09/07/07/09/08/16/08
X      /06/05/05/18/13/10/11/11/11/06/11/14/11/13/05/07
X      /08/07/05/07/10/08/11/13/11/13/11/09/05/08/10/06
X      /08/05/05/06/07/04/10/13/11/14/10/10/17/08/05/01
X      /05/04/03/10/17/18/09/07/09/10/11/14/16/12/08/10
X      /09/10/13/15/16/09/10/06/10/07/08/15/11/15/14/14
NOTE      WS - WIND SPEED (KNOTS)
NOTE      WST - ACTUAL WIND SPEED DATA (KNOTS)
R      FWPU,KL=CLIP(CLIP(PPD.K,0,DOWN.K,DTA+1),PPD.K,DTAR.JK,2) 7
C      DTA=15 7.1
NOTE      FWPU - FLYWHEEL POWER USAGE (KW)
NOTE      CLIP - DYNAMO LOGIC FUNCTION
NOTE      PPD - PUMP POWER DEMAND (KW)
NOTE      DOWN - DOWN TIME (HOURS/DAY)
NOTE      DTA - DOWN TIME ALLOWED (HOURS/DAY)
NOTE      DTAR - DOWN TIME ACCUMULATION RATE (KW)
A      PPD.K=PR/TEFF 8
C      PR=100 8.1
C      TEFF=.90 8.2
NOTE      PPD - PUMP POWER DEMAND (KW)
NOTE      PR - PUMP RATING (KW)
NOTE      TEFF - COMBINED FLYWHEEL-TO-PUMP AND FLYWHEEL
NOTE      EFFICIENCIES (DECIMAL FRACTION)
R      TPU,KL=CLIP(TPIFW.K,0,DOWN.K,DTA+1) 9
NOTE      TPU - TRACTOR POWER USAGE (KW)

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OPTION 1 WPI

```

X      1/1/1/1/1/1/1/0/1/1/1/1/1/1/0
NOTE      SSI - SYSTEM STATUS INDEX (DIMENSIONLESS)
NOTE      SSIT - SYSTEM STATUS INDEX TABLE
A      ESW1,K=MAX(TAE,K-FWEC,0)      15
NOTE      ESW1 IS USED TO EVALUATE THE ROTOR SIZE -
NOTE      FLYWHEEL SIZE COMBINATION
NOTE      ESW1 - ENERGY SURPLUS WIND (1ST INDEX) (KWH)
NOTE      MAX - DYNAMO FUNCTION FOR 'MAXIMUM'
NOTE      TAE - TOTAL AVAILABLE ENERGY (KWH)
NOTE      FWEC - FLYWHEEL ENERGY CAPACITY (KWH)
L      TESW1,K=TESW1.J+(DT)*(ESW1.J)*8      16
N      TESW1=0      INITIAL CONDITIONS      16.1
NOTE      TESW1 - TOTAL ENERGY SURPLUS WIND (1ST INDEX) (KWH)
NOTE      DT - TIME INTERVAL (DAYS)
NOTE      ESW1 - ENERGY SURPLUS WIND (1ST INDEX) (KWH)
A      ESW2,K=CLIP(RE*8.36E-5*RS*(WS,K*WS,K*WS,K*(EXP(.42857*LOGN(HSF))))
X      -CIS*CIS*CIS)-PFR,K,0,WS,K,RWS)      17
NOTE      ESW2 IS USED TO EVALUATE THE RATED WIND SPEED OF THE SYSTEM
NOTE      ESW2 - ENERGY SURPLUS WIND (2ND INDEX) (KWH)
NOTE      CLIP - DYNAMO LOGIC FUNCTION
NOTE      RE - ROTOR EFFICIENCY (DECIMAL FRACTION)
NOTE      8.36E-5 - CONSTANT COEFFICIENT TO CONVERT TO DESIRED UNITS
NOTE      RS - ROTOR SIZE (SQUARE METERS)
NOTE      WS - WIND SPEED DATA (KNOTS)
NOTE      EXP(.42857)*LOGN(HSF) - HEIGHT POWER FUNCTION
NOTE      HSF - HEIGHT SCALING FACTOR = WINDMILL HEIGHT
NOTE      (IN METERS) DIVIDED BY ANEMOMETER HEIGHT
NOTE      CIS - CUT-IN-SPEED (KNOTS)
NOTE      PFR - POWER FROM THE ROTOR (KW)
NOTE      RWS - RATED WIND SPEED (KNOTS)
L      TESW2,K=TESW2.J+(DT)*(ESW2.J)*8      18
N      TESW2=0      18.1
NOTE      TESW2 - TOTAL ENERGY SURPLUS WIND (2ND INDEX) (KWH)
NOTE      DT - TIME INTERVAL (DAYS)
NOTE      ESW2 - ENERGY SURPLUS WIND (2ND INDEX) (KWH)
A      CC,K=TTEU,K*TECC+RS*RCC+FWEC*FWCC      19
C      TECC=.20      19.1
C      RCC=100      19.2
C      FWCC=35      19.3
NOTE      CC - (TOTAL) CAPITAL COST ($)
NOTE      TTEU - TOTAL TRACTOR ENERGY USED (KWH)
NOTE      TECC - TRACTOR ENERGY CAPITAL COST ($/KWH)
NOTE      RS - ROTOR SIZE (SQUARE METERS)
NOTE      RCC - ROTOR CAPITAL COST ($/SQUARE METER)
NOTE      FWEC - FLYWHEEL ENERGY CAPACITY (KWH)
NOTE      FWCC - FLYWHEEL CAPITAL COST ($/KWH)
R      TOTAR,KL=SWITCH(MIN(DTA,DOWN,K),0,SSI,K)*8      20
NOTE      TOTAR - TOTAL DOWN TIME ACCUMULATION RATE (HOURS)
NOTE      SWITCH - DYNAMO LOGIC FUNCTION
NOTE      (SEE APPENDIX 2)
NOTE      MIN - DYNAMO FUNCTION FOR 'MINIMUM'
NOTE      DTA - DOWN TIME ALLOWED (HOURS/DAY)
NOTE      DOWN - DOWN TIME (HOURS/DAY)
NOTE      SSI - SYSTEM STATUS INDEX (DIMENSIONLESS)
L      DNTOT,K=DNTOT.J+(DT)*(TOTAR.JK)      21
N      DNTOT=0      INITIAL CONDITIONS      21.1
NOTE      DNTOT - TOTAL DOWN TIME ACCUMULATED (HOURS)
NOTE      DT - TIME INTERVAL (DAYS)

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OPTIL V 1 WPI

NOTE DTAR - TOTAL DOWN TIME ACCUMULATION RATE (HOURS)
A LOADFAC.K=1-DNTOT.K/(24*TIME.K) 22

NOTE LOADFAC - LOAD FACTOR (DIMENSIONLESS)

NOTE THE LOAD FACTOR IS THE PERCENT OF THE
NOTE TIME THE SYSTEM IS TURNED ON DURING
NOTE JUNE, JULY, AND AUGUST.

NOTE DNTOT - TOTAL DOWN TIME ACCUMULATED (HOURS)

NOTE

NOTE CONTROL CARDS

C DT=.125

A PRTDPR.K=CLIP(1,0,TIME.K,60)

A PLTPPR.K=CLIP(0,CLIP(.125,0,TIME.K,20),TIME.K,30)

PRINT 1)WS/2)PTFW/3)FWE/4)ESW1/5)TESW1/6)ESW2/7)TESW2/8)DTAR/9)DOWN/

X 10)FWEU/11)TPU/12)TTEU/13)CC/14)LOADFAC

PLT KS=1(0,60)/FWE=2(0,1000)/TTEU=3(0,90E2)/CC=4(105E3,147E3)

C LENGTH=90

RUN 1

OPTION 2

OPTION 2 WPI

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*   OPTION 2 WPI
L   H2SL.K=MAX(0,H2SL.J+(DT)*(H2PR.JK-H2UR.JK+PUR.JK)*24*H2SEFF)  1
N   H2SL=H2LO  INITIAL CONDITIONS  1.1
C   H2LO=0  1.2
C   H2SEFF=.95  1.3
NOTE   H2SL - HYDROGEN STORAGE LEVEL (KWH)
NOTE   MAX - DYNAMO FUNCTION FOR 'MAXIMUM'
NOTE   DT - TIME INTERVAL (DAYS)
NOTE   H2PR - HYDROGEN PRODUCTION RATE (KW)
NOTE   H2UR - HYDROGEN USAGE RATE (KW)
NOTE   PUR - PROPANE USAGE RATE (KW)
NOTE   H2SEFF - HYDROGEN STORAGE EFFICIENCY
NOTE           (DECIMAL FRACTION)
?   H2PR.KL=H2FC.K  2
NOTE   H2PR - HYDROGEN PRODUCTION RATE (KW)
NOTE   H2FC - HYDROGEN FROM (ELECTROLYSIS) CELL (KW)
A   H2FC.K=EPFR.K*REFF*CEFF  3
C   REFF=.95  3.1
C   CEFF=.9  3.2
NOTE   H2FC - HYDROGEN FROM (ELECTROLYSIS) CELL (KW)
NOTE   EPFR - ELECTRICAL POWER FROM ROTOR (KW)
NOTE   REFF - RECTIFIER EFFICIENCY (DECIMAL FRACTION)
NOTE   CEFF - (ELECTROLYSIS) CELL EFFICIENCY
NOTE           (DECIMAL FRACTION)
A   EPFR.K=CLIP(PEF.K*AEFF.K,0,PEF.K,0)  4
NOTE   EPFR - ELECTRICAL POWER FROM ROTOR (KW)
NOTE   CLIP - DYNAMO LOGIC FUNCTION
NOTE   PEF - POWER FROM ROTOR (KW)
NOTE   AEFF - ALTERNATOR EFFICIENCY (DECIMAL FRACTION)
A   AEFF.K=TABHL(AEFFT,PEF.K,0,.5*ALTRAT,.05*ALTRAT)  5
N   ALTRAT=RE*8.36E-5*RS*(PWS*RWS*RWS*(EXP(.42857*LOGN(HSF))))-
X   CIS*CIS*CIS)  5.1
C   HSF=5  5.2
T   AEFFT=0/.15/.33/.50/.63/.75/.86/.93/.94/.945/.95  5.3
NOTE   AEFF - ALTERNATOR EFFICIENCY (DECIMAL FRACTION)
NOTE   TABHL - TABLE (HIGH - LOW) FUNCTION
NOTE   AEFFT - ALTERNATOR EFFICIENCY TABLE
NOTE   PEF - POWER FROM ROTOR (KW)
NOTE   ALTRAT - ALTERNATOR RATING (KW)
NOTE   RE - ROTOR EFFICIENCY (DECIMAL FRACTION)
NOTE   8.36E-5 - CONSTANT COEFFICIENT TO CONVERT TO DESIRED UNITS
NOTE   RS - ROTOR SIZE (SQUARE METERS)
NOTE   RWS - RATED WIND SPEED (KNOTS)
NOTE   EXP(.42857)*LOGN(HSF) - HEIGHT POWER FUNCTION
NOTE   HSF - HEIGHT SCALING FACTOR = WINDMILL HEIGHT
NOTE           (IN METERS) DIVIDED BY ANEMOMETER HEIGHT
NOTE   CIS - CUT-IN-SPEED (KNOTS)
A   PEF.K=RE*8.36E-5*RS*(WSA.K*WSA.K*WSA.K*(EXP(.42857*LOGN(HSF))))-
X   CIS*CIS*CIS)  6
C   RE=.30  6.1
C   RS=700  6.2
C   CIS=8  6.3
NOTE   PEF - POWER FROM ROTOR (KW)
NOTE   RE - ROTOR EFFICIENCY (DECIMAL FRACTION)
NOTE   8.36E-5 - CONSTANT COEFFICIENT TO CONVERT TO DESIRED UNITS
NOTE   RS - ROTOR SIZE (SQUARE METERS)
NOTE   WSA - WIND SPEED (ADJUSTED) (KNOTS)
NOTE   EXP(.42857)*LOGN(HSF) - HEIGHT POWER FUNCTION

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OPTION 2 WPI

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NOTE      HSF - HEIGHT SCALING FACTOR = WINDMILL HEIGHT
NOTE      (IN METERS) DIVIDED BY ANEMOMETER HEIGHT
NOTE      CIS - CUT-IN-SPEED (KNOTS)
A          WSA,K=CLIP(RWS,WS,K,WS,K,RWS)      7
C          RWS=22      7.1
NOTE      WSA - WIND SPEED (ADJUSTED) (KNOTS)
NOTE      CLIP - DYNAMO LOGIC FUNCTION
NOTE      RWS - RATED WIND SPEED (KNOTS)
NOTE      WS - WIND SPEED DATA (KNOTS)
NOTE
A          RS,K=TABLE(WST,TIME,K,DS,DF,.,125)      8
C          DS=0      8.1
C          DF=94      8.2
NOTE      DS - (WIND) DATA STARTING TIME
NOTE      DF - (WIND) DATA FINAL TIME
NOTE      ACTUAL WIND DATA FROM 1965. DATA FOR SEPT, OCT, NOV.
T          WST=0
X          /17/16/15/14/20/22/19/15/11/10/08/10/14/10/12/16
X          /13/11/10/07/14/07/14/07/01/06/06/06/07/09/14/09
X          /13/13/13/22/24/22/17/08/18/12/14/13/15/18/13/08
X          /10/07/08/08/08/05/03/03/09/17/15/19/14/13/13/10
X          /06/09/04/05/15/15/20/13/15/14/11/16/14/12/12/12
X          /11/07/06/05/14/15/13/14/13/12/10/15/12/15/10/10
X          /11/03/11/16/18/13/13/09/07/06/05/04/03/11/13/10
X          /12/13/12/16/18/11/07/06/03/07/07/05/09/11/12/10
X          /08/03/13/16/16/13/17/13/13/07/05/19/10/06/07/12
X          /13/12/08/09/07/13/25/20/13/14/13/11/08/04/04/07
X          /04/03/06/11/11/15/14/12/15/06/04/03/10/10/08/04
X          /16/06/06/15/11/05/15/12/15/15/13/15/03/10/06/05
X          /03/07/09/07/11/09/10/07/03/10/17/16/11/10/10/06
X          /06/07/06/05/10/08/12/08/09/07/12/11/15/14/07/08
X          /09/05/08/16/16/15/13/13/06/09/18/17/24/13/19/13
X          /16/16/12/19/19/10/09/16/10/12/06/17/17/10/20/18
X          /15/19/14/26/20/20/15/08/09/03/09/07/10/04/07/03
X          /07/09/03/08/05/06/05/04/03/06/06/13/10/13/09/09
X          /11/07/08/11/18/16/03/10/03/08/15/14/20/18/16/13
X          /11/09/05/11/16/11/06/06/03/11/12/19/18/20/07/06
X          /07/09/10/09/03/06/06/07/09/15/17/13/10/05/04/05
X          /07/07/07/08/17/17/06/20/20/18/18/15/15/16/08/04
X          /06/03/07/15/17/19/10/11/09/11/03/10/12/13/13/11
X          /08/08/05/05/08/09/05/03/03/03/06/05/05/08/06/08
X          /14/10/08/09/18/20/12/17/14/14/12/16/15/20/10/06
X          /07/09/10/17/18/13/07/10/11/08/09/11/13/19/05/06
X          /05/05/07/12/18/20/11/10/12/10/14/14/17/16/07/08
X          /03/07/09/08/08/12/07/07/09/10/12/11/17/16/07/07
X          /07/06/06/05/12/13/11/13/13/10/03/13/17/14/08/08
X          /09/03/07/05/04/06/03/07/07/08/07/07/14/10/07/07
X          /08/03/07/06/03/11/08/08/03/10/11/12/15/15/07/11
X          /03/12/12/12/10/09/07/07/03/10/13/19/17/14/06/06
X          /05/07/09/14/13/16/09/13/10/13/10/14/18/24/17/17
X          /12/16/14/13/08/04/12/12/14/10/10/13/04/03/03/05
X          /02/11/07/12/15/12/08/08/10/08/10/17/17/18/08/10
X          /12/13/07/11/17/13/03/10/09/07/05/20/20/15/13/12
X          /03/04/07/09/17/15/03/15/14/11/11/15/11/05/06/07
X          /10/10/10/13/12/12/05/04/10/14/15/12/15/10/03/06
X          /03/10/12/14/15/09/07/03/04/04/04/09/16/20/17/17
X          /14/14/10/09/05/07/06/05/13/10/14/11/17/09/05/01

```

OPTION 2 - MPI

```

X      /08/05/06/10/13/14/14/11/16/06/06/07/12/09/03/05
X      /07/09/06/09/17/08/07/11/09/09/05/05/06/05/04/03
X      /09/07/06/07/08/06/10/07/08/10/08/08/08/09/06/08
X      /07/08/09/10/12/16/06/13/09/14/12/10/06/06/05/08
X      /11/08/10/04/15/11/09/07/07/09/15/16/23/21/07/08
X      /10/07/07/09/16/03/03/06/10/13/12/14/21/16/07/08
X      /08/07/10/09/07/08/03/07/07/08/09/13/18/16/06/16
NOTE
NOTE      WS - WIND SPEED (KNOTS)
NOTE      WST - ACTUAL WIND SPEED DATA (KNOTS)
R      H2UP.KL=CLIP(CLIP(PPD.K,0,DOWN.K,DTA+1),PPD.K,DTAR.JK,2)  9
C      DTA=0  9.1
NOTE      H2UR - HYDROGEN USAGE RATE (KW)
NOTE      CLIP - DYNAMO LOGIC FUNCTION
NOTE      PPD - PUMP POWER DEMAND (KW)
NOTE      DOWN - DOWN TIME (HOURS/DAY)
NOTE      DTA - DOWN TIME ALLOWED (HOURS/DAY)
NOTE      DTAR - DOWN TIME ACCUMULATION RATE (KW)
A      PPD.K=CLIP(CLIP(0,PR/PEFF,TIME.K,IRROFF),0,TIME.K,IRRON) 10
C      PR=60  10.1
C      PEFF=.3  10.2
C      IRRON=276  10.3
C      IRROFF=366  10.4
NOTE      PPD - PUMP POWER DEMAND (KW)
NOTE      CLIP - DYNAMO LOGIC FUNCTION
NOTE      PR - PUMP RATING (KW)
NOTE      PEFF - PUMP EFFICIENCY (DECIMAL FRACTION)
NOTE      IRROFF - TIME IRRIGATION IS TURNED OFF
NOTE      IRRON - TIME IRRIGATION IS TURNED ON
R      PUR.KL=CLIP(PPD.K,0,DOWN.K,DTA+1)  11
NOTE      PUR - PROPANE USAGE RATE (KW)
NOTE      CLIP - DYNAMO LOGIC FUNCTION
NOTE      PPD - PUMP POWER DEMAND (KW)
NOTE      DOWN - DOWN TIME (HOURS/DAY)
NOTE      DTA - DOWN TIME ALLOWED (HOURS/DAY)
L      PU.K=PU.J+(DT)*(PUR.JK)*24  12
N      PU=0  INITIAL CONDITIONS  12.1
NOTE      PU - PROPANE USED (KWH)
NOTE      DT - TIME INTERVAL (DAYS)
NOTE      PUR - PROPANE USAGE RATE (KW)
L      DOWN.K=SSI.J*(DOWN.J+CLIP(0,DTI,H2SL.J,LEL))  13
N      DOWN=0  INITIAL CONDITIONS  13.1
C      DTI=3  13.2
C      LEL=225  13.3
NOTE      DOWN - DOWN TIME (HOURS/DAY)
NOTE      SSI - SYSTEM STATUS INDEX (DIMENSIONLESS)
NOTE      CLIP - DYNAMO LOGIC FUNCTION
NOTE      DTI - DELTA TIME INTERVAL = (DT)*24 (HOURS)
NOTE      H2SL - HYDROGEN STORAGE LEVEL (KWH)
NOTE      LEL - LOW ENERGY LEVEL (KWH)
R      DTAR.KL=CLIP(1,PPD.K,H2SL.K,LEL)  14
NOTE      DTAR - DOWN TIME ACCUMULATION RATE (KW)
NOTE      CLIP - DYNAMO LOGIC FUNCTION
NOTE      PPD - PUMP POWER DEMAND (KW)
NOTE      H2SL - HYDROGEN STORAGE LEVEL (KWH)
NOTE      LEL - LOW ENERGY LEVEL (KWH)
A      SSI.K=TARHL(SSIT,TIME.K,IRRON,IRROFF,.125)  15
T      SSIT=0/

```

NOTE SSI - SYSTEM STATUS INDEX (DIMENSIONLESS)

NOTE TABHL - DYNAMO TABLE (HIGH - LOW) FUNCTION

NOTE - SSIT - SYSTEM STATUS INDEX TABLE

NOTE IRR OFF - TIME IRRIGATION IS TURNED OFF

NOTE: IRRON - TIME IRRIGATION IS TURNED ON

A $ESW2.K = CLIP(PE*8.36E-5*RS*(WS.K*WS.K*WS.K*(EXP(.42857*$

```
X      LOGN(HSF))) - CIS=CIS=CIS) - PFR.K,0,NS.K,RWS)      16
```

NOTE FSW2 IS USED TO EVALUATE THE RATED WIND SPEED OF THE SYSTEM

NOTE ESW2 - ENERGY SURPLUS WIND (2ND INDEX) (KWH)

NOTE CLIP - DYNAMO LOGIC FUNCTION

NOTE RE - ROTOR EFFICIENCY (DECIMAL FRACTION)

NOTE 8.36E-5 - CONSTANT COEFFICIENT TO CONVERT TO DESIRED UNITS

NOTE RS - ROTOR SIZE (SQUARE METERS)

NOTE WS - WIND SPEED DATA (KNOTS)

NOTE EXP(.42857)=LOGN(HSF) - HEIGHT POWER FUNCTION

NOTE HSF - HEIGHT SCALING FACTOR = WINDMILL HEIGHT

NOTE (IN METERS) DIVIDED BY ANEMOMETER HEIGHT

NOTE CIS - CUT-IN-SPEED (KNOTS)

NOTE RWS - RATED WIND SPEED (KNOTS)

```

L      TFSW2,K=TESW2,J+(DT)(ESW2,J)*8      17

```

N TESSW2=0 17.1

NOTE TESW2 - TOTAL ENERGY SURPLUS WIND (2ND INDEX) (KWH)

NOTE DT - TIME INTERVAL (DAYS)

NOTE ESW2 - ENERGY SURPLUS WIND (2ND. INDEX) (KWH)

CC.K=RS*PCC+ALTRAT*ALCC+CELLRAT*CELLCC+TANKCC+PU.K*PCC 18

C RCC=100 18.1

C	ALCC=50	18.2
---	---------	------

```
N      CELLRAT=ALTRAT*REFF      18.3
```

C	CFLLCC=60	18.4
---	-----------	------

C	TANKCC=36	18.5
---	-----------	------

C PCC=8.7753E-3 18.6

NOTE CC - (TOTAL) CAPITAL COST (\$)

NOTE RS - ROTOR SIZE (SQUARE METERS)

NOTE: RCC - ROTOR CAPITAL COST (\$/SQUARE METER)

NOTE ALTRAT - ALTERNATOR RATING (KW)

OPTION 2 WPI

```

NOTE      ALCC  -  ALTERNATOR CAPITAL COST (INCLUDING
NOTE      INSTALLATION AND RECTIFIER COSTS) ($/KW)
NOTE      CELLRAT - CELL RATING (KW)
NOTE      CELLCC - CELL CAPITAL COST ($/KW)
NOTE      TANKCC - TANK CAPITAL COST ($/YEAR)
NOTE      PU    - PROPANE USED (KWH)
NOTE      PCC   - PROPANE CAPITAL COST ($/KWH)
NOTE
NOTE      CONTROL CARDS
C      DT=.125
N      TIME=TD
C      TO=0
C      LENGTH=94
A      PRTPER.K=CLIP(1,0,TIME.K,270)
A      PLTPER.K=CLIP(1,0,TIME.K,270)
NOTE
PRINT  (1)WS/(2)PFR/(3)EPR/(4)H2FC/(5)ESW2/(6)TESW2/(7)H2SL/(8)H2UR/(9)PP/(10)
X      PUP/(11)PU/(12)DOWN/(13)DTAP/(14)CC
PICT   WS=1(0,50)/H2SL=2/PH=3/CC=4
RUN    1

```


APPENDIX 2
A SHORT GUIDE TO DYNAMO

A SHORT GUIDE TO DYNAMO

1. VARIABLE NAMES

Variable names consist of from one through seven alphabetic or numeric characters, the first of which must be alphabetic.

Example:

Q
INV
LIST7

2. EQUATION TYPES

There are two main variables in a dynamic model; level variables and rate variables. Accordingly, the equations defining these variables are called level and rate equations. There are other types of equations, too, such as auxiliary, supplementary, and initial-value equations. When writing a model, the type of equation should be specified in the first column of the punched card. Example:

```
card
col
12345678...
L      L1.K=L1.J+DT*(INFL.JK-OTFL.JK)
R      RATT.KL=LEV.K/DELT
```

Other equation types are specified as follows:

```
A      Auxiliary
S      Supplementary
N      Initial Condition or Initial-Value
```

Constants. Constants are designated by the letter C in the first column. Several constants may be specified on a card.
Example:

```

card
col
12345678...
C      DTA=15
C      A=5,CAT=13.00,HPF=5.125E-7

```

Equation Writing. The basic format of an equation is:

quantity name = expression

The arithmetic operations used to form an expression are:

```

+ Addition
- Subtraction
* Multiplication
/ Division

```

Exponentiation is not available as an operation, but powers and roots can be calculated using the functions available in DYNAMO. When more than one operation appears within an expression, multiplication and division are computed before addition and subtraction with the order of operation being from left to right. Parentheses may be used to alter these normal "precedences" and to eliminate the need for the symbol * for representing the multiplication of two quantities. Example:

$A=(B+C)*(D+E)$ is equivalent to $A=(B+C)(D+E)$

Subscripts. Level variables are always single-subscripted, such as:

L1.K or LEV3.J

The same is true for auxiliary and supplementary variables, but their single subscript is always K.

Rate variables are double-subscripted, such as:

RATT.JK or FLOWOUT.KL

Table A2.1 should be helpful in identifying the correct subscripts (11).

TABLE A2.1 SUBSCRIPT TABLE

Quantity Type on Left of Equation	Subscript on Left	Subscripts on Quantities on Right if Quantity is:					
		L	A	R	S	C	N
L Level	K	J	J	JK	np	none	none
A Auxiliary	K	K	K	JK	np	none	none
R Rate	KL	K	K	JK	np	none	none
S Supplementary	K	K	K	JK	K	none	none
C Constant	none	np	np	np	np	np	np
N Initial Value or computed constant	none	none	none	none	none	none	none

np = not permitted

Card Punching. Equation or quantity type is to be punched in column 1. The equation should start in column 7. No blanks are allowed within the equation or statement; if there is any blank, the compiler ignores what comes after the blank. Comments may then be written on statement cards provided they are preceeded by at least one blank. Should the material not fit on the first card, one or more continuation cards may be used. These are punched with an X in column 1, and the material is continued starting in column 7. If the material is continued it need not go through column 72 of the original card, but may be broken after a quantity name, number, or arithmetic operator. The unused portion of the card must be blank, i.e. no comments are permitted within the information.

Numerical Computations. In DYNAMO there is no provision for fixed-point arithmetic. All computations are carried out in floating-point form. The numerical values, however, may be specified as fixed-point values; the compiler converts them into floating-point values. Up to 8 digits, in addition to sign and decimal point, may be used to express numerical values. For very large or small numbers the number may be expressed as a number multiplied by some power of 10 by writing the number followed by the letter E and the desired power of ten. Example:

82 billion can be written as 82E+9 or as 82E9 and

1 ten-thousandth can be written as 1E-4

3. DIRECTION CARDS

Direction cards are used to specify the length of the simulation run, time interval, printing and plotting instructions, and quantities to be printed or plotted. They are as follows:

Identification Card. This is the first card of any model, which provides a title for the model. It begins with an asterisk (*) in the first column; the title cannot be more than 40 characters in length nor can any word be more than 8 letters long.

Example:

```
card.
col
12345678...
*      WPI - OPTION 1
```

Run Card. Each run and rerun is assigned a run number, by which it is filed. The run card is the last card of any model, and the run number can have up to 8 characters. Example:

```
card
col
12345678...
RUN   STD.
      or
RUN   RS=700
```

SPEC Card. This card provides values for the following four parameters necessary for any simulation:

DT	the interval of TIME between TIME.J and TIME.K
LENGTH	the value of TIME when the run is to be terminated
PRTPER	the interval of TIME between each tabulation of the results
PLTPER	the interval of TIME between each plot output of the results

These four parameters may be defined on the same SPEC card or as constants on separate constant cards. Example:

```

card
col
12345678...
SPEC DT=.125/LENGTH=90/PRTPER=1/PLTPER=.125

```

or as

```

C      DT=.125
C      LENGTH=90
C      PRTPER=1
C      PLTPER=.125

```

PRINT Card. This card specifies what values are to be printed and in what form. In any table of printed values, TIME is automatically supplied by the compiler. Up to 14 quantities can be printed in a table output in addition to TIME. A PRINT card such as:

```

card
col
12345678...
PRINT ABC,DEF,LEV,RATT

```

is equivalent to

```
PRINT ABC/DEF/LEV/RATT
```

and will result in a printed output such as:

```
TIME   ABC   DEF   LEV   RATT
```

But a PRINT statement such as:

```

card
col
12345678...
PRINT ABC,DEF/LEV,RATT

```

will print the results in an output such as:

```
TIME   ABC   LEV
      DEF   RATT
```

In printing, DYNAMO gives only up to 5 significant digits. If values are very small or very big, they are scaled by some power of 10. The scaling factor will appear in the title of the tabulated output. The scaling factor will be automatically provided by the compiler. However, the user may specify the scaling factor if he wishes. For example:

```
card
col
12345678...
PRINT A(4.2)/B(3.4)
```

will print the values of A after dividing them by 10^4 , and choosing 2 significant decimal places after the decimal point. The values of B are divided by 10^3 , and 4 decimal places are chosen to the right of the decimal point.

PLOT Cards. DYNAMO has an automatic plotting feature which enables the user to plot up to 10 quantities on a single graph. The scales may be chosen by the user or by the compiler. All plots are verses TIME. Each quantity should be assigned a character by which that quantity is to be represented on the graph. Example:

```
card
col
12345678...
PLOT LEV=L/RATT=$
```

will plot quantities LEV and RATT, represented by L and \$ respectively.

Scales may be specified by the user, or else they will be chosen by the compiler. It is possible to specify only the upper or lower limit of the scale, leaving it up to the compiler to

specify the other one. The unspecified limit is given as an asterisk (*). Example:

```
card
col
12345678...
PLOT ABC=*/DEF=D(0,200)/LEV=L(0,*)
```

will plot variable ABC to a scale chosen by the compiler using the * character, DEF to a scale from 0 to 200 using the D character, and LEV to a scale with a lower limit of 0 and an upper limit to be chosen by the DYNAMO compiler using the character L.

4. COMMENT CARDS

Comments may be made on NOTE cards. Example:

```
card
col
12345678...
NOTE FWE - FLYWHEEL ENERGY LEVEL (KWH)
```

Comments may also be added to a statement card following at least one blank. Example:

```
card
col
12345678...
N      L1=0  INITIAL CONDITIONS FOR L1
```

5. RERUNS

A model may be rerun several times, for different parameter values. Only constants, table values, and direction cards may be changed in a rerun. Each rerun should also be assigned a run number.

6. FUNCTIONS

DYNAMO has a number of built-in functions, and also has

provisions to accept user-written functions. The built-in functions are described below.

Common Functions. Common functions defined in DYNAMO are:

EXP(A)	$A \leq 174$	Exponential
LOGN(A)	$A > 0$	Natural Logarithm
SQRT(A)	$A \geq 0$	Square Root
SIN(A)	$A < 823,000$	Sine Function
COS(A)	$A < 823,000$	Cosine Function

The sine and cosine functions are used frequently to generate functions of TIME. Raising numbers to a power can be computed as:

$Y=A^B$ is the same as $Y=EXP(B*LOGN(A))$

Random Number Generator. DYNAMO has two random number generators:

1) NORMRN(MEAN,SDEV) generates random numbers normally distributed with mean equal to MEAN, and standard deviation equal to SDEV.

2) NOISE() generates random numbers uniformly distributed between -0.5 and +0.5. Note that the parentheses are necessary but that there are no arguments.

Third-Order Delays. DYNAMO has two third-order delay functions:

1) DELAY3(IN,DEL) is a material delay and

2) DLINF3(IN,DEL) is an information delay where:

IN = input to the delay

DEL = magnitude of the delay

PULSE Function.

PULSE(HGHT,FRST,INTVL)

produces a pulse train of height HGHT, with width of DT. The first pulse will appear at time FRST, and thereafter at regular intervals of length INTVL. Neither HGHT nor INTVL need be constant.

RAMP Function.

RAMP(SLP,STRT)

is equivalent to Figure A2.1:

RAMP=0	if TIME \leq STRT
RAMP= $\sum_{STRT}^{TIME} SLP*DT$	if TIME > STRT

SAMPLE Function.

SAMPLE(X,INTVL,ISAM)

sets SAMPLE equal to X at sample times separated by intervals of length INTVL, and holds the value until the next sampling time. ISAM is the initial value of SAMPLE.

STEP Function.

STEP(HGHT,STTM)

is equivalent to Figure A2.2:

STEP=0	if TIME \leq STTM
STEP=HGHT	if TIME > STTM

Both HGHT and STTM may be variables.

MAX and MIN Functions.

MAX(P,Q)

sets:

MAX=P	if P \leq Q
MAX=Q	if P > Q

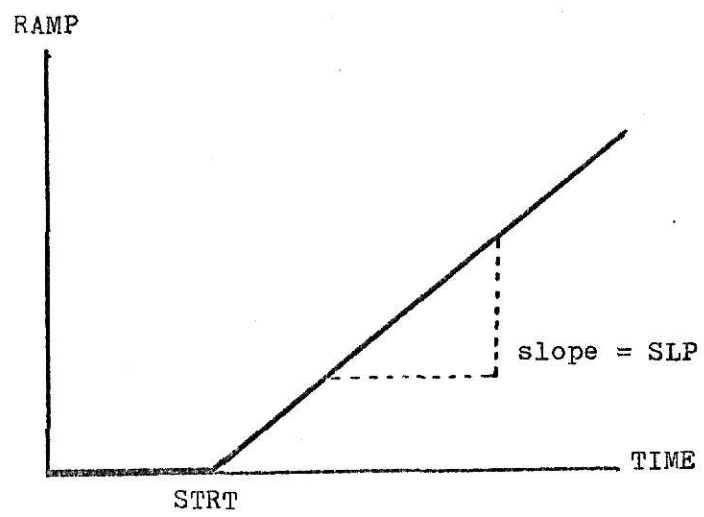


Figure A2.1 - RAMP Function

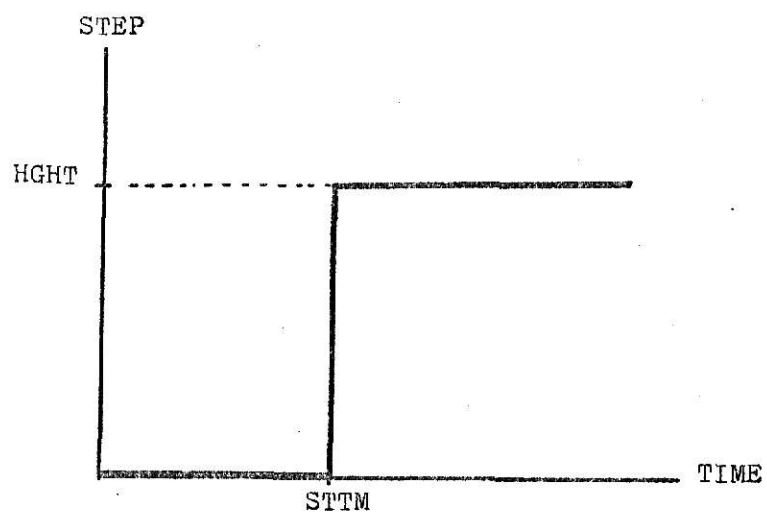


Figure A2.2 - STEP Function

Similarly:

MIN(P,Q)

sets:

MIN=P if $P \leq Q$

MIN=Q if $P > Q$

CLIP Function.

CLIP(P,Q,R,S)

sets:

CLIP=P if $R \leq S$

CLIP=Q if $R > S$

SWITCH Function.

SWITCH(,P,Q,R)

sets:

SWITCH=P if $R = 0$

SWITCH=Q if $R \neq 0$

TABLE Function. It may be desirable to express the values of one variable in terms of the values of another variable. This was the case in both Option 1 and Option 2 for the wind speed with respect to TIME. The TABLE function serves this purpose. The form of a table look-up function is:

TABLE(TNAME,X,XINITL,XFINAL,XINCR)

where:

TNAME - name of the table

X - independent variable

XINITL - initial value of range of X

XFINAL - final value of range of X

XINCR - increment of X

Example:

Suppose that the following values of auxiliary variable Z are given with respect to independent variable X:

<u>X</u>	<u>Z</u>
10	35
20	40
30	45
40	80
50	85
60	120

Z can be expressed as:

```
card
col
12345678...
A      Z.K=TABLE(TNAME,X.K,10,60,10)
T      TNAME=35/40/45/80/85/120
```

Note that a T in column 1 is used to denote a TABLE function. Linear interpolation is used by DYNAMO to compute the values that are not specifically given in the table.

In TABLE functions, X can not exceed the specified range without generating an error. The TABHL function extends the extreme values of the dependent variable if the independent variable exceeds the specified range. In the above example, if TABHL is used in place of TABLE, Z will have a value of 120 for all values of X greater than 60 and a value of 35 for all values of X less than 10.

SMOOTH Function. This function exponentially smooths a quantity, and has the following form:

SMOOTH(IN,DEL)

where:

IN - input to be smoothed

DEL - smoothing constant or delay

This is only an abbreviated guide to DYNAMO. For more information, refer to reference (11).

WIND POWERED IRRIGATION IN KANSAS
A SYSTEM DYNAMICS APPROACH

by

JOEL A. BUCK

B.S.E.E., Kansas State University, 1975

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

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1976

ABSTRACT

In recent years the public has become acutely aware of the energy crisis that has been inevitable since man first became dependent on finite fossil fuels. Today there is emphasis on developing "alternate" energy sources. The use of wind power for irrigation of farm fields is investigated in this paper.

Many options have been proposed for harnessing wind power for irrigation. Here, two options are investigated using a system dynamics approach. The first option uses mechanical energy extracted from the wind as input to a mechanical pump. A flywheel serves as a buffer and as storage for low wind periods. The second option uses the mechanical output from the windmill to generate electricity. This electricity is then fed into an electrolysis cell to produce hydrogen gas. This gas is then burned in an internal combustion engine which drives the pump. Surplus hydrogen is stored in depleted natural gas wells for use during low wind periods. A back up system is provided in both options for when the wind is not blowing and the stored energy has been exhausted.

1965 wind data from the U.S. Weather Bureau Office in Dodge City, Kansas, is used in the simulation of the two proposed systems. 1965 wind data is used because it tends to be a "typical" wind year. The summer months, during which the irrigation will be taking place, have average wind velocities within one half a standard deviation of a 25 year average for the area. The other nine months each have average wind velocities within two standard deviations of a 25 year average.

First, the general concepts of system dynamics are explained. Then, models of the two options are formulated and tested by

simulating their performance over a "typical" year using the DYNAMO compiler. The results of these simulations are then compared with each other and with the current methods of farm irrigation.

Finally, a glance to the future is proposed which reveals that, though the systems proposed are presently more expensive than current forms of energy, this very well might not be the case in 10 to 15 years.