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Hybrid2 - The Hybrid Power System Simulation Model

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ABSTRACT

There is a large-scale need and desire for energy in remote communities, especially in the developing world; however the lack of a user friendly, flexible performance prediction model for hybrid power systems incorporating renewables hindered the analysis of hybrids as options to conventional solutions. A user friendly model was needed with the versatility to simulate the many system locations, widely varying hardware configurations, and differing control options for potential hybrid power systems. To meet these ends, researchers from the National Renewable Energy Laboratory (NREL) and the University of Massachusetts (UMass) developed the Hybrid2 software. This paper provides an overview of the capabilities, features, and functionality of the Hybrid2 code, discusses its validation and future plans. Model availability and technical support provided to Hybrid2 users are also discussed..

INTRODUCTION

With the increasing need for electrical generation in the developing world, the market potential for renewable based hybrid power systems is emerging. In order to address this emerging market, an analysis tool was required by industry, researchers, and development institutions to accurately model the performance and economics of alternative hybrid designs. This analysis tool would require enough versatility to model the many system locations, widely varying hardware configurations, and differing control options for potential hybrid power systems. In response to this need, researchers from the National Renewable Energy Laboratory (NREL) and the University of Massachusetts (UMass) developed the Hybrid2 software. Hybrid2, like its predecessor HYBRID1, is a time-series/probabilistic model that uses time-series resource and load information, combined with statistical analysis, and manufacturers data for hybrid system equipment to accurately predict the performance and cost of hybrid power systems. Hybrid2 is also a user friendly tool that allows for the direct comparison of many different renewable and non-renewable power system designs.

Hybrid2 was designed to study a wide variety of hybrid power systems. The hybrid systems may include three types of electrical loads, multiple wind turbines of different types, photovoltaics, multiple diesel generators, battery storage, and four types of power conversion devices. Systems can be modeled on the AC, DC, or both buses. A variety of different control strategies/options may be implemented which incorporate detailed diesel dispatch as well as interactions between diesel gensets and batteries (Barley, 1995). An economic analysis tool is also included that calculates the economic worth of the project using many economic and performance parameters. The Hybrid2 code employs a user-friendly Graphical User Interface (GUI) and a glossary of terms commonly associated with hybrid power systems. Hybrid2 is also packaged with a library of equipment to assist the user in designing hybrid power systems. Each piece of equipment is commercially available and uses the manufacturers' specifications. In addition the library includes sample power systems and projects that the user can use as a template. Two levels of output are provided, a summary and a detailed time step by time step description of power flows. A Graphical Results Interface (GRI) allows for easy and in-depth review of the detailed simulation results.

The validation and verification of the Hybrid2 code is ongoing and very positive. Comparisons have been made among a number of operational hybrid power systems and the Hybrid2 code with validation efforts continuing during the summer of 1996. The Hybrid2 code is also heavily based on its predecessor, HYBRID1, which has been extensively validated (Manwell et al., 1994; Baring-Gould, 1995). The validation of the Hybrid2 code is discussed in greater detail later in this document.

CODE OVERVIEW

Hybrid2 was designed to be a very flexible and easy to use tool to conduct predictions of potential hybrid power system long-term performance and cost. The developers have provided enough structure to allow users with limited knowledge of hybrid systems to evaluate them as one of the electrification solutions while also facilitating detailed analysis for those with more design experience. Hybrid2 is not a complete system design tool, but a middle step to provide a preliminary system performance predictions before the final system design is completed. Hybrid2 is not a dynamic model and will not account for system transients and stability on the order of 30 seconds or less. The Hybrid2 user interface is divided into five modules that comprise a project. The project is a specific power system applied to a particular community or site. The five modules are the community loads, the site/resource information, the proposed power system, an all-diesel power system for comparison and system economics. Each of these modules are discussed below.

Loads Module

Hybrid2 allows for a system to contain loads on both the AC and/or DC buses. The code also provides for the use of three types of loads, primary, deferrable and optional.

The primary load is used to specify the load served on-demand for the community under analysis. The primary load is made up of time series data. An inter-time step variability or standard deviation can also be included which allows for a more accurate prediction of the power systems operation. The primary load must be supported by the power system and any load that is not met is reported. If time series data is not available, Hybrid2 includes a matrix load generator that may be used. This allows the user to specify the average load for each hour of a typical day, generated with a separate worksheet provided with Hybrid2, and a monthly scale factor. The user is still required to specify the variability in the load.

Deferrable and optional loads are two forms of managed loads that can have economic value on small electric grids. Deferrable loads are electrical load that contains a limited amount of storage and thus may be deferred to utilize excess energy. If the deferrable load is not met over a given time period the load is treated as a primary load and must be supplied. Examples of a deferrable loads are an icemaker or water cistern. An optional load represents a useful application for excess electricity that is never served as a primary load, such as space or water heating. If no excess energy is available to meet such a load then it is either unserved or met by other means.

Site/Resource Module

The Site/Resource Module allows the user to merge a combination of resource data and site parameters to include in different projects. There are three types of resource input data that can be used in simulation runs of Hybrid2: wind speed, solar insolation and ambient temperature. Each of these types of resource data take the form of time series averages. The wind resource may also include an inter-time-step standard deviation or variability. Key parameters that affect those resources, such as wind turbulence, and ground reflectivity may also be specified.

Power System Module

The Hybrid2 code is based on a two bus system (AC and DC) but also can model a "coupled diesel" system, in which a diesel is directly connected to a rotary converter. The diverse structure of the model allows for many combinations of wind turbines, photovoltaic arrays, diesel generators, power converters, and battery storage, both in AC, DC, or two-bus systems, as shown in Figure 1. Both buses may be active in a given system with loads and generating sources applied to each bus simultaneously. The power system is defined with components selected from the on-line library. Each type of component is included in a subsystem that is used to define all of the relevant parameters associated with that technology. For example; a specific photovoltaic module from the Hybrid2 library is inserted into the PV subsystem where all the parameters associated with the PV array are defined. This component methodology allows for a wide flexibility in the definition of a power system, as well as giving users the ability to include new components in project analysis.

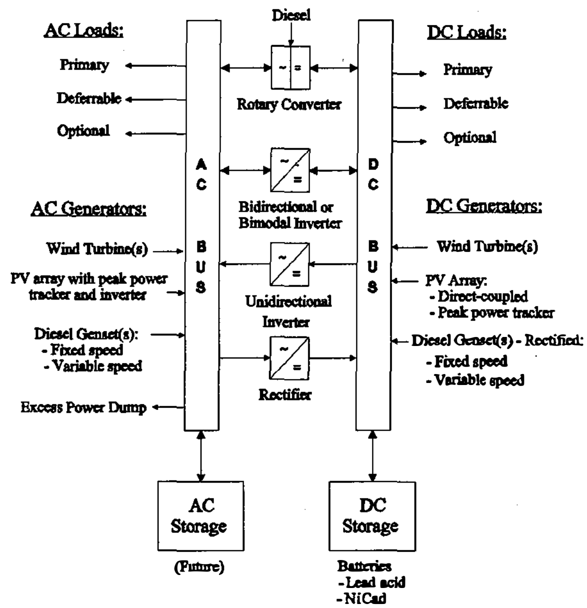

FIGURE 1. CONFIGURATIONS FOR HYBRID2 POWER SYSTEMS

Hybrid2 allows for many different control strategies for systems that contain battery storage and/or diesels. Since the renewable power output and the load are given for a specific simulation, the only true control questions are in the operation of the diesel generator, the battery bank, and any interaction between the two. Hybrid2 allows for more than 180 different dispatch configurations considering questions such as these: How the batteries are used? When does the diesel start? At what power level is it operated when running? When is it shut down (Barley, 1996)? The model also allows the user to specify dispatching specific to each diesel.

Base Case Module

The Hybrid2 code allows for the specification of a base case all-diesel system to use as a comparison to the hybrid system. The base case system is described by one or more diesels, some operation criteria, and a dispatch order. This module is not required to run Hybrid2 simulations.

Economics Module

Hybrid2 includes a detailed economic model that allows the user to determine basic economic figures-of-merit for a particular project. It has been provided to allow for comparisons between differing power system options and to determine approximate system costs. The economics engine uses performance information from a simulation run and economic data supplied by the user to calculate parameters such as payback period, internal rate of return, cash flow, and equipment replacement expenses. The user has wide flexibility in determining the expenses of the project and what detail of inputs to include. Parameters such as grid extension, import tariffs, system administration costs, and taxes can be included in the analysis. Economics simulations can be conducted independently of the simulation engine to make it possible to conduct wide ranging parametric analysis of any economic input without repeating performance simulations.

CODE STRUCTURE

The program is structured in four blocks. The first is the GUI in which the project to be analyzed is specified and created. The second block consists of the simulation engine in which the performance of the system is calculated. The third block is the GRI in which the user can plot and view both the system performance and inter-system component interaction. The user may preform an analysis of the performance output and then modify the original project and conduct additional simulations if required. The final block is the economics module in which an analysis can be conducted varying certain key economic parameters. Both performance and cost simulations can be repeated until an acceptable design is achieved. Hybrid2 is not an optimization software and presently parametric analysis must be conducted manually.

Graphical User Interface

The GUI allows the user to create all aspects of the hybrid system project and start the simulation in a user-friendly windows-based environment. The GUI also performs range checking and a completeness check to insure that each section is complete before the user is allowed to continue. In addition, prior to the execution of the project simulation, Hybrid2 performs a consistency check on the project.

The GUI includes three main features that assist in the creation, use, and storage of projects. First an on-line library includes sample projects, time series data, sample power systems, and manufactures data on system components. The user may use the existing library records, modify library records to update performance information, or enter data for components not presently included in the NREL library. All user records become part of the library and can be used at a later date and in multiple projects. All of the component records that make up the Hybrid2 library are defined by information that is usually provided on a manufacturer's specifications sheets. This library allows users to easily create, combine and, reuse whole modules and individual components. Second, a Glossary is provided to help the user by providing on-line definitions of all of the parameters used in the Hybrid2 code. The glossary also provides, if applicable, an example, default values, recommended ranges and hard limits for all code input. Third, an Import/Export function has been included that not only allows the user to transfer projects and components to other copies of Hybrid2 but also allows for the backup and long term storage of projects that are not currently being analyzed. The GUI is described extensively in Baring-Gould, 1996.

Simulation engine

Hybrid2 uses an energy balance approach within each time step such that the sum of the average outputs of all the energy sources (such as wind, PV, gensets, and storage output) must equal the sum delivered to all the energy sinks (typically loads, storage input, and losses). A probabilistic method is used within each time step to account for the short-term fluctuations in the load and renewable resources (Manwell et al., 1996). These inter-time-step fluctuations, which are input by the user, can have a significant impact on diesel dispatch and subsequently the performance of a system. The spacing between turbines in a multi-turbine system is also considered to account for the power smoothing effect of multiple wind turbine arrays (Beyer et al., 1989).

Hybrid2 can use time steps typically between 5 minutes to 2 hours in length. It should be noted that all of the main component algorithms used in Hybrid2 are based on industry accepted research.

Within each time step of a simulation, system performance is calculated by the following steps. The "Net Load" is determined which refers to all of the load(s) on the system less the contribution of the renewable energy sources. When this value is positive, energy must be supplied by the diesel genset(s), battery storage or both. When the net load is negative, there is extra power available which may go to storage, a deferrable or an optional load. The effect of the probabilistic method is that the net load is not a single value during a time step. Rather it is a distribution of values; in Hybrid2 it is assumed that the values are normally distributed. In extreme cases, the net load may be positive for part of the time, but negative for the rest. The most significant aspects of the net load are its mean and its range (maximum and minimum) which will affect the determination of which diesels are on line, how much power they produce, and how much fuel they use. Next, the energy flow to or from the battery will be calculated and surplus energy will be made available to either deferrable or optional loads. If the power system is incapable of meeting the load during a time step, the unserved load is tabulated and reported. For power systems configured with fewer components or loads than in the discussion above, this process is simplified appropriately. (Manwell et al., 1996)

Graphical Results Interface

The Hybrid2 code includes a GRI that allows the user to view the results of a simulation from within the Hybrid2 code. Hybrid2 creates two levels of output from the simulation engine, a summary output file and a detailed output file. The summary file is a tab-delineated ASCII text file that reports the general results of the simulation. The detailed files report simulation output and power flows for each time step of the simulation run. These detailed files are space delimited and is used by the GRI or can be imported into a spreadsheet for further analysis. The GRI can be used to quickly look at the results a run just completed or previous simulation runs. The GRI can plot multiple time series data or X-Y plots of different parameters. Plots created with the GRI can be copied and pasted into reports or other documents.

The output for the economics package also comes in a summary and detailed form. The summary file provides all of the economic parameters while the detailed output file includes a year by year breakdown of revenues, expenses, and overhaul expense schedules. The summary and detailed files are readable by standard text editors and spreadsheets respectively.

MODEL TESTING

As with any simulation model, Hybrid2 must be tested to ensure that it is accuracy and to build confidence in the use of the model. The model developers are conducting a test program with three main components: verification, validation, and beta-testing. Expected outcomes of Hybrid2 testing are to establish confidence that the model is technically sound, to demonstrate its effectiveness and usefulness, and to clearly identify limitations of which users should be aware.

Verification is the process of confirming that the selected mathematical models have been accurately expressed in the source code. Essentially, this means debugging the code to ensure that the programming has been done correctly. The verification is conducted by designing probable scenarios for which the output can be determined by hand calculations and comparing these results to those of the simulation.

Validation refers to comparisons of simulated performance to measured performance data from operating systems. Validation is useful to demonstrate the degree of correspondence between the model and real power systems and to identify limitations of the model. Four validations planned for Hybrid2 are noted in Table 1 below. Others may be done as data sets become available and resources permit.

Beta-testing is model testing conducted by individuals outside of the development team. In April 1996, a group of about 20 potential Hybrid2 users were trained to use the model and then asked to exercise the model to simulate power systems of interest to them. Feedback on the models useability, effectiveness, and acceptance was received and incorporated into the software. Beta-test results may be qualitative to a great degree, but they are, nevertheless, an important measure of the overall effectiveness of the model.

TABLE 1. PLANNED VALIDATION EXERCISES FOR HYBRID2.

Source of Measured Data	Power System Description	Length of Data Set, Sampling Rate
Frøya Island, Norway	Wind/Diesel/Battery/Dump Load 50-kW nominal	17 days of 10-minute data
Xcalac, Mexico	Wind/PV/Battery 40-kW nominal	84 days of 1-hour data
New World Power Technology Corp. tested at NREL	Wind/Diesel/Battery/Dump Load 50-kW nominal	Testing underway 2/96, 10-minute data
Wind/Diesel System Test Bed University of Massachusetts	5 Different Configurations of Wind/Diesel/Battery 15-kW nominal	12 data sets, each consisting of 2 hours of 2-sec data

Validation of HYBRID1
HYBRID1, the predecessor to the Hybrid2 simulation code, underwent an extensive validation effort before the code release in 1993 (Baring-Gould et. al., 1994 and Baring-Gould, 1995). Since the Hybrid2 model is a direct outgrowth of the HYBRID1 model, it is our view that the rigorous validation efforts undertaken for the earlier version of the code buttress the ongoing validation of Hybrid2. The validation effort consisted of performing a series of tests with the University of Massachusetts Wind/Diesel System Testbed (WDSTB) and them comparing the results to corresponding predications from HYBRID1. Some of these tests will be repeated as part of the validation process using the UMass WDSTB test data.

Verification
The verification process included performing more than 300 different tests using 68 different system configurations isolating certain code algorithms. Verification tests using data taken during the Department of Energy MOD-0A wind/diesel experiments at Block Island, Rhode Island (Jeffries, 1992) were also conducted. The Block Island data was not detailed enough to be used in a validation test, but did allow valuable tests of the wind turbine and diesel algorithms. This verification work gives us confidence that the system algorithms incorporated in Hybrid2 are correctly implemented.

Validation
Two of the four planned validations have been completed by the time of this report: the validations based on the data from Frøya Island, Norway and Xcalac, Mexico. While the report on Xcalac is in draft form, the complete validation of Frøya Island is described in van Dijk and Baring-Gould, 1996. The final two

validation efforts will be undertaken during the summer and fall of 1996. Because each validation effort will be different and depends greatly on the quality of the data and the power system configuration, each individual validation will not cover all aspects of the Hybrid2 code. For this reason, four validation tests will be undertaken so that the overlap between the different validation exercises will give confidence that the model has been thoroughly tested. For each validation, two simulations are done for which the input parameters for the components and dispatch strategy are derived from (1) manufacturers' specifications or (2) the measured data. In the first case, the components and dispatch strategy are modelled using their *expected* performance, according to system design. This demonstrates the accuracy that can be expected when modeling potential systems with the Hybrid2 model. In the second case, the input parameters for each component and the dispatch strategy are derived from the measured data, which shows their *realized* performance and shows the maximum accuracy of the Hybrid2 system performance model. Due to space limitations only the second series of tests will be discussed here.

The Frøya hybrid power system, which is located on the Norwegian island of Frøya about 100 miles north of Bergen, uses a Wincon 55 wind turbine, a 50-kW Cummins diesel and a 20-kWh NiCad battery bank. The system also contains a BBV, 37.5-kW converter and a dump load. The short-term battery storage covers fluctuations in the load and wind energy, thereby preventing rapid on-off cycling of the diesel generator. When the diesel is off and the battery supplies power, the diesel generator acts as a synchronous condenser to provide reactive power. The data set used included primary load, wind speed, the main energy flows and total fuel consumption. A detailed description of the prototype system can be found in Uhlen, 1989.

The 17-day data set was made available by EFI, the Norwegian Electrical Research Institute of Norway. EFI also provided characteristics of the components and the dispatch strategy, obtained from manufacturers' data or from other measurements. The same data set was used earlier to validate the European Wind Diesel Logistic Modelling Package (WDL) (Infield, 1994). This makes it possible to compare the results of the validation for Hybrid2 with the results for these six models.

TABLE 2. COMPARISON OF THE MEASURED AND THE SIMULATED PERFORMANCE OF THE FROYA SYSTEM WITH HYBRID2.

	Measured	Hybrid2
Primary Load (kWh)	8196	8202
Wind Turbine Net Energy (kWh)	4801	4873 (+1)
- Production	4897	4970 (+1)
- Consumption	96	97 (+1)
Diesel Energy Production (kWh)	4944	5045 (+2)
Dump Energy (kWh)	1261	1297 (+3)
Converter Input Energy (kWh)	223	300 (+35)
Converter Output Energy (kWh)	141	151 (+7)
Diesel Run Time (h)	284	282 (-1)
Number of Diesel Starts	29	22 (-24)
Total Fuel Consumption (l)	1812	1909 (+5)

Note: The values between brackets give the percentage with which the simulated value differs from the corresponding measured value.

Tables 2 compares the Hybrid2 summary results with the measured data while Figure 3 shows time series data for diesel operation, a good indicator of how well a hybrid power system is being modeled. Table 3 shows the results compared to validation tests using the same input as was used for the validation of three of the European WDL models (Infield et al., 1993).

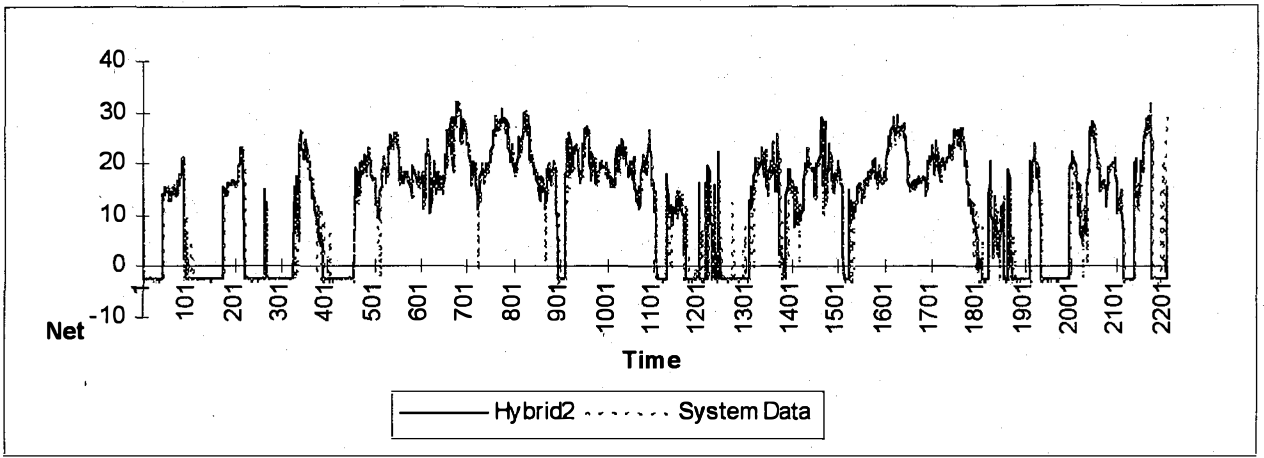

FIGURE 3. TIME SERIES OF FROYA ISLAND DIESEL POWER AND PREDICTION OF HYBRID2.

TABLE 3. HYBRID2 COMPARED TO THE SELECTED EUROPEAN HYBRID SYSTEM MODELS

	Measured Data	Hybrid2	Netherlands SOMES	Denmark WDILOG	Norway VINDEC
Diesel Run Time (h)	284	282(-1)	-	299(+5)	-
Number of Diesel Starts	29	22(-24)	20(-31)	45(+55)	23(-21)
Total Fuel Consumption (l)	1812	1909(+5)	1707(-6)	1919(+6)	1752(-3)

The tables and time series indicate that the model is an excellent predictor of system performance. Further, Hybrid2 compares favorably to the WDL models which are among the best wind-diesel models available.

The specific conclusions of this validation are:

- Hybrid2 can model the performance of a wind turbine to within 1% to 4%. This number will vary depending on the accuracy of the power curve used as the input to the simulation.
- Hybrid2 can model the performance of a diesel genset, either net energy production or fuel consumption, to within 2% to 5%.
- The validation of the battery algorithm in Hybrid2 is inconclusive in this study due to the lack of manufacturer's data for the battery and due to the relatively small (< 2%) contribution the battery subsystem makes to the primary load. It should be noted that even with this lack of knowledge, Hybrid2 predicts the converter power as well as the best European models.
- Hybrid2 does well in modelling the general role of short-term storage and the impact this has on diesel usage. This is evident in the ability of the model to predict the number of diesel starts to an acceptable degree of accuracy, an error of less then one start every two days, as well as the very close approximation of fuel use and diesel operational hours.

Xcalac, Mexico, is a small fishing village on the Yucatan peninsula in southeastern Mexico, about 200 miles south of Cancun, Mexico. The hybrid power system is made up of six Bergey Excel, 10-kW DC wind turbines, a 11.2-kW photovoltaic array of Siemens M75 modules connected in 13 parallel strings, a 125-kW

SELMEC diesel generator, and an AES Sinemax 40-kW static inverter. The system also includes a 1738 Ah battery bank made up of 216 GNB Resource Commander 6-75C23 flooded lead acid batteries. The data set that was selected for the validation is comprised of 84 days of data with one day missing. The sensor used to monitor AC power to the loads was not operational during this period. The system is therefore modeled without the diesel and the community load was taken to be the input power to the inverter on the DC bus.

Table 4 shows the comparisons between the Hybrid2 simulation and the actual system performance data. The error in PV array output shows one of the shortcomings of the Hybrid2 code. In an effort to insure that all of the parameters defining each component are easily available, some of the algorithms used to model a component are simple in nature. Because of this, there may be some specific components, like the Siemens M75 PV modules used here, that are not modeled well by Hybrid2. Whether the error in the PV performance is due strictly to component mis-modeling, errors in the collection of the resource data or other factors will require further validation exercises and analysis. The code does provide some guidance to the user by pointing out limitations in the model's ability to predict the performance of certain system components.

TABLE 4. XCALAC MEXICO VALIDATION RESULTS

	Measured	Predicted
DC Primary load (MWh)	23.82	23.82
Unmet load (MWh)	-	2.20
Excess energy (MWh)	-	1.75
Wind turbine output (MWh)	23.30	23.29 (0%)
PV array output (MWh)	3.68	3.01 (-18%)
Net Battery energy (MWh)	3.16	2.97 (-6%)

Note: The values in brackets give the percentage in which the simulated value differs from the measured value. DC Primary load taken from DC power into inverter(code input).

Clearly, the results of the two simulations discussed here, although indicating areas for improvement and further analysis, demonstrate that the Hybrid2 code does predict the performance of hybrid power systems to a high degree of accuracy. Because Hybrid2 allows so many combinations of system and control structures, it would be virtually impossible to check every possible combination. As Hybrid2 is undergoing its first widespread release, the development team is actively encouraging researchers to report problems and any other comments in regards to the software.

CODE INFORMATION

The code has been made to keep the hardware requirements associated with Hybrid2 as simple as possible. To operate the Hybrid2 code the user is required to have an IBM or compatible 386 PC with a math co-processor. A faster machine will greatly enhance the speed and ease of the code use. The PC must be running under a DOS operating system with Microsoft Windows 3.1 or better, have at least 4 MB of Random Access Memory, 15 MB of free hard disk space, a mouse, a VGA video driver, and a 3.5" disk drive for loading the software. Hybrid2 will function on most laptops and in Microsoft Windows95..

As noted above, NREL would like a more extensive evaluation of Hybrid2. Researchers and users interested in participating in an evaluation should contact the authors at NREL. Evaluation participants must be willing to share modeling experience with NREL and provide feedback on operational problems. The University of Massachusetts is under contract to support the code by offering technical assistance, making code improvements, and providing code updates over the coming year. Participating researchers can obtain the executable code, related manuals and the Frøya Island validation report.

FUTURE PLANS/CONCLUSION

There are plans for the further development of the Hybrid2 code although they are dependent on the future funding of the Hybrid2 program. The first order of business will be to address any bugs uncovered by users. We also plan to improve the code by adding more system consistency checks and including other modules such as micro-hydro power or other types of generators.

The Hybrid2 code provides a very powerful tool that will help those in the hybrid and renewable power industry, funding agencies as well as government agencies assess the potential of incorporating renewable power in their plans for the energy needs of the future.

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