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Validation of Hybrid2 with the Frøya Island Data Set

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Foreword

Hybrid System Performance Modeling

New markets for renewable hybrid power systems are emerging driven by the growing need for electrical generation in the developing world. In order to address these emerging markets, an analysis tool is required by industry, researchers, and development institutions for conducting preliminary hybrid system design and evaluation. To respond to this need, engineers at the National Renewable Energy Laboratory and the University of Massachusetts, with funding from the U.S. Department of Energy, have developed the Hybrid2 model for the simulation of the performance and cost of hybrid power systems. Hybrid2 is sufficiently versatile to simulate the many system locations, widely varying hardware configurations, and differing control strategies being proposed for potential hybrid systems. It is hoped that Hybrid2 will help to facilitate the broader application of renewable energy sources, wind and photovoltaic, into remote power systems in both domestic and international markets.

Model Testing

As with any simulation model, Hybrid2 must be tested to ensure that it is sound and to build confidence in the use of the model. The model developers, NREL and the University of Massachusetts, are conducting a test program with three main components: (1) verification, (2) validation, and (3) beta-testing. Expected outcomes of the 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. We also expect to demonstrate that model results have a reasonable correspondence to a few real systems for which historical data are available.

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. Over 300 different tests are being conducted using 68 different configurations. Beta-testing is model testing conducted by individuals outside of the development team. A group of about 20 potential users of Hybrid2 have been trained to use the model and then asked to exercise the model to simulate power systems of interest to them. We have received valuable feedback as to model useability, effectiveness, and acceptance.

The subject of this report is validation. Validation refers to comparisons of simulated performance to measured performance data from operating systems. Validation is useful to demonstrate the degree of correspondence of between the model and real power systems and to identify limitations of the model. Four validations planned for Hybrid2 are noted in the table below. Additional validations may be conducted, as well, as quality data sets become available and as resources permit.

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	83 days of 1-hour data
New World Power Technology Corp. tested at NREL	Wind/Diesel/Battery/Dump Load 50 kW nominal	Testing underway, 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

This report documents the first of these validations with the Frøya Island data set. A future report will summarize the results of the overall Hybrid2 test program once that program is complete.

Jim Green
Technical Monitor
National Wind Technology Center

6-21-96
Date

Executive Summary

To validate the simulation model Hybrid2, we simulated the performance of the Frøya system and compared it to measured data. The hybrid system, located on the Norwegian island of Frøya, is a wind/diesel with short-term battery storage and a dump load. Almost 17 days of system operation data are available from EFI, the Norwegian Electrical Research Institute of Norway. The same data set has been used to validate the European Wind Diesel Logistic Modelling Package (WDL) (Infield 1993, 1994).

We input the measured time series of primary load and wind speed for this validation. As was the case for the validation of WDL, we modified the primary load to account for a gap in the measured energy balance. The wind speed was also corrected to account for the temporary unavailability of the wind turbine.

The input parameters for the components and the dispatch strategy are obtained in two ways. Because manufacturer's data is not available for the components, we obtained the input parameters for the Hybrid2 code from the component characteristics as provided by EFI. This was done to study the accuracy of Hybrid2 for system design. Because the measured output of the wind turbine and minimum diesel load differs slightly from the EFI specifications, we also conducted a simulation run with parameters for these components derived from the measured data. In this way, we obtained maximum accuracy for a Hybrid2 performance simulation of the Frøya system.

When the Hybrid2 simulation is performed using the EFI input parameters for these components, the simulated energy production of the wind turbine and diesel is within 2% of the measured values. The simulated battery efficiency is much lower than was indicated in the measurements (which may be the case because the Alcad battery that was used in the simulation is not the same as the battery used in the Frøya system). Even so, the role of this short-term storage and the dispatch strategy is well represented, as shown by the good correspondence of 31% between the measured and simulated number of diesel starts. In addition, simulated fuel consumption was within 2% of the measured value, an accuracy sufficient for most design studies.

For the next simulation, some parameters were changed to reflect trends observed in the measured data. A slight modification was made to the wind turbine power curve around the cut-in wind speed. Also, the primary load was modified to account for the standing losses in a synchronous condenser, a component that can not be modelled directly by Hybrid2. This simulation resulted in an improved prediction of wind turbine net output, to within 1%. There was also a better match between the predictions for diesel energy production and the measured data.

Overall, Hybrid2 was found to be an excellent predictor of the performance of the Froya Island system and to have accuracy comparable to the best of the European WDL models.

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Introduction

This report presents a validation of Hybrid2 (Version 1.0) with measured data from the Frøya hybrid power system. Hybrid2 is a time-series model for the simulation of the long-term performance of renewable energy systems that use wind and photovoltaic (PV) power (Green and Manwell 1995). Hybrid2 was developed by the National Renewable Energy Laboratory (NREL) and the University of Massachusetts with funding from the U.S. Department of Energy.

The Frøya system, which is located on the Norwegian island of Frøya, uses both wind and diesel power with battery storage 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. Almost 17 days of systems operation data are available from 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 1993, 1994). This package consists of a user interface that gives access to six embedded models. This makes it possible to compare the results of the validation for Hybrid2 with the results for these six models.

When validating Hybrid2, we want to obtain an accurate measure of system performance. When events in the measuring period are not part of normal system operation, systematic error in the simulation would result. We can then remove these events from the simulation, in accordance with the WDL validation procedure.

For this Hybrid2 validation, the time-series input data consist of measured data of the primary load and resource. Two simulations were done for which the input parameters for the components and dispatch strategy are derived either (1) from manufacturers' specifications or (2) from the measured data. In the first case, Run 1, 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, Run 2, we derive the input parameters for each component and the dispatch strategy from the measured data, which shows their *realized* performance and shows the maximum accuracy of the Hybrid2 system performance model.

This work will describe the background of the Frøya system, the data set, and the power system. We will then discuss the input parameters for modelling this system in Hybrid2. The measured primary load and wind speed are modified to remove a constant gap in the energy balance and abnormal operation of the wind turbine. Next, the parameters for the components and dispatch strategy are identified and an overview is given of the various simulation runs. The results of the various runs are then presented and discussed. Finally, we discuss the accuracy with which Hybrid2 can simulate the Frøya system.

Background

In 1986, EFI started research on wind/diesel systems to supply electricity to villages without grid connection or to villages on islands where an existing underwater cable had to be replaced. In cooperation with EB-Energy, EFI designed a wind/diesel system with battery storage to satisfy this need. In this design, when the battery supplies power, the diesel generator acts as a synchronous condenser to provide reactive power. A dump load dissipates excess power.

A prototype system was installed on Frøya Island, located on the west coast of Norway, about 100 km NE of Trondheim. There it was connected to an existing wind turbine and operated with a simulated load. In autumn 1989, part of the island's electric grid was separated from the main grid and connected to the wind/diesel system. From this period, a data set of almost 17 days is available with measured data of 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).

Load and Resources

Little specific information about the characteristics of the load and site are available. The site is known to have relatively low turbulence in the winds which come off the ocean.

The Power System

The wind/diesel system with battery storage at Frøya Island consists of the following components:

- a Wincon 55-kW, three-bladed, stall-regulated wind turbine with induction generator
- a Cummins diesel generator set comprising a 50 kW turbocharged diesel engine, a 65-kVA brushless synchronous generator, and an electromagnetic clutch
- a BBC line-commutated converter rated at 37.5-kW and connected to a battery storage bank of 170 NiCd cells of 115 Ah each. With an average load of 20 kW in the Frøya system, this corresponds to about 1 hour of storage capacity. The converter may be operated in parallel with the diesel. The converter is bidirectional, providing capability to recharge the battery.
- a 55-kW, switched, resistor-type dump load.

The electrical components are connected in parallel to the common alternating current (AC) bus-bar. Figure 1 shows the schematic layout of the system. When the diesel does not run, the clutch is disengaged so that the generator acts as a synchronous condenser to provide reactive power. The battery is charged with power from the wind turbine and diesel generator. When the battery is full, the dump load dissipates excess power. The wind turbine simulator shown in figure 1 was not in use during the 17-day test period.

The dispatch strategy is as follows. The diesel is started when the wind turbine and the battery cannot supply the load. While the diesel is operating it supplies the load and charges the battery.

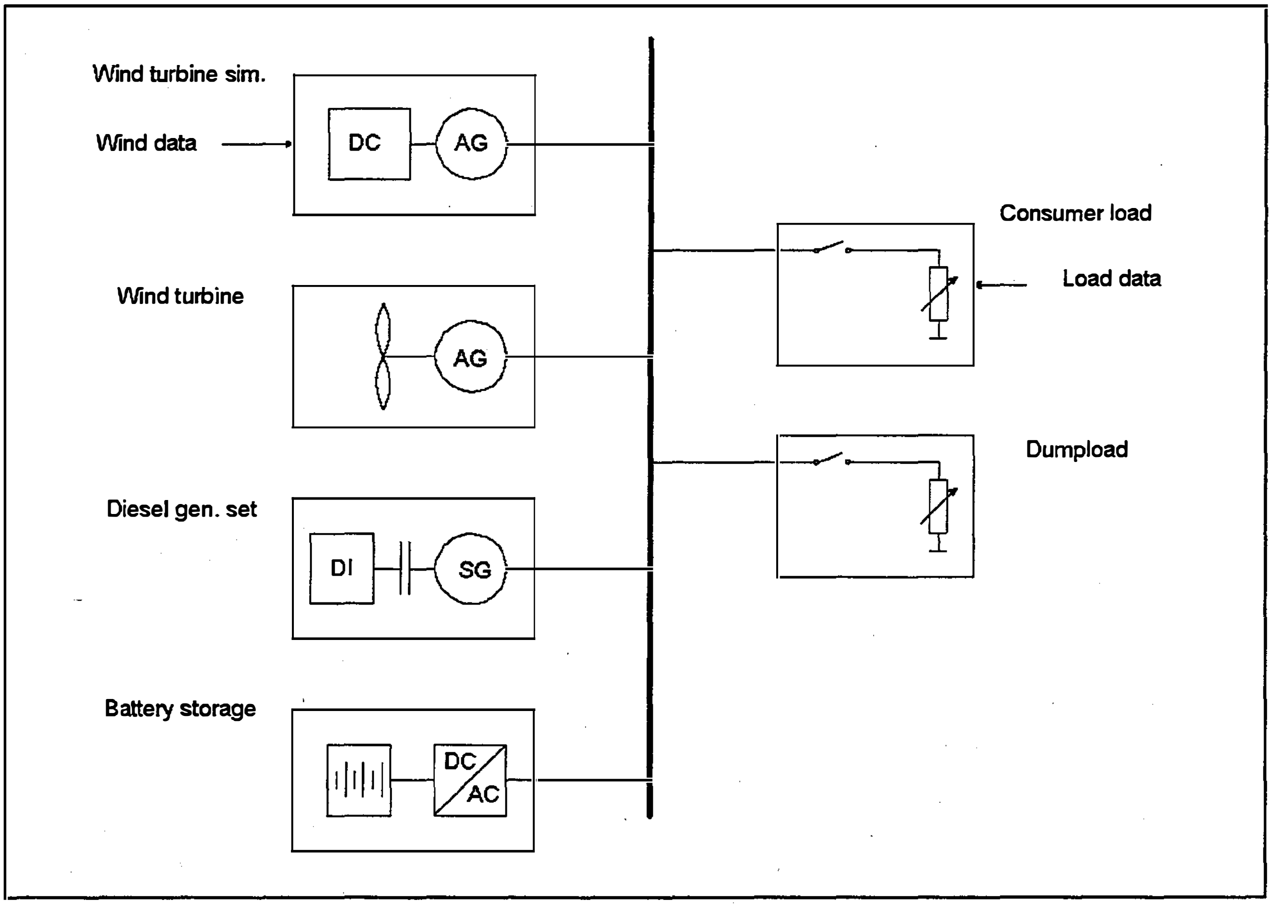


Figure 1. Schematic layout of the wind/diesel system with battery storage, Frøya Island

It is stopped when the following two conditions are fulfilled: (1) the mean wind power, measured ver the last 10 minutes, is larger than 1 kW; (2) the mean wind power exceeds the mean load by 2 kW or 0.6 times the mean wind power plus 11 kW exceeds the mean load and the storage is full.

The Data Set

The system operation was recorded by a PC-based data acquisition system. Data, which was sampled at a frequency of 1 Hz, were stored as average values over 10.72 minutes (643 seconds). The data set was taken during a long-term (almost 17 days or 394 hours) system test conducted in the autumn of 1989. The following data parameters were recorded:

- Primary load
- Wind speed
- Energy produced by the wind turbine generator or consumed by the wind turbine generator when motoring
- Energy produced by the diesel generator or consumed by the synchronous condenser when the clutch is disengaged

- Energy consumed by the dump load
- Energy flow to or from the battery. This was measured on the AC side of the converter and therefore includes losses associated with the converter.
- Total number of diesel starts.
- Total fuel consumption.

Figure 2 shows the measured primary load, wind speed, and energy flows. The primary load has a daily pattern with a minimum value of about 15 kW around midnight, and peaks around noon and early evening to as much as 30 kW. The average value of the primary load is 20-kW. The wind speed during this period was highly variable, with long periods of light wind and days with a strong gale. The average wind speed is 6.2 m/s, with a maximum recorded 10-minute average of 21 m/s.

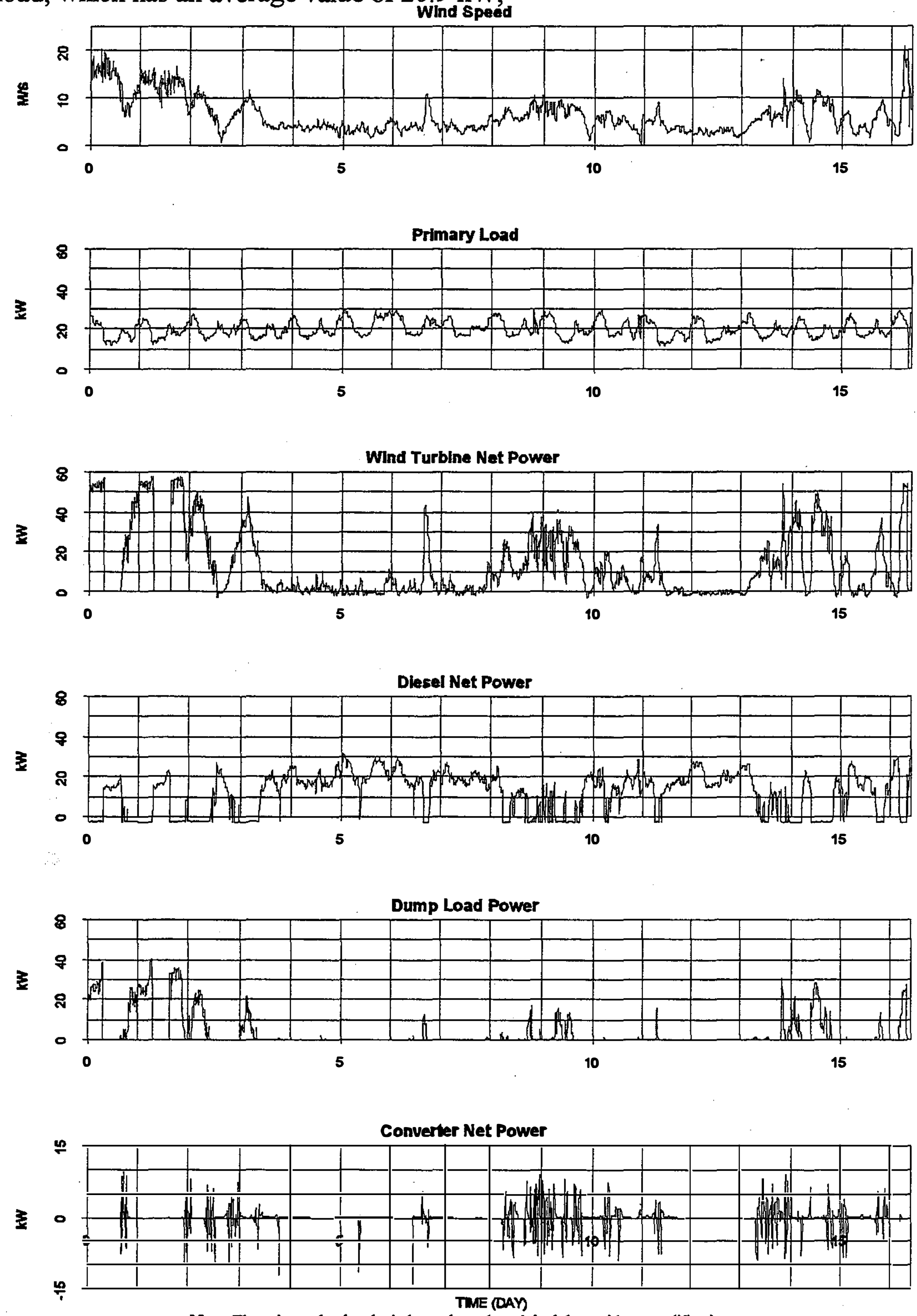
In the measuring period, the wind turbine and the diesel each produce about half of the required energy. About 13% of the energy produced is dumped, and 2% of the energy goes through the battery. The diesel started 29 times, which corresponds to 1.8 starts per day, and ran about 70% of the time.

The Input for Hybrid2

EFI provided the time-series data, characteristics of the system components and the dispatch strategy. These characteristics were supplied in the form of an input file for WDL. We derived a set of input parameters for Hybrid2 from these specifications, which we call "Run 1." However, by analyzing the measured data, it was observed that some of the components behaved slightly differently from what was provided by EFI. For these components, we derived an alternative set of input values, which we call "Run 2." Using the two different ways of determining the input data, much can be learned about using the Hybrid2 model. Run 1, using component specifications obtained from EFI, is akin to using the model to make technical estimates on the performance of future systems while a simulation using component characteristics take from the system data allows a more precise assessment of the accuracy of the Hybrid2 model.

The following gives an overview of the main input parameters for Hybrid2. Where applicable, we show both the input parameter as derived from the characteristics provided by EFI and the alternative value as estimated from the measured data. The derivation of the main input parameters, which are shown in Table 1, is discussed in detail. Net power, as shown for both wind and diesel, is power production minus the power consumption for each component. Appendix A contains a list of all of the input parameters.

- **Primary load**. In the validation study of WDL, it was observed that the energy production was, on average, 0.86 kW higher than the energy consumption. According to EFI, the difference was caused by unmeasured loads in the system, such as fans, heaters, and power supply to electronic equipment. To correct for the unmeasured loads, a constant load of 0.86 kW was added to the measured primary load. The modified primary load, which has an average value of 20.9 kW,



Note: The primary load and wind speed are the original data without modifications.

Figure 2. The measured time-series data of the primary load, the wind speed, and the power flows.

Table 1. The Main Input Parameters for the Simulation of the Frøya System with Hybrid2

	Run 1	Run 2 (when different from Run 1)
Primary Load		
Modified Load Data	Constant 0.86 kW added to each time step to correct for unmeasured loads	Additional constant load of 2.5 kW added to each time step to model standing losses in synchronous condenser
Load Variability	0.1 (estimated), constant for all time steps	
Wind Speed		
Modified Wind Speed Data	Speed set to zero during time steps when the wind turbine was unavailable	
Anemometer Height	24 m	
Wind Variability	0.15 (estimated), constant for all time steps	
Wind Turbine		
Type	Wincon 55 kW	
Rated Power	55 kW	
Hub Height	24 m	
Number of Wind Speed/Power Pairs	21	
Power Curve	Provided by EFI	corrected for wind turbine motoring at low wind speeds
Diesel		
Type	Cummins 50 kW	
Rated Power	50 kW	52.5 kW (losses for windage and friction taken out of diesel model to model standing losses in synchronous condenser)
Minimum Allowed Running Power	7.5 kW	0 kW as no minimum allowed running power is observed in the data
Full-Load Fuel Consumption	14.19 l/h	
No-Load Fuel Consumption	2.63 l/h	2.06 l/h (losses for windage and friction taken out of diesel model to model standing losses in synchronous condenser)
Synchronous Condenser Standing Losses	Not modelled	modelled as constant load of 2.5 kW
Dump Load		
Rated Power	55 kW	

Table 1. The Main Input Parameters for the Simulation of the Frøya System with Hybrid2 (Continued)

	Run 1	Run 2 (when different from Run 1)
Battery Bank		
Type	Alcad MR	
Capacity	340 Ah	
Number of Cells in Series	170	
Number of Cells in Parallel	1	
Battery Bank Scale Factor	0.337	
Maximum Charge Rate	1.0 Ah/Ah discharged	0.775 Ah/Ah discharged
Bidirectional Converter		
Type	BBC 55 kW	
Operation Mode	parallel	
Rated Power	55 kW	
Inversion No-Load Loss	0 kW	
Inversion Full-Load Efficiency	95 %	
Rectification No-Load Loss	0 kW	
Rectification Full-Load Efficiency	95%	
Dispatch Strategy		
Battery Discharge Code	All or part of the average load	
Battery Minimum SOC	60%	
Diesel Minimum Run Time	10 minutes (One simulation time period)	
Code for Allowed Diesel Shutdown	All diesels	
Diesel Operating Power Level	At maximum battery charge rate	
Code for Diesel Start	To meet the load or to charge the batteries when depleted	
Diesel Shutdown Code	When renewables can cover the load	
Battery SOC at Which Recharge by Diesel Starts	60%	
Battery SOC at Which Recharge by Diesel Stops	95%	

was used for the validation of WDL. We used the same modified primary load in the Hybrid2 simulations. EFI did not measure the standard deviation of the primary load; therefor a constant variability of 0.1 for all primary load data was estimated. This value has been used repeatedly as a good indicator for the variability in power use in remote power systems and was considered by Kjetil Uhlen of EFI as an acceptable value for the variability in the load at Frøya.

- **Wind speed**. In the validation study of WDL, it was also noticed that, during the first 40 hours, the wind turbine was shut down several times by its own protection system. EFI attributed the shutdown to overcurrent in the yaw motor. To represent the non-availability of the wind turbine in this period, the wind speed file was changed by setting the wind speed to zero during the wind turbine shutdowns. The modified wind speed, which has an average value of 5.6 m/s, was used for the validation of WDL. We used the same modified wind speed for the validation of Hybrid2. The standard deviation of the wind speed was not measured by EFI; however a variability of 15 % was recommended by Kjetil Uhlen of EFI to be an acceptable value for the variability of the wind at the Frøya Island site. The variability in the load and wind data were not used as "fudge factors" in the validation of Hybrid2. Values that seemed to represent the site, taken from experience at other locations and the limited information about Frøya Island, were used.

- **Wind turbine**. The power curve of the wind turbine was measured by EFI using separate measurements and is shown in Figure 3. However, in the data set that we used there were periods at low wind speeds when the wind turbine was seen to be motoring. During these

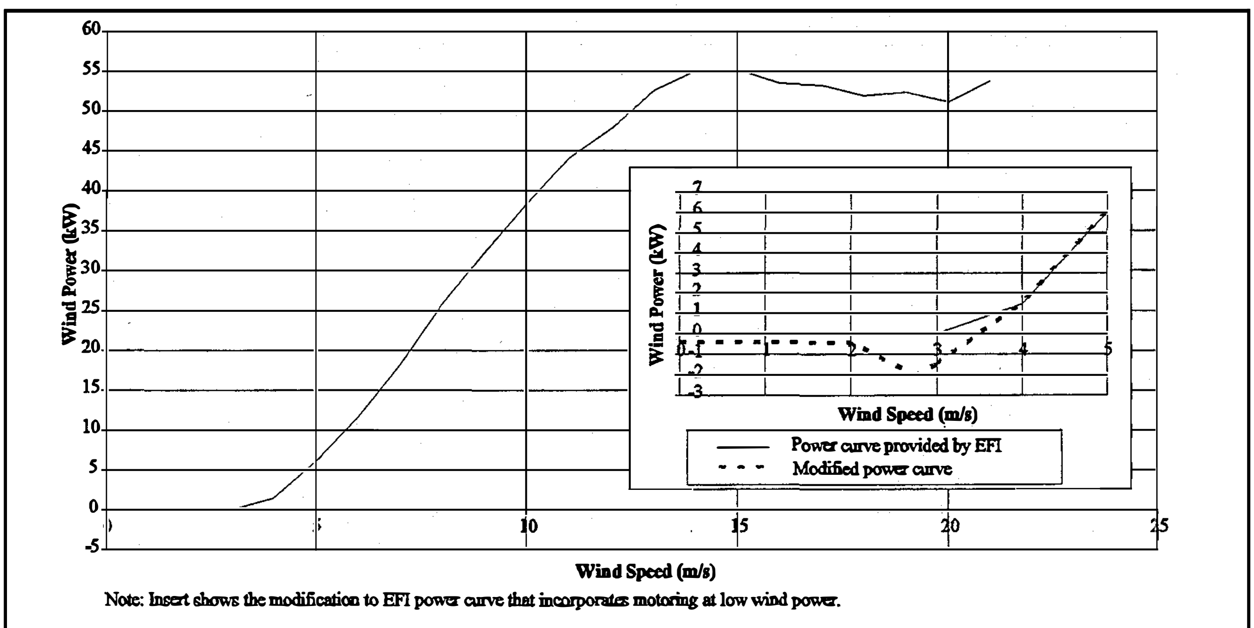


Figure 3. Original Frøya Island wind turbine power curve, provided by EFI, and modified curve derived from test data (insert)

occurrences the measured output of the wind turbine can become negative, with values of as much as -3 kW, as seen in Figure 4. These negative values were not included in the power curve provided by EFI. To capture this effect, a second power curve was calculated, which is the same as the EFI power curve for wind speeds above 4 m/s, but includes the negative power values found for wind speeds below this value. The modification to the EFI power curve is shown as the dashed line in the insert to Figure 3.

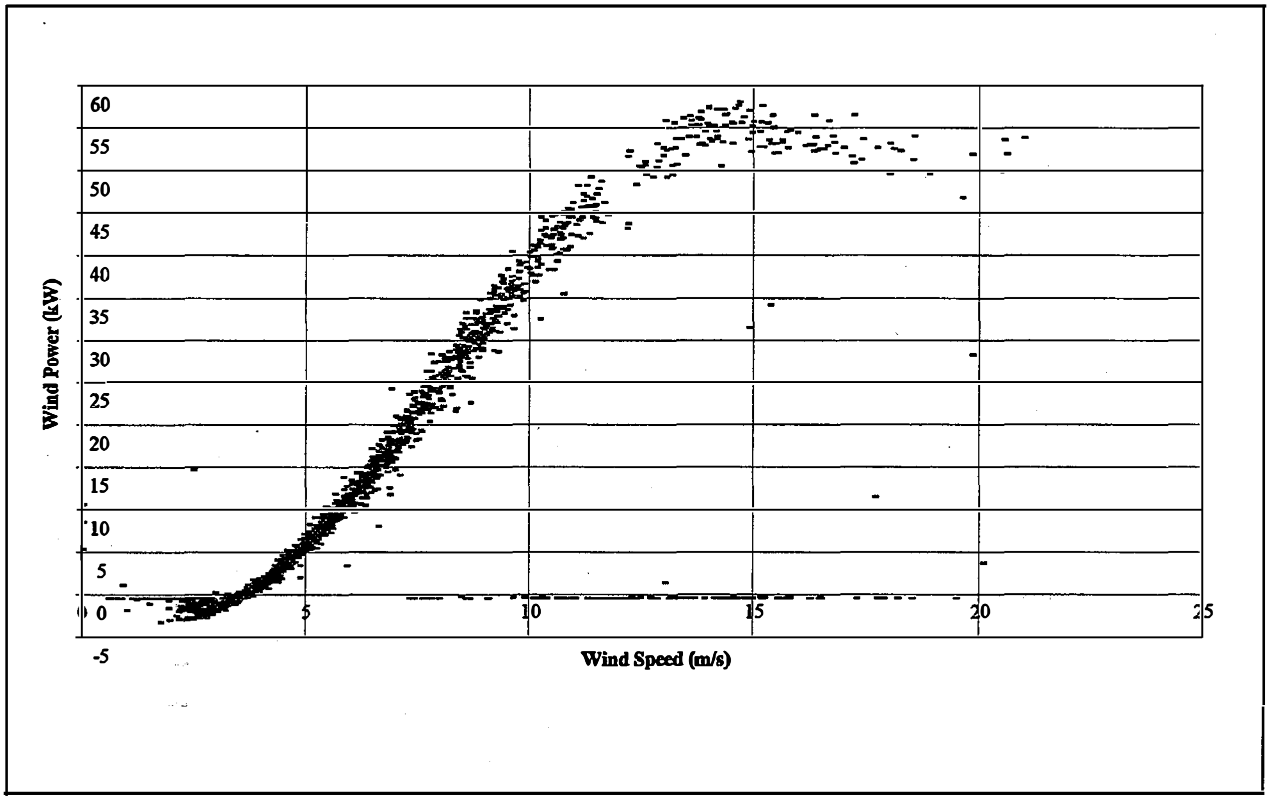


Figure 4. The measured pairs of wind speed and wind turbine output energy from the data set of the Frøya system

- **Diesel**. The rated power of the Cummins diesel generator is 50 kW. The minimum-allowed running power is specified as 7.5 kW; however, we could not observe a minimum power in the measured data. The fuel curve is specified by EFI as a second-order function of the output power:

$$F = 0.0021P_{diesel}^2 + 0.126P_{diesel} + 3.492 \qquad \textbf{(1)}$$

where

F = the fuel consumption (l/hr)

P_{diesel} = the diesel generator power (kW).

We derive the fuel consumption at full load and at no-load, which in Hybrid2 characterizes the genset performance, from a first-order fit to the measured curve (Figure 5): the fuel consumption at 50 kW output is 14.19 l/h, and the no-load fuel consumption is 2.63 l/h.

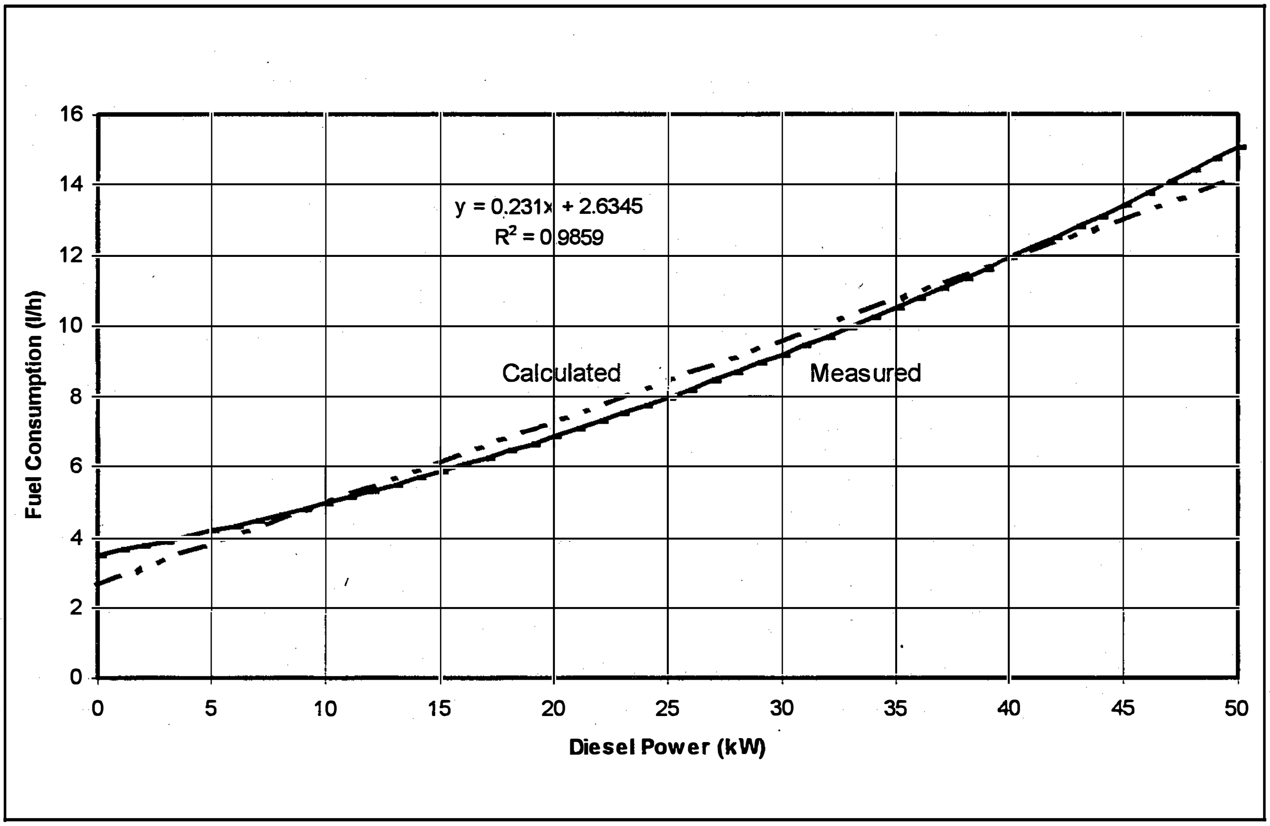


Figure 5. The fuel curve of the Cummins diesel generator as provided by EFI and the linear fuel curve used by Hybrid2

- **Synchronous Condenser**. The standing losses in the synchronous condenser are 2.5 kW. Standing losses are not part of the diesel model in Hybrid2 however, they can be modeled in an ad-hoc fashion. When the diesel does not run, standing losses are the losses for windage and friction in the synchronous condenser that is still operating. When the diesel runs, the losses for windage and friction are part of the losses in the generator of the diesel generator set and are accounted for in the diesel fuel consumption curve. To model standing losses in Hybrid2, we take out these losses as a constant load of 2.5 kW from the losses in the diesel. At this point, the diesel in Hybrid2 represents a diesel generator set without losses for windage and friction in the generator. The losses from the synchronous condenser are then reintroduced as a constant added to the primary load. Therefore, during the simulation when the diesel is not operating, the constant load represents the standing losses in the synchronous condenser. When the diesel is operating, the constant load represents the losses for friction and windage in the generator. To model this occurrence in Hybrid2, we added a constant load of 2.5 kW to the primary load and changed the full-load fuel consumption of the diesel from 14.19 l/h at 50 kW to 14.19 l/h, at 52.5 kW. The no-load fuel consumption was also adjusted from 2.63 l/h to 2.06 l/h and the minimum allowed running power of the diesel was changed from 7.5 kW to 10 kW. From the Hybrid2 output, we subtract 2.5 kW from the simulated primary load for each time step to get the original primary load. For those periods when the diesel is operational, 2.5 kW is subtracted from the simulated diesel output to predict the actual electrical output of the diesel generator set.

- **Dump load**. The dump load, which has eight resistors on each phase controlled by static relays, is modelled as a continuous dump load with a rated power of 55 kW.

- **Battery**. No information was available on the NiCad battery used in the Frøya, system except for the nominal capacity of 115 Ah. For simulation purposes, an Alcad MR battery was used to represent a typical NiCad battery. Specifications for the M30P were obtained from the battery manufacturer (Alcad 1993). To account for the larger maximum capacity (341 Ah) of the Alcad MR the Hybrid2 battery bank scale factor was set to 115 Ah/341 Ah = 0.337. The initial battery capacity was set to 77.5 % State of Charge (SoC), a value half way between full charge of 95 % SoC and discharged which occurs at 60 % SoC. It is also known that the battery bank was rather old when these tests were conducted. This is reinforced by the fact that the maximum charge provided to the battery during any time step is 9.7 kW, or 40 amps based on the nominal voltage. This was modeled in Run 2 by decreasing the allowable charge rate of the battery bank in Hybrid2 to a level similar to that seen in the data.

- **Inverter/Rectifier**. We model the inverter-rectifier in Hybrid2 as a bidirectional converter. EFI supplied the power rating and efficiency values, although the operation mode was not specified. The WDL validation effort states that the converter could operate in parallel, a factor supported by the data from Frøya Island. The converter was modeled as operating in this fashion

- **Dispatch strategy**. In Hybrid2 the dispatch strategy is modelled as follows:
  - The battery can be discharged to cover the entire load, or a portion of the load.
  - According to EFI, the energy capacity of the battery bank is 27 kWh, calculated as 170 cells x 115 Ah x 1.4 V, and the effective capacity 15 kWh. This is modelled by setting the battery minimum state of charge to 60% of the battery full state of charge at which point the diesel must be used to cover any deficit in renewable power .
  - Following the practice by EFI, the diesels are run in cyclic manner with the diesels being used to charge the batteries while it was are operating.
  - The diesels are started when the load can not be covered by the combination of wind energy and energy from the storage. The diesel will start charging the batteries once it has started.
  - EFI's diesel stop criteria allowed the diesel to stop either; (1) when the mean wind power exceeds the mean load with 2 kW or (2) when 0.6 times the mean wind power, plus 11 kW, exceeds the mean load and the storage is full. This dispatch cannot be modelled by Hybrid2 because it does not allow an offset between mean wind power and mean load. We can

approximate the stop criterium, however, by running the diesel until the wind power and the batteries can cover the load. The modeling of the dispatch strategy is one of the most difficult elements in the validation effort. The dispatch strategy also provides perhaps the most likely source for error in the validation effort.

Description of the Tests

To validate Hybrid2, we made runs with two different input sets. First we studied the accuracy of Hybrid2 for system design by using the input parameters provided by EFI for the components (Run 1). Second, we investigated the maximum accuracy with which Hybrid2 can model the Frøya system by using the input as derived from measured data (Run 2). The two runs differ with respect to the following input parameters, Table 2.

Table 2. The Two Runs and Respective Models that Were Used to Simulate the Frøya System with Hybrid2

Run Number	Run 1	Run 2
Wind Turbine Power Curve	original	modified
Diesel Minimum Allowed Running Power	7.5 kW	0 kW
Synchronous Condenser Standing Losses	not modelled	modelled
Battery Charge Rate	Standard Charge Rate	Charge Limiting

Run 1: Accuracy of Hybrid2 for system design with the inputs provided by EFI.
The wind turbine power curve provided by EFI was used. The minimum-allowed running power of the diesel is 7.5 kW. We don't model standing losses, as this is not part of the diesel model in Hybrid2. The batteries were modeled without regard to the charge limiting seen in the test data. This test run typifies the type of simulation that may be conducted when doing an initial analysis for a potential hybrid power system.

Run 2: Maximum accuracy of Hybrid2 with the inputs modified using the field data.
We used the modified power curve for the wind turbine and the diesel minimum allowed running power is set to zero. The standing losses are modelled by adding a constant load of 2.5 kW to the primary load and modifying the diesel fuel curve. The charge rate of the battery bank was limited to account for this effect seen in the Frøya data. In this way, the Hybrid2 input parameters in represented the conditions during the measuring period during which data was recorded.

Results of the Simulation

Table 3 compares the results of the two simulation runs with the measurements. Both absolute values and percent deviation from the measured values are shown. For the wind turbine and the diesel, the category "net energy" is the energy production minus the energy consumption by that component. The energy production and energy consumption are also shown separately. "Converter Input/Output Energy" is the energy flows measured on the AC bus to or from the

Table 3. Comparison of the Measured and the Simulated Performance of the Frøya System with Hybrid2.

	Measured	Run 1	Run 2
INPUT FOR Hybrid2			
Wind Turbine Power Curve	-	original	modified
Diesel Minimum-Allowed Running Power	-	7.5 kW	0 kW
Synchronous Generator Standing Losses	-	not modelled	modelled
Battery Charge limit	-	standard limit	limited
RESULTS			
Primary Load (kWh)	8196	8202	8202
Wind Turbine Net Energy (kWh)	4801	4997 (+4)	4873 (+1)
- Production	4897	4997 (+2)	4970 (+1)
- Consumption	96	-	97 (+1)
Diesel Net Energy (kWh)	4656	4919(+6)	4764 (+2)
- Production by Generator	4944	4919 (-1)	5045 (+2)
- Consumption by Synchronous Condenser	288	-	281 (-2)
Dump Energy (kWh)	1261	1583 (+26)	1297 (+3)
Converter Input Energy (kWh)	223	285 (+28)	300 (+35)
Converter Output Energy (kWh)	141	145 (+3)	151 (+7)
Diesel Run Time (h)	284	273 (-4)	282 (-1)
Number of Diesel Starts	29	20 (-31)	22 (-24)
Total Fuel Consumption (l)	1812	1855 (+2)	1909 (+5)

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

power converter in the battery storage subsystem. Diesel performance parameters - run time, number of starts, and fuel consumption - are given at the bottom of the table. Appendix B and C included complete time series comparisons between measured data and the Hybrid2 simulation for Run 1 and 2 respectively. To illastrate the validation comparison, a two day segment of time series data has been extracted for both runs, Figures 6 - 13. This time series demonstrates both the good correlation between the Frøya data and the simulations but also point out some of the simulation errors.

Discussion

Run 1

When using the input provided by EFI the wind turbine net energy is overestimated by 4% and the diesel net energy by 6%. However, the correspondence is better than 2% with regard to the energy production for both components. This indicates that the overestimation of the wind turbine and diesel net energy in the simulation is mainly due to the neglect of the energy consumption by the wind turbine at low wind speed and by the synchronous condenser when the diesel engine is off. This can clearly be seen in Figures 6 and 7 when the net power in the measured data is negative. As a result of this neglected power consumption, the dumped energy is overestimated

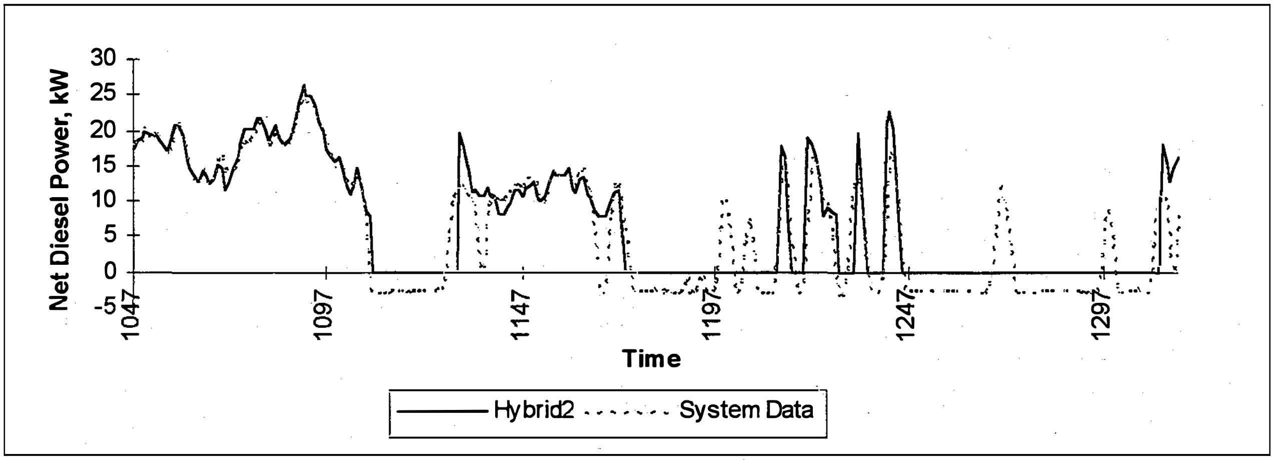


Figure 6. Net diesel power for Frøya system and Hybrid2 simulation, Run 1

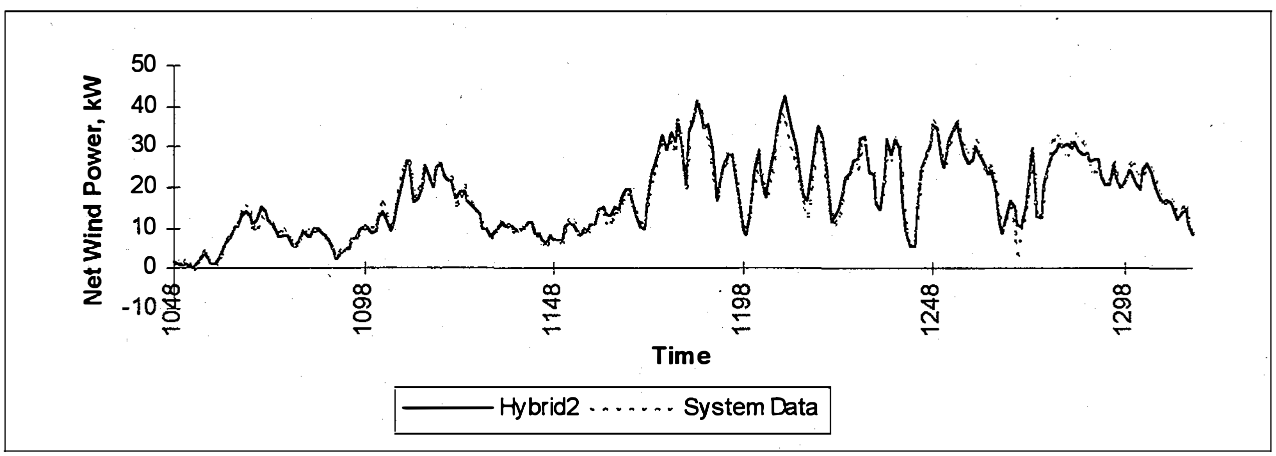


Figure 7. Net wind turbine power for Frøya system and Hybrid2 simulation, Run 1

by 31%, Figure 8. The measured and simulated number of diesel starts are within 31% and the fuel consumption is slightly overestimated, by 2%. These accuracies should be sufficient for most design studies. The good correspondence for the diesel production shows that Hybrid2 can fairly well represent the dispatch strategy of the Frøya system. The error in the number of diesel starts do indicate that the exact start/stop switching of the diesel generator is not well simulated. This can also be seen in Figure 6 where there are a number of diesel starts seen in the data that are not reflected in the Hybrid2 simulation. The reason for the difference in diesel starts is likely due to the 2 kW control offset used in the real system that can not be modeled in Hybrid2. It should be noted that the over the 17 day simulation, the error in diesel starts amounts to an error of only one diesel start every other day.

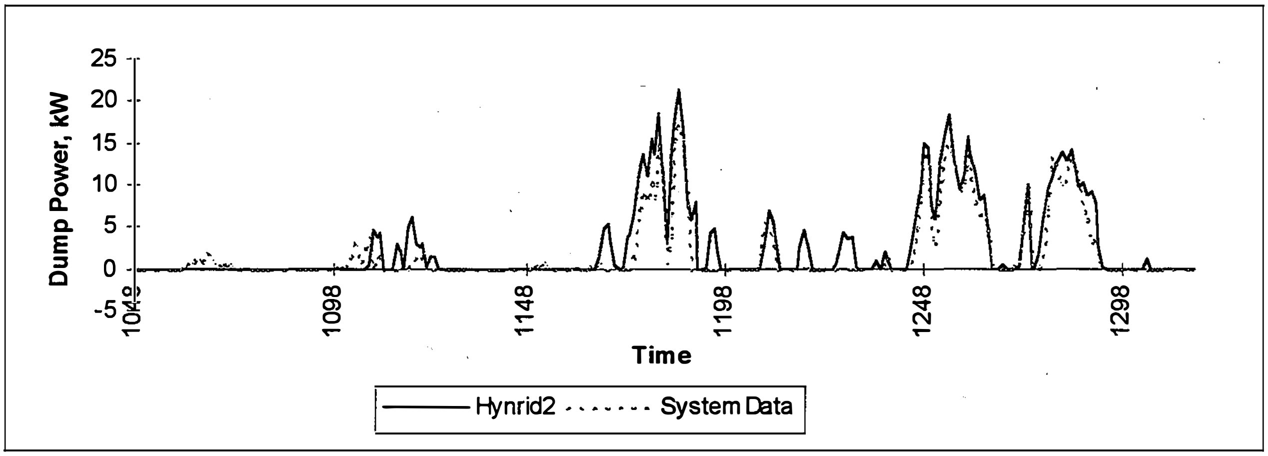


Figure 8. Dump power for Frøya system and Hybrid2 simulation, Run 1

The simulated converter output energy is close to the measured value, however the converter input is much larger in the simulation than in the measurement. The overall efficiency of the converter and the battery is only 51% in the simulation whereas it is 63% in the measurement. In Hybrid2, the energy losses of the battery are calculated using the Extended Kinetic Battery Model. The energy losses are related to the battery voltage, where the more the calculated voltage deviates from the voltage at zero current for a specified state-of-charge, the higher the energy losses. The short-term battery storage in the Frøya system results in high battery currents. Using the battery parameters reported for an "Alcad" brand battery leads to high battery voltages during charge and low battery voltages during discharge. Subsequently, higher energy losses are reported than were measured. Due to the presence of excess wind power at the start of the simulation, which charges the batteries fully within the first few time steps, the initial battery capacity at the start of the simulation has little effect on the overall simulation. The lack of data for the Frøya battery makes this validation of the battery model inconclusive. However, because of the small size of the short term storage and the small power flows to and from the battery bank relative to the rest of the hybrid system, these uncertainties seem to have little impact on the simulation performance. The battery subsystem output is less than 2% of the system primary load. The effects of the presence of short term storage in the Frøya system, as compared to a system with no storage and to a diesel-only power system are presented in Appendix D. Figure 9 shows a time series data for the converter power. It is clear that although the time series are not identical, the size and concentration of converter power flows shown good correlation.

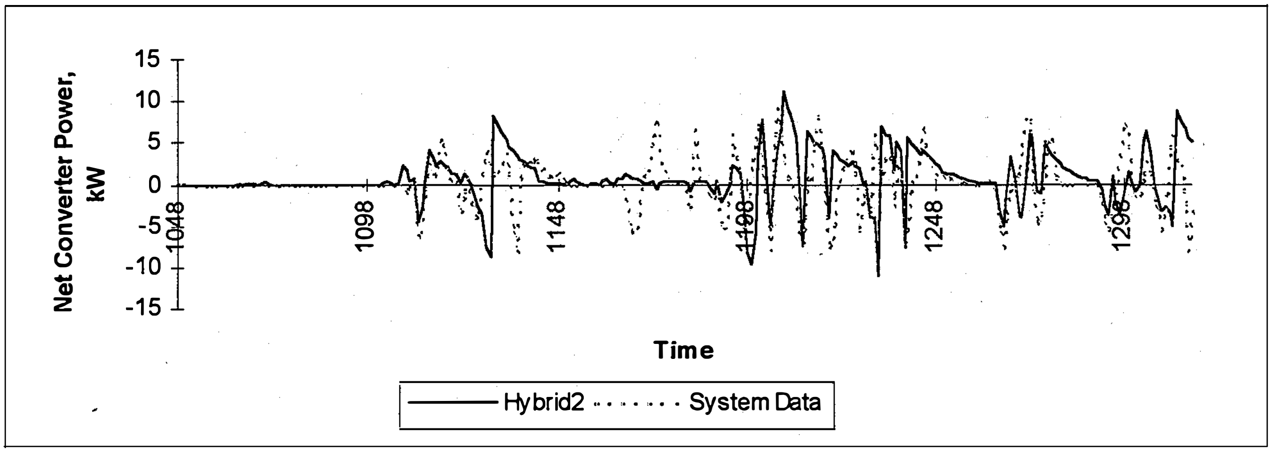


Figure 9. Net Converter power for Frøya system and Hybrid2 simulation, Run 1

Run 2

In Run 2, where the maximum performance of the Hybrid2 code is obtained for this system, the modeling of the wind turbine performance is better than in Run 1. The use of a wind turbine power curve that is derived from the measured data improves the correspondence between simulated and measured wind turbine net energy from 4% to 1%. This is apparently the maximum accuracy that can be obtained with a power curve to estimate the power production of the wind turbine from the wind speed for this system. Figure 10 also demonstrates this accuracy.
The simulated diesel performance is also closer to the measured performance, Figure 11. The simulated diesel net output is within 2% of the measured value and the simulated run time is

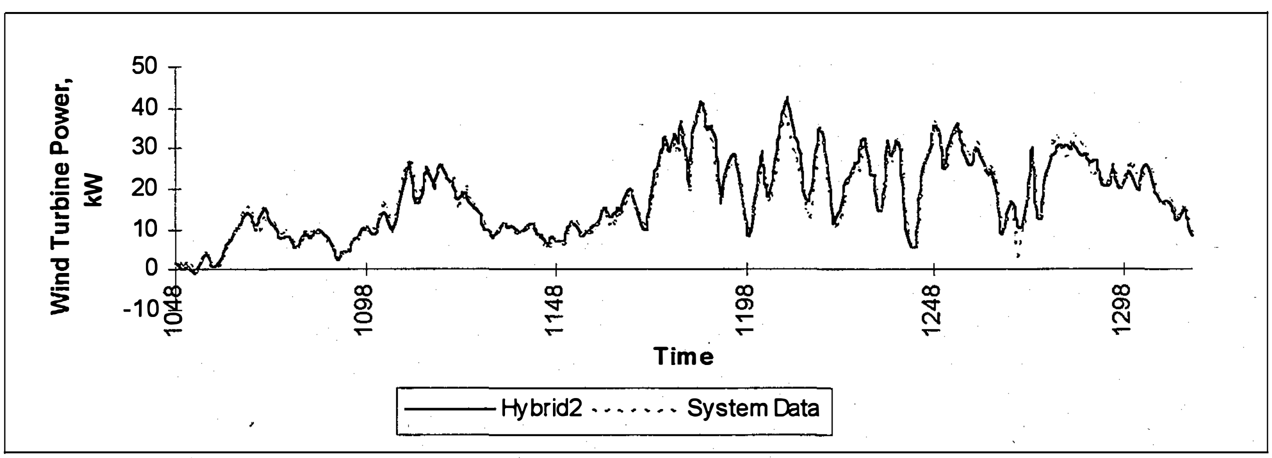


Figure 10. Net wind turbine power for Frøya system and Hybrid2 simulation, Run 2

energy, number of diesel starts, and run time are closer to the measured values than in Run 1. For both of the simulation runs, the converter output energy is close to the measured value.

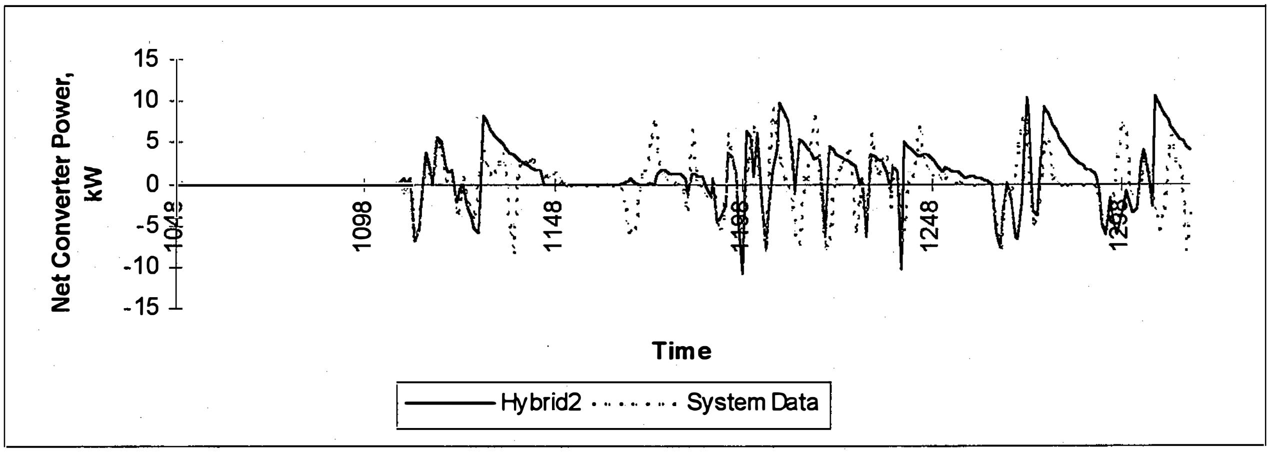


Figure 12. Net converter power for Frøya system and Hybrid2 simulation, Run 2

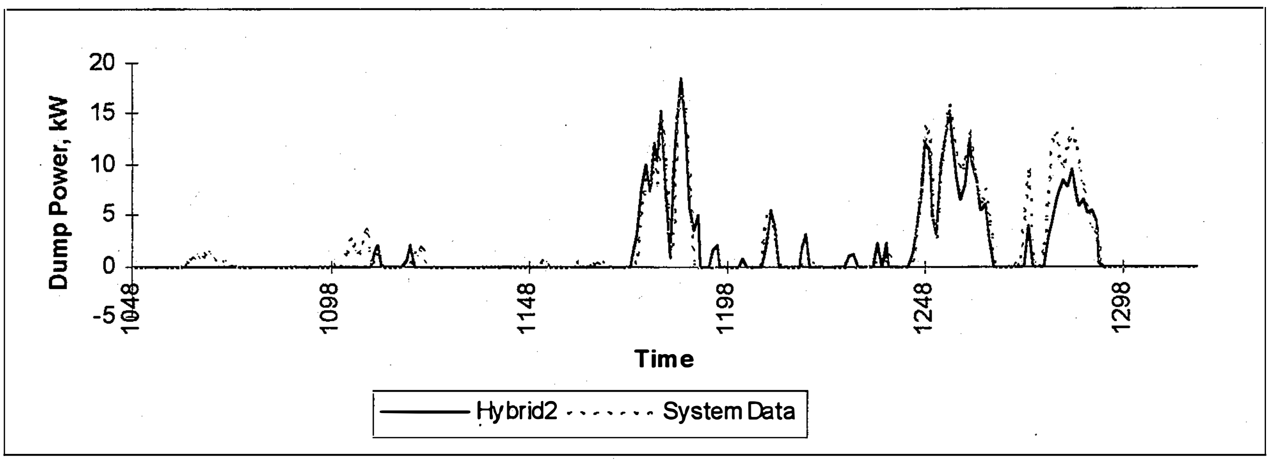


Figure 13. Net dump power for Frøya system and Hybrid2 simulation, Run 2

The use of statistical analysis by Hybrid2 to model the variability in the wind and load likely contributes to the quality of the results. The inclusion of variability allows for a more accurate representation of performance than would be available in a quasi-steady, time series model. Since the data obtained for the Frøya system did not include variability, a validation of these algorithms in Hybrid2 could not be conducted.

Comparison to WDL validation

The performance of the Frøya system has previously been simulated with the WDL models (Infield 1993, 1994). This allows for a direct comparison between Hybrid2 and the six European models. The results for each of the six simulation models that are embedded in WDL, along with Hybrid2 results and the measured data are shown in Table 4. To conduct a direct comparison, an additional simulation run, Run 1A, was conducted. Run 1A used the inputs for each of the components provided by EFI, a standard battery charge rate and the standing losses in the synchronous condenser were modelled. It can be seen that the results from the six European models vary widely. For example, the simulated wind turbine net energy varies from -2 to +13% of the measured value, and the simulated diesel net energy from -5 to +10%. The predictions for total fuel consumption range from -10% to 6% of the measured value. The differences are larger for the number of diesel starts and converter energy. It must be realized that some of these simulation models were designed for some specific system architectures, which might not include a wind/diesel system with short-term battery storage. The accuracy with which Hybrid2 can simulate the performance of the Frøya system is of the same order, or better than, the best European models.

Conclusions

The Hybrid2 model has been tested by comparing its prediction of the performance of the Frøya Island wind-diesel system to a measured, 17-day data set. This validation shows the model to be an excellent predictor of system performance. Further, Hybrid2 compares very favorably to the WDL models which are among the best wind-diesel models available. The primary shortcoming of Hybrid2 revealed in this study was its inability to model the losses of a synchronous condenser. This was managed by manually accounting for that loss in the input and output data sets. 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 manufacturers 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 knowledge, Hybrid2 predicts the converter power as well as the best European models.
- The validation of the statistical algorithms in Hybrid2 that account for variability in the wind and load are also inconclusive because the original data obtained for the Frøya system did not include variability.
- Hybrid2 does well in modelling the 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 as well as the very close approximation of fuel use and diesel operational hours.

Table 4. Comparison of the Simulation of the Frøya System with Hybrid2 and the Six Simulation Models that are Embedded in WDL

	Measured	Hybrid2 (Run 1A)	SOMES	VINDEC	E_WISDA	WDILOG	RALMOD	TKKMOD
Primary Load (kWh)	8196	8203	8193	8195	8192	8200	8175	8200
Wind turbine Net Energy (kWh)	4801	4997 (+4)	4942 (+3)	4991 (+4)	4934 (+3)	4897 (+2)	5442 (+13)	4685 (-2)
Diesel Net Energy (kWh)	4656	4711 (+1)	4524 (-3)	4504 (-3)	4709 (+1)	4757 (+2)	4423 (-5)	5099 (+10)
Dump Energy (kWh)	1261	1344 (+7)	1160 (-8)	1219 (-3)	1339 (+6)	1412 (+12)	1690 (+34)	1209 (-4)
Converter Input Energy (kWh)	223	326 (+46)	385 (+73)	279 (+25)	364 (+63)	151 (-32)	-	238 (+7)
Converter Output Energy (kWh)	141	156 (+11)	308 (+118)	197 (+40)	252(+79)	107 (-24)	-	201 (+43)
Diesel Run Time (h)	284	282 (-1)	-	-	273 (-4)	299 (+5)	290 (+2)	275 (-3)
Number of Diesel Starts	29	22 (-24)	20 (-31)	23 (-21)	17 (-41)	45 (+55)	2684 (++)	40 (+38)
Total Fuel Consumption (l)	1812	1896 (+5)	1707 (-6)	1752 (-3)	1810 (0)	1919 (+6)	1636 (-10)	1818 (0)

Note: For comparison, we also show the measured results and the results of a run with Hybrid2, with the input provided by EFI and the modelled standing losses in the synchronous condenser (Run 1A). The values in parentheses give the percentage's that the simulated value's differ from the corresponding measured values. The results for WDL are taken from Infield (1993, 1994).

This validation is strong evidence that Hybrid2 is technically sound and reasonably accurate for modelling wind/diesel systems. This validation is just one part of a larger test program to assess the accuracy and quality of the model that includes model verification, beta-testing, and four separate validations against measured data.

Acknowledgements

This material is part of an effort by NREL to develop the Hybrid2 simulation model and was funded by the U.S. Department of Energy. We thank K. Uhlen of EFI for making available the data on the Frøya system collected as part of the European study.

References

Alcad, Standby Batteries, M Range Nickel Cadmium Batteries. (August 1993), Northhaven, CT: Alcad Incorporated.

Green, H.; Manwell, J. (1995). "Hybrid2 - A Versatile Model of the Performance of Hybrid Power Systems." Presented at the American Wind Energy Association's Windpower '95 Conference, Washington D.C., 27-30 March [1995].

Infield, D.G., et al. (November 1993) "Engineering Design Tools for Wind Diesel Systems: Presentation and Validation of the Logistic Modelling Package." European Community Wind Energy Conference. Traavemünde: H.S. Stephens & Associates; pp. 316-319.

Infield, D., et al. (1994) "Engineering Design Tools for Wind Diesel Systems." Final report on CEC contract JOUR-0078. Report RAL-94-001/007, Didcot: RAL.

Uhlen, K., Skarstein, O., Toftevaag, T., Tande, J.O., (1989). "Design and Operation of the Full Scale Norwegian Wind/Diesel Laboratory Model." European Wind Energy Conference, Glasgow, Scotland: Peter Peregrinus Ltd. pp. 209-213.

Appendix A: The Hybrid2 Files for the Frøya System

o Project File: froya1a.prj

"Power system used on Froya Island, Norway. This data was used as one of the validation exercise for the Hybrid2 code. This data was also used in the validation of the European WDL models. The project shown represents the system as designed. The system is a test wind/diesel/battery system that has run autonomously and connected to the larger island grid."
"DAY" "Time Unit of the Simulation Period: MINUTE, HOUR, or DAY"
1 "Start Value of the Simulation period (Time Units, 1 starts at first data point in files)"
17 "Duration of the Simulation period (Time Units)"
10.72 "Simulation time step, 5 TO 120 minutes"
"Y" "AC Primary Load Present: (y/n)"
"N" "AC Deferrable Load Present: (y/n) "
"N" "AC Optional Load Present: (y/n)"
"N" "DC Primary Load Present: (y/n)"
"N" "DC Deferrable Load Present: (y/n)"
"N" "DC Optional Load Present: (y/n)"
"N" "Base Case Present: (y/n)"
"N" "Economic Input Present: (y/n)"
"froya2.acp" "AC Primary Load File Name"
1 "AC Primary Load Scale Factor, normally = 1"
"none.acd" "AC Deferable Load File Name"
"none.aco" "AC Optional Load File Name"
"none.dcp" "DC Primary Load File Name"
1 "DC Primary Load Scale Factor, normally = 1"
"none.dcd" "DC Deferable Load File Name"
"none.dco" "DC Optional Load File Name"
"froya.sit" "Site/Resource File Name"
"froya1.pow" "Power System File Name"
"none.eci" "Economic Input File Name"
1 "Number of Diesel Types (Base Case), 1 to 7 allowed"
"none.acg" 1 "Diesel File Name and Number of Specified Diesels (Base Case)"
1 "Diesel Minimum Run Time (Base Case); hours"
1 "Code for Diesel Shut Off (Base Case): (1) all diesels (2) all but one"
"N" "Code for Diesel Dispatch Order (Base Case): (Y) prescribed (N) minimum fuel consumption"

o Primary load file: froya2.acp

"Froya Wind, 394 h, 10.72 min averages; constant power consumption of 0.858 kW added to original load"
10.72 "Data Time Step; minutes"
0.2 "Code for Fluctuations: (-1) Standard Deviation, (0 to 1) Value of Variability (>1) Value of Std. Dev."
7.988 (modified to model standing losses in synchronous condensor: 10.488)
28.558 (modified to model standing losses in synchronous condensor: 31.058)
27.938 (modified to model standing losses in synchronous condensor: 30.438)

o Wind speed file: froya2.wnd

"Froya Wind, 394 h, 10.72 min averages; wind speeds were the wind turbine was shut down were set to zero."
"Metric" "Wind Speed Units, (English) or (Metric)"
10.72 "Data Time Step; minutes"
20 "Anemometer Height; meters"
0.2 "Code for Fluctuations: (-1) Std. Dev. in File; (0 to 1) Value of Variability; (>1) Value of Std. Dev."
3.460
19.570
17.970

o Site/resource file: froya.sit

"Froya site/resource file. Turbulence intensity set to default value, code for air density to constant density ratio of 1."
"Metric" "User Input Units, (English) or (Metric)"
"froya2.wnd" "Wind Speed File Name"
1 "Wind Speed Scale Factor, normally = 1"
0.143 "Power Law Exponent, 0.1-1.0"
100 "Turbulence Length Scale, 10-1000 meters"
10 "Reference Wind Velocity for Turbulence Length Scale, 2-20 meters/sec"
0.15 "Nominal Turbulence Intensity, normally 0.01-0.5"
1 "Code for Air Density Model: (1) Density Ratio (2) Ideal Gas Law (3) Adiabatic Lapse Rate "
1 "Air Density Model 1st Parameter: (1) Density Ratio (2;3) Ambient Temperature"
0 "Air Density Model 2nd Parameter: (1) 0 (2) Height/Altitude (3) Air Pressure"
"none.sol" "Insolation File Name"
.2 "Ground Reflectivity, 0 to 1.0"
"N" "Code for Ambient Temperature Data: (Y) File (N) Nominal Value"
"none.amb" "Ambient Temperature File Name"
20 "Nominal Ambient Temperature; (ignored if temp file used)"

o Power system file: froya1.pow

"Power system used for Froya Island, Norway. This power system was used for run 1A of the Froya validation exercise for the Hybrid2 code. This system was also used in the validation of the European WDL models. This power system mimics the one used in the WDL validation."
"Metric" "User Input Units: (English) or (Metric)"
"Y" "AC Wind Turbine Present: (y/n)"
"N" "AC PV Array Present: (y/n)"
"Y" "AC Diesel Present: (y/n)"
"Y" "Dump Load Present: (y/n)"
"N" "DC Wind Turbine Present: (y/n)"
"N" "DC PV Array Present: (y/n)"
"N" "DC Diesel Present: (y/n)"
"Y" "Battery Bank Present: (y/n)"
"Y" "Bi-directional Converter Present: (y/n)"
"N" "Inverter Present: (y/n)"
"N" "Rectifier Present: (y/n)"
"N" "Rotary Converter Present: (y/n)"
"N" "Coupled Diesel Present: (y/n)"

"h2sim.ctl" "Dispatch File Name"
1 "Number of Types of AC Wind Turbines, Maximum number of turbines is 50"
"h2sim1.acw" 1 "AC Wind Turbine File Name and Number of Specified Wind Turbines"
1 "AC Wind Power Scale Factor, normally = 1"
100 "Spacing Between AC Wind Turbines, 0-100000 meters"
1.5 "AC Wind Power Response Factor, 1-3"
"h2sim.pvm" "PV Module File Name"
1 "Number of PV Modules in Series, Sets Voltage"
1 "Number of PV Modules in Parallel, Sets Power"
.0096 "PV array loss, Percent of Rated Power"
1 "Code for PV Rack or Tracker: (1) Fixed, (2) Noon Adj. (3) E-W Adj., (4-5) N-S Adj. (6) Two Axis"
0 "PV Array Slope, For Fixed Slope Only, 0-90 degree"
0 "PV Array Azimuth, For Fixed Slope Only, 0-360 degrees, 0 for south facing"
0 "PV Rack or Tracker Capital Cost; $"
0 "PV Array Installation Cost; $"
"Y" "MPPT Present: (y/n)"
.01 "AC PV MPPT Loss Efficiency: Given as fraction in file, 0-1"
.01 "DC PV MPPT Loss Efficiency: Given as fraction in file, 0-1"
0 "MPPT Capital Cost; $"
1 "Number of Types of AC Diesels, Maximum is 7 diesels"
"h2sim1.acg" 1 "AC Diesel File Name and Number of Specified Diesels"
"h2sim.dmp" "Dump Load File Name"
1 "Number of Types of DC Wind Turbines, Maximum number of turbines is 50"
"h2sim1.dcw" 0 "DC Wind Turbine File Name and Number of Specified Wind Turbines"
1 "DC Wind Power Scale Factor, normally = 1"
100 "Spacing between DC Wind Turbines, 0-100000 meters"
1.5 "DC Wind Power Response Factor, 1-3"
1 "Number of Types of DC Diesels, Maximum is 7 diesels"
"h2sim1.dcg" 0 "DC Diesel File Name and Number of Specified Diesels"
"h2sim.btr" "Battery File Name"
170 "Number of Batteries in Series, Sets Voltage"
1 "Number of Battery Banks in Parallel, Sets Capacity"
.337 "Battery Bank Scale Factor, normally = 1"
.5 "Initial Capacity of Battery Bank, 0-1.0"
0 "Battery Bank Installation Costs; $"
"h2sim.cnb" "Bi-directional Converter File"
"h2sim.cni" "Inverter File Name"
"h2sim.cnr" "Rectifier File Name"
"h2sim.cns" "Rotary Converter File Name"
"h2sim.acg" "Coupled Diesel File Name"
0 "Balance of System Capital Cost; $"
0 "System Operation and Maintenance Cost; $"
0 "Yearly Administrative Cost; $"
0 "Wind Turbine Operation and Maintenance Cost; $/kWh"
0 "Diesel Generator Operation and Maintenance Cost; $/kWh"

- Wind turbine file: wincon55.wtg

"Wincon stall regulated wind turbine, 3-blade, upwind, with asynchronous induction generator; power curve taken from file stdinp.kju (standard input file by Kjetil Uhlen, EFI)."
"Metric" "User Input Units: (English) or (Metric)"
55 "Rated Power; kW"
20 "Hub Height; meters"

10.72 "Power Curve Averaging Interval; minutes"
0 "Capital Cost of Domestically produced wind turbine components (excluding tower); $"
0 "Capital Cost of Internationally produced wind turbine components (excluding tower); $"
0 "Tower Capital Cost; $"
0 "Installation Cost; $ "
0 "Overhaul Cost; $"
10 "Overhaul Period; years"
1.0 0.000 (modified power curve: -0.4)
2.0 0.000 (modified power curve: -0.4)
2.75 0.000 (modified power curve: -2.0)
3.0 0.000 (modified power curve: -1.5)
4.0 1.464
5.0 6.006
6.0 11.494
7.0 18.119
8.0 25.730
9.0 32.191
10.0 38.286
11.0 44.068
12.0 47.989
13.0 52.556
14.0 54.983
15.0 55.145
16.0 53.465
17.0 53.179
18.0 51.956
19.0 52.340
20.0 51.140
21.0 53.750

- Diesel file: Cumm50.acg

"Cummins 50 kW turbocharged diesel engine, with 65 kVA brushless synchronous generator and electromagnetic clutch"
"Metric" "User Input Units; (English) or (Metric)"
50 "Rated Power; kW " (modified to model standing losses in synchronous condensor: 52.5)
7.5 "Minimum Allowed Running Power; kW" (modified to model zero minimum allowed running power : 0 kW)
2.63 "No Load Fuel Consumption; l/h" (modified to model standing losses in synchronous condensor: 2.06 l/h)
14.19 "Full Load Fuel Consumption; l/h"
0 "Capital Cost; $"
0 "Balance of Plant Cost; $"
0 "Overhaul Cost; $"
20000 "Overhaul Period; hours"

- Dump load file: froya.dmp

"Dump load of 8 resistors per phase controlled by static relays. Dump load is only used for dissipating excess power, not for phase balancing"
55 "Rated Power; kW"
0 "Capital Cost; $"
0 "Installation Cost; $"
20 "Life; yr"

- Battery file: Alcad340.btr

"Alcad M Range M340P NiCad Battery (simple model). Alcad Incorporated, 73 Defco Park Road, Wharton Brook Industrial Park, North Haven, CT. 06473. USA."
2 "Nominal Battery Voltage; V"
341 "Nominal Battery Capacity; Ah"
495.55 "Maximum Discharge Capacity; Ah"
.844 "Kinetic Battery Model (KiBam) Capacity Ratio, c"
.383 "Kinetic Battery Model (KiBam) Rate Constant, k"
1 "Charging Rate Limit, A/Ah remaining, normally = 1"
"L" "Code for Battery Voltage Calculation: (C) Calculated (L) Linear"
1.3 "1st Constant of Discharge Voltage Curve Fit"
-.3 "2nd Constant of Discharge Voltage Curve Fit"
0 "3rd Constant of Discharge Voltage Curve Fit"
0 "4th Constant of Discharge Voltage Curve Fit"
1.52 "1st Constant of Charge Voltage Curve Fit"
.15 "2nd Constant of Charge Voltage Curve Fit"
0 "3rd Constant of Charge Voltage Curve Fit"
0 "4th Constant of Charge Voltage Curve Fit"
.00026 "Internal Resistance; ohms"
"N" "Code for Battery Life Calculation: (C) Calculate (N) Nominal Value"
10 "1st Constant of Cycle Life Fit"
0 "2nd Constant of Cycle Life Fit"
0 "3rd Constant of Cycle Life Fit"
0 "4th Constant of Cycle Life Fit"
0 "5th Constant of Cycle Life Fit"
0 "Capital Cost; $"
.025 "Operation and Maintenance Cost; % of capital cost per year"
" User input: capacity curve"
984,.27333 "User Input: Capacity, Current"
742,12.36667 "User Input: Capacity, Current"
594,49.5 "User Input: Capacity, Current"
487,121.75 "User Input: Capacity, Current"
402,201 "User Input: Capacity, Current"
262,262 "User Input: Capacity, Current"
196,294 "User Input: Capacity, Current"
163,326 "User Input: Capacity, Current"
112,336 "User Input: Capacity, Current"
43,344 "User Input: Capacity, Current"
"User input: Discharge voltage curve"
20,1.3 "User Input: DOD, Voltage (Discharge)"
80,1 "User Input: DOD, Voltage (Discharge)"
"User input: Charge voltage curve"
20,1.67 "User Input: DOD, Voltage (Charge)"
80,1.52 "User Input: DOD, Voltage (Charge)"
"user input: Life data"

- Bi-directional converter file: bbc55_2.cnb

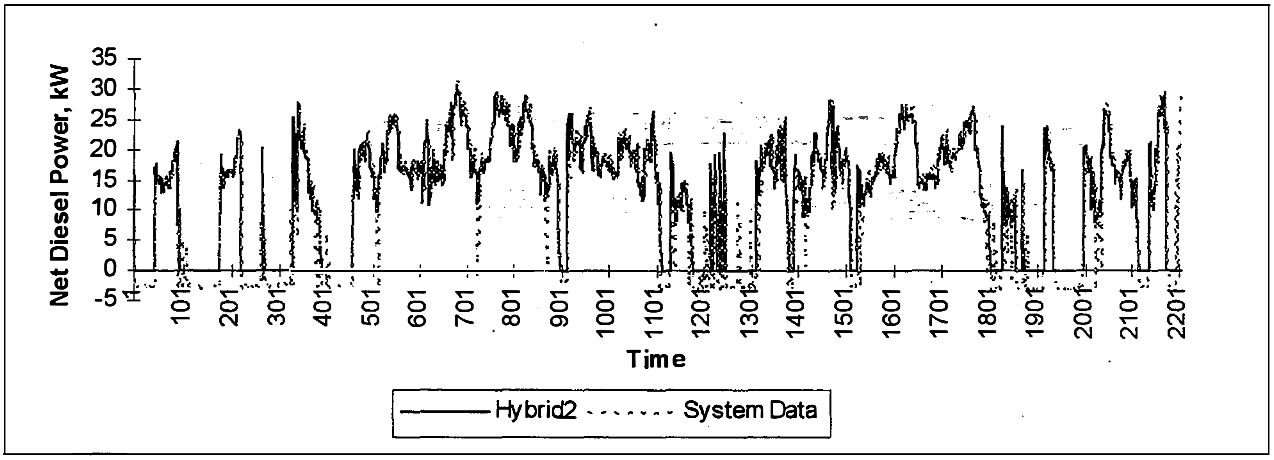
"Froya line-commutated bi-directional Converter"
"N" "Operation Mode; (Y) Switched, (N) Parallel"
37.5 "Inversion Rated Power; kW"

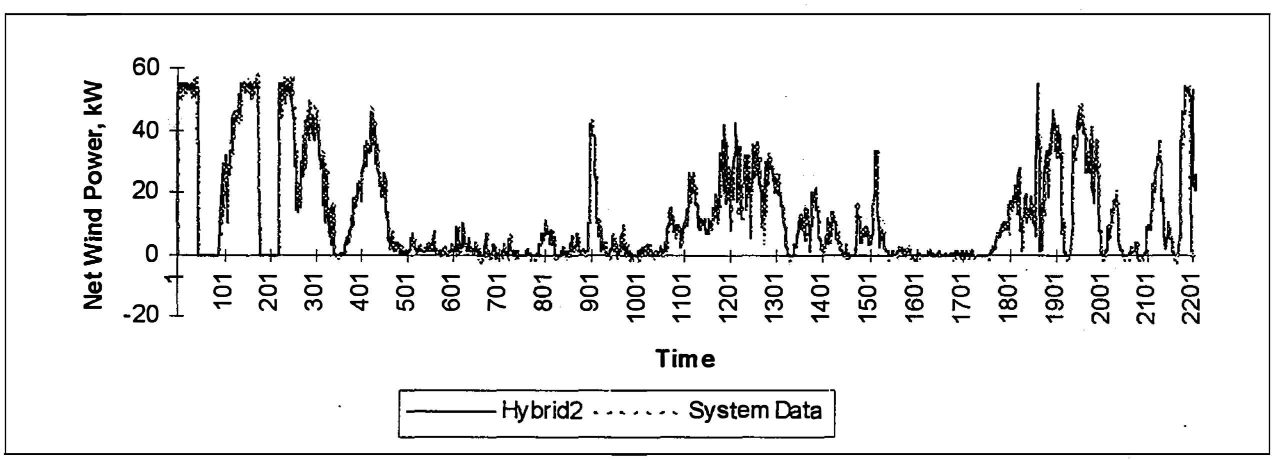
0 "Inversion No Load Losses; kW"
0.95 "Inversion Full Load Efficiency; %"
0 "Rectification No Load Losses; kW"
0.95 "Rectification Full Load Efficiency; %"
0 "Capital Cost; $"
0 " Installation Cost; $"
10 "Life; yr"

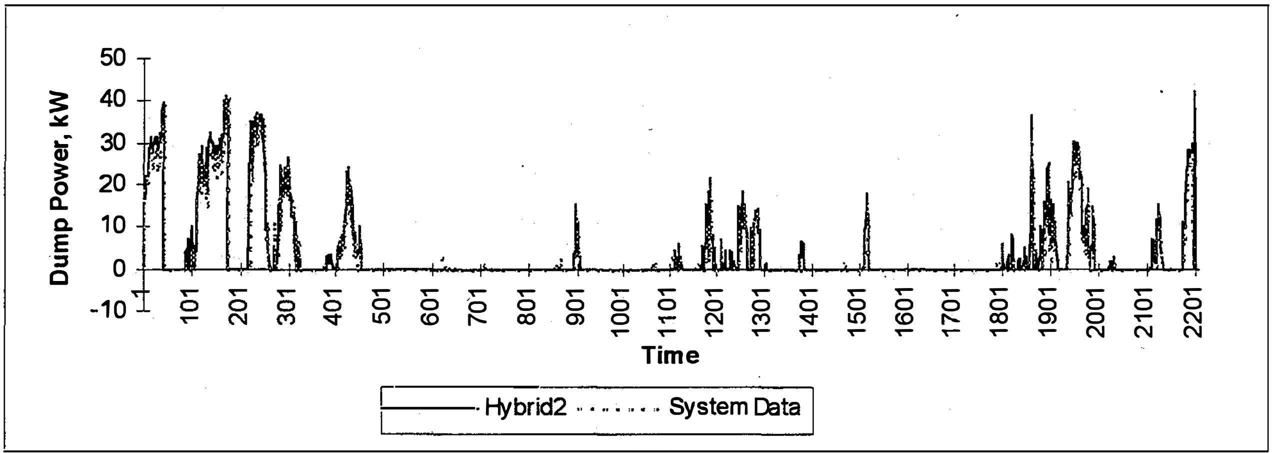
o Dispatch strategy file: froya1.ctl

"Froyä system dispatch file"
.6 "Battery Minimum Level (State of charge; SOC)"
1 "Battery Discharge Code: (0) Transient Load Peaks Only, (1) All or Part of the Average Load"
0 "Code for Boost Charge: (0) Never, (1) Next Diesel Start, (2) Force Diesel Start"
1000 "Time Interval between Boost Charges; hour"
.95 "Battery Boost Level (SOC), From 0 to 1.0"
0.1 "Diesel Minimum Run Time; hour"
1 "Code for Allowed Diesel Shutdown: (1) All Diesels (2) All But One"
0,0,0,0 "Forced Diesel Shutoff Period, 24 hour day starting at midnight"
1 "Diesel Operating Power Code: (0)Load w/ Bat Max, (1)At Max Charge Limit, (2)Load w/ Dsl Max"
1 "Code for Diesel Start: (0) Meet the Load (1) Meet the Load or Charge the Batteries When Depleted"
2 "Diesel Shut Down Code: (1)Bat & Renew, (2)Renew, (3)Renew & chrg, (4)Batt Charge, (5) Mult Dsl"
.95 "Battery State of Charge At Which Recharge by Diesel Stops (SOC)"
.6 "Battery State of Charge At Which Recharge by Diesel Starts (SOC)"
"N" "Code for Diesel Operating Order: (Y) User Prescribed (N) Minimum Fuel Consumption"

Appendix B: Time Series Data, Run 1







Dump Power, kW
50
40
30
20
10
0
-10
101
201
301
401
501
601
701
801
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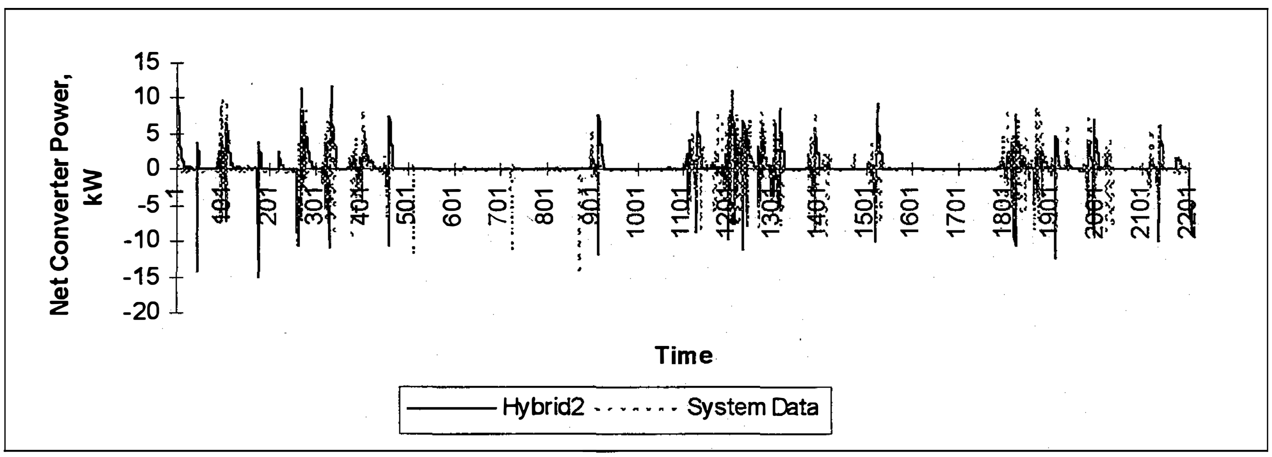
2001
2101
2201
Time
Hybrid2
System Data



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0
-5
-10
-15
-20
101
201
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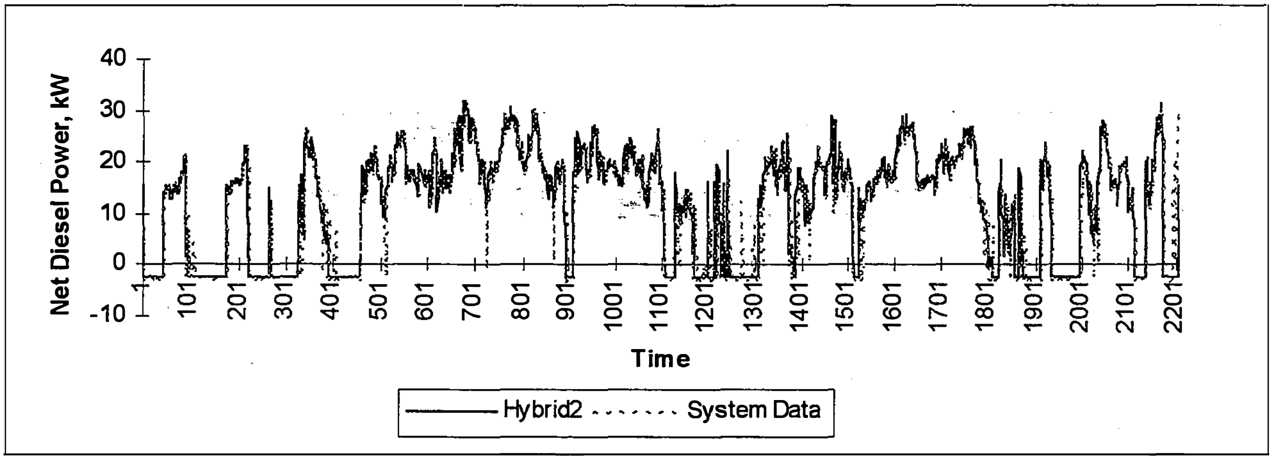
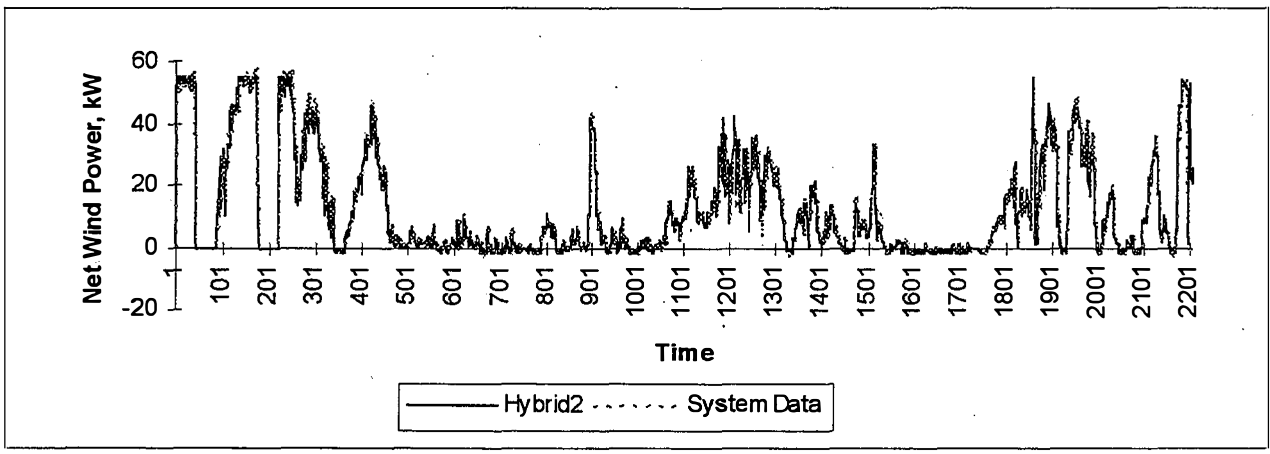
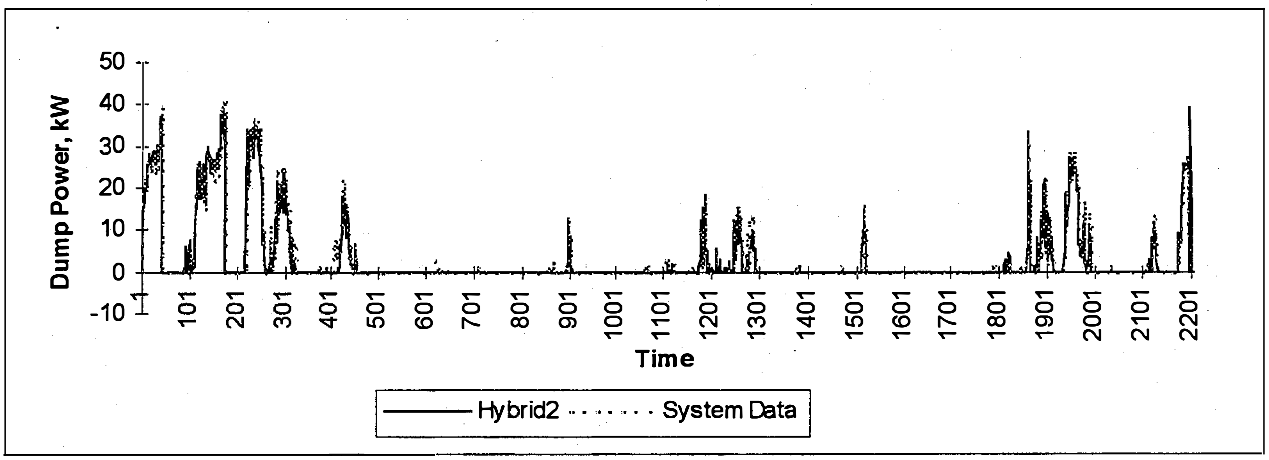
2101
2201
Time
Hybrid2
System Data

Appendix C: Time Series Data, Run 2






Dump Power, kW
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40
30
20
10
0
-10
1
101
201
301
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501
601
701
801
901
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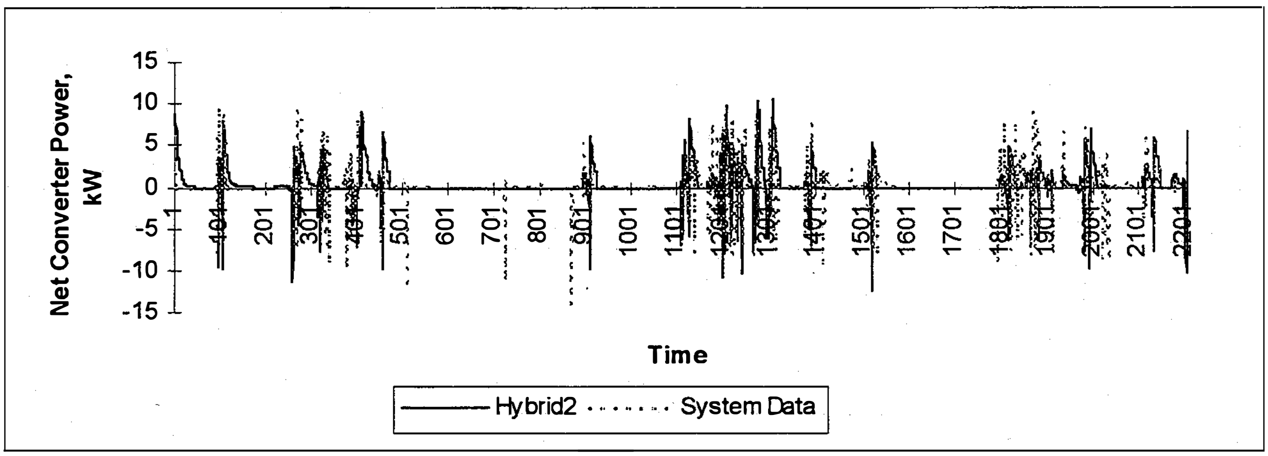
1801
1901
2001
2101
2201
Time
Hybrid2
System Data


Net Converter Power, kW
15
10
5
0
-5
-10
-15
101
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Time
Hybrid2
System Data

Appendix D: Simulating the Frøya System without Storage

The Frøya system has short-term battery storage. Although this storage does not contribute much relative to the total system load, it allows the diesel to be shut off when there is enough wind. To demonstrate the importance of modeling the short-term storage instead of just ignoring it, we also simulated the Frøya system without the converter and storage, in which case the diesel had to be run continuously in load-following mode. The other input parameters for the simulation were the same as in Run 2, so the power curve of the wind turbine was derived from the measured data, and there was no minimum load on the diesel.

The accumulated results for this run are shown as Run 3 in Table 5; for comparison, the results of the measurement and the simulation from Run 2 are listed. Without storage, the simulated energy production of the diesel is 1% lower than in the measured value. This is because the diesel does not have to charge the batteries. However, as an effect of the continuous running of the diesel, the fuel consumption is 29% higher than in the measurement. This can be viewed as a minimum value: the difference will be larger when there is a minimum load on the diesel. Also shown is a comparison run for a system that contained only the diesel generator. This case, which we called Run 4, diesel only, indicates the benefit of including renewable sources, in this case wind power, into diesel power systems.

Table 5: Comparison of the Measured Performance of the Frøya System Simulated with Storage(Run 2), Without Storage(Run 3), and Diesel Only(Run 4)

	Measured	Run 2 With Storage	Run 3 Without Storage	Run 4 Diesel Only
Primary Load (kWh)	8196	8203	8203	8203
Wind Turbine Net Energy (kWh)	4801	4873 (+1)	4873 (+1)	0
- Production	4897	4970 (+1)	4970 (+1)	0
- Consumption	96	97 (+1)	97 (+1)	0
Diesel Net Energy (kWh)	4656	4764 (+2)	4807 (+3)	8203
- Production by Generator	4944	5045 (+2)	4807 (-3)	8203
- Consumption by Synchronous Condenser	288	281 (-2)	0	0
Dump Energy (kWh)	1261	1297 (+3)	1477 (+17)	
Converter Input Energy (kWh)	166	300 (+35)	-	-
Converter Output Energy (kWh)	159	151 (+7)	-	-
Diesel Run Time (h)	284	282 (-1)	394(+39)	394(+39)
Number of Diesel Starts	29	22 (-24)	1	1
Total Fuel Consumption (l)	1812	1909 (+5)	2150 (+29)	2934
Fuel Consumption, Relative to Diesel Only(%)	62	65	73	100

Note: The values in parentheses give the percentage that the simulated values differ from the corresponding measured value's.

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13. ABSTRACT *(Maximum 200 words)*

This report presents a validation fo Hybrid2 (Version 1.0) with measured data from the Frøya hybrid power system. Hybrid2 is a time-series model for the simulation of the long-term performance of renewable energy systems that use wind and photovoltaic power. Hybrid2 was developed by the National Renewable Energy Laboratory and the University of Massachusetts.

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