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Simulation and Configuration of Hydrogen Assisted Renewable Energy Power System

V. Karri, W. K. Yap, and J. Titchen

***Abstract*—**A renewable energy system discussed in this paper is a stand-alone wind-hydrogen system for a remote island in Australia. The analysis of an existing wind-diesel power system was performed. Simulation technique was used to model the power system currently employed on the island, and simulated different configurations of additional hydrogen energy system. This study aims to determine the suitable hydrogen integrated configuration to setting up the prototype system for the island, which helps to reduce the diesel consumption on the island. A set of configurations for the hydrogen system and associated parameters that consists of wind turbines, electrolysers, hydrogen internal combustion engines, and storage tanks has been purposed. The simulation analyses various configurations that perfectly balances the system to meet the demand on the island.

***Keywords*—**Hydrogen power systems, hydrogen internal combustion engine, modeling and simulation of hydrogen power systems.

I. Introduction

THE use of stand-alone energy system for remote area is now becoming common for isolated communities around the world. Power resources for the small-scale renewable energy system are typically photovoltaic cells, wind turbines, or the combinations of resource depending on the availability of resource. Currently diesel-driven generators serve primary load on the large-scale system. Advances in hydrogen technology and equipment such as electrolysers, fuel cells, hydrogen storage techniques in the recent years make the storage of excess renewable energy a high-potential alternative, and also increase the possibility to make the remote areas and isolated community self-sufficient [1].

King Island wind farm is the second national commercial wind farm established in northern part of Tasmania, Australia. On the first installation, three wind turbines were installed at the crest of Huxley Hill, generating 20 percent of the electricity supplied to the community on the island. After the installation, overall emission was reduced by 2000 tonnes of Carbon Dioxide gas a year [2]. Two additional wind turbines were installed on the second improvement at the end of year 2002. King Island wind farm is now generating up to 40% of the total electricity demanded on the island. Since King Island is a large community with high power consumption, diesel generators system is now used as a primary power source for the island. The background of adding hydrogen system to this island is a further emission control program that using local natural resources to isolate the energy system for remote area. On the other hand, using the local renewable energy can reduce the cost of diesel consumption and transportation, electricity production and overall emissions.

Computer modeling had been used in various literatures to help in determining the suitable configurations and parameters of the system. Niet and Mclean demonstrated that a particular system could achieve 100 % Renewable Energy Penetration (REP) [3]. REP is the percentage of load energy that is met by renewable sources. It is one variable to measure the performance of a wind-hydrogen-diesel power system.

Dutton et. al. examined the effects of using three different Wind Energy Conversion System (WECS) rating, with the fixing other variables to a specific value [4]. The electrolyser output was examined in this case. Besides that, Glockner et. al. fixed the electrolyser rating equal to the WECS rating to ensure no energy from the WECS was wasted [5]. The WECS rating required to achieve 100 % REP was then determined. Niet also determined the WECS rating required to achieve a 100% REP, and the electrolyser rating was included in the model [6].

The mentioned studies above are just some example how important computer modeling is to determine a suitable set of configurations and parameter values for a wind-hydrogen-diesel stand alone power system.

Simulation models were programmed on Simulink 5.0 of Matlab program in this paper. The overall objective of this simulation is to determine appropriate configuration of wind-hydrogen power system by sizing the components of the hydrogen system, and to study the feasibility of replacing an existing wind-diesel power system on the island by the renewable system. The results of simulation were analysed by mainly comparing the amount of existing annual usage of diesel fuel on the island, and comparing of system parameters of the selected different configurations.

V. Karri is with the School of Engineering, University of Tasmania, Hobart Tasmania 7001, Australia (phone: +603-6226 2142; fax: +603-6226 7247; e-mail: Vishy.Karri@ utas.edu.au).

W. K. Yap is with the School of Engineering, University of Tasmania, Hobart Tasmania 7001, Australia (e-mail: wkyap@utas.edu.au).

J. Titchen is with Hydro Tasmania, GPO Box 355 Hobart Tasmania 7001, Australia (e-mail: John.Titchen@hydro.com.au).

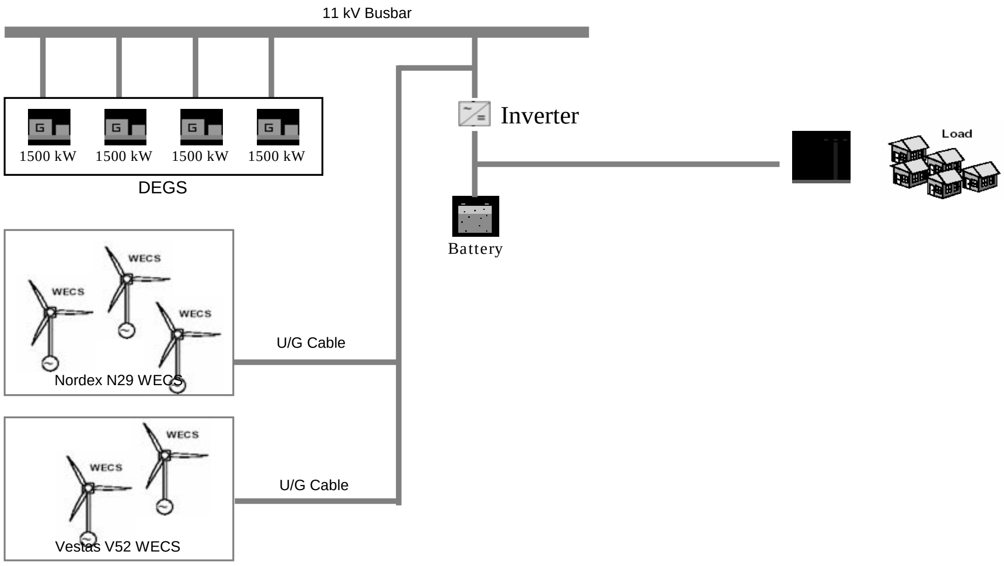

Fig. 1 Wind-Diesel Power Grid System for King Island

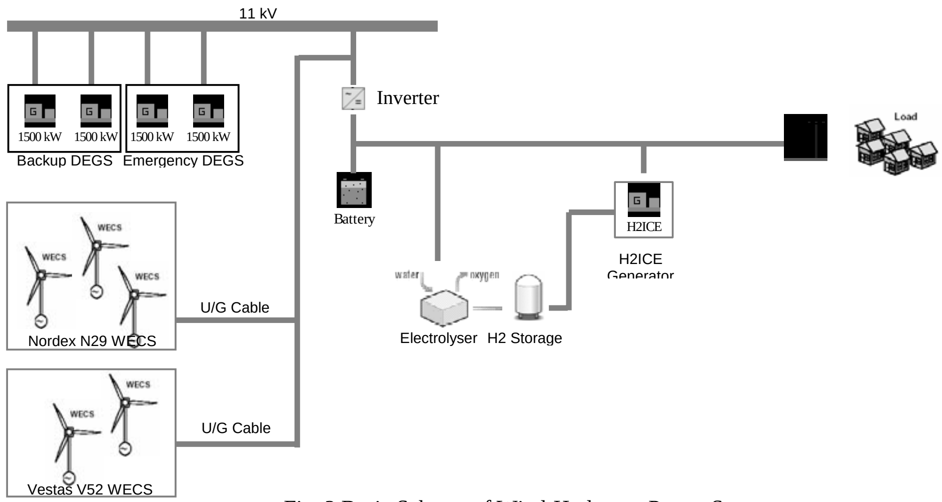

Fig. 2 Basic Scheme of Wind-Hydrogen Power System

II. EXISTING SYSTEM AND THE BASIC SCHEME

A. *Wind Diesel Power Grid System*

The certainty of meeting load demands at all time is greatly enhanced by a hybrid system using more than one power source [7]. The power system on King Island is a wind-diesel grid system composed of three of Nordex N29 wind turbines [8], two of Vestas V52 wind turbines [9], and four of 1500 kW diesel generators. The wind energy conversion systems (WECS) can generate 1250 kW approximately at an average wind speed, generating the maximum power of 2450 kW when there is strong wind. Two diesel generators are normally run to produce electricity and cater for 10% reserved power above the demand. In addition to the diesel generators, 200 kW battery banks are used to meet short-time load fluctuation. The other two diesel engines are currently set to be the backup generators when there is extra peak load on the power system or there is no wind available. Prior to this study, an annual average electricity produced from this system was about 14.6 GWh. A diagram of wind-diesel power system is shown in Fig. 1. The following section details the proposed wind-hydrogen energy system and its basic configuration.

B. *Wind-Hydrogen Energy System and the Basic Scheme*

This section deals with the concept of energy storage using hydrogen produced from the wind conversion systems as stored fuel. A basic scheme of a stand-alone wind hydrogen system for King Island is shown in Fig. 2. At the design stage, it was determined that a hundred percent of the island electrical load would be reliably met by the wind-hydrogen system. The five existing wind turbines were initially used as a primary power source for residential area and the hydrogen system. Three new basic components, which are electrolysers, hydrogen storage tanks and hydrogen internal combustion

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engines (H2ICE), were added into the existing wind-diesel system. New wind turbines could also be installed in addition to the existing wind conversion systems depending on the requirement of input power to electrolysers. The limitations of intermittent wind energy source are potentially overcome by the hydrogen system. Excess power is converted and stored in form of hydrogen gas in storage tank. The H2ICE were designed to use as a secondary power supply that provide power to the load when the renewable source is inadequate. Diesel generators were adjusted to use as a contingency only in emergency to cater for power supply.

III. Simulation Parameters

Before the simulation parameters and associated configuration to highlight ideal setup is deserved, a brief note on the existing hardware and load profiles is deserved.

A. Wind Turbines and Power Curves

There are two different wind conversion systems on King Island. The first system consists of three Nordex N29/250 kW turbines mounted on the 30 meters towers with rotor swept area of 693 square meters. This system produces a maximum power of 750 kW. The larger system is made up of two Vestas V52/850 kW turbines, covering 2,124 square meters of rotor swept area installed at 60 meters hub height producing the maximum power of 1500 kW. The combination of WECS produces an average annual power output of 10,760 MWh. Manufacturers of wind turbines provide power curves and technical data of wind turbines. Power contribution from the wind conversion systems has been simulated using linear interpolation to the input data of wind speed [10]. Figs. 3 and 4 illustrate power curves for the wind conversion systems.

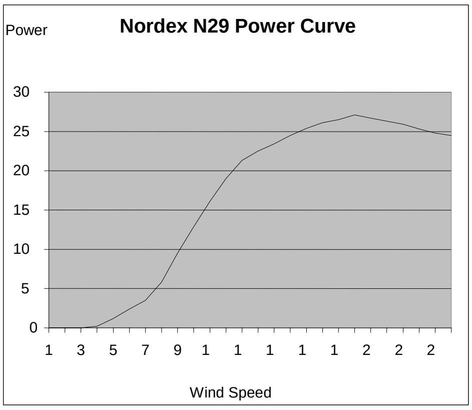

Fig. 3 Nordex N29/250 kW power curve

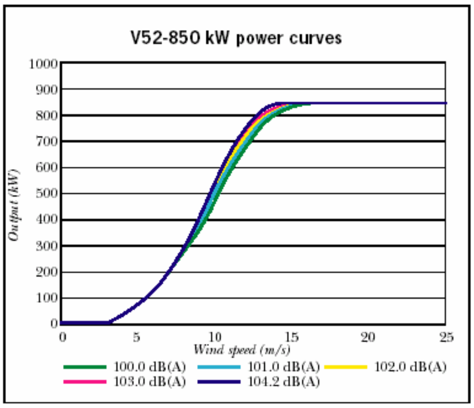

Fig. 4 Highlights the Vestas Turbines Operation at Various Noise Levels and the Corresponding Power Output

B. Wind Speed Data

Huxley Hill on King Island was determined to be the best location for wind farm by Hydro-Tasmania. Turbines are installed and sitting on the crest at 130 metres above the sea level. A reference annual average wind speed was measured at 30 metres height as 9.2 m/s (33 km./Hr) [2] which is considered to be “an excellent wind speed condition” to generate electricity from the wind farm [7].

After the installation of the wind farm, data for average wind speed on King Island was recorded at 30 minutes intervals. A one-year time series was selected from the period of 1996 - 2003 to use as an input for the simulation model. Descriptive statistical technique was used to analyse the wind data. Average annual wind speed in year 2002 was 7.88 m/s that is a bit lower than the referenced annual average. September was the windiest month of the year while April and May are the least windy. Wind speed for King Island is best described by Weibull distribution function with the value of shape parameter (k) 2.46 and a scale parameter (c) 8.90, as shown in Fig. 5.

For different height of wind turbines systems, selected wind data was multiplied by windshear coefficient factor to estimate the wind speed at effective level. Estimation of wind speed at different height is given by the formula below [7]:

$$v = v_{ref} \ln\frac{z}{z_0} / \ln\frac{z_{ref}}{z_0} \qquad (1)$$

Where v = wind speed at height z above ground level.
v_{ref} = reference speed

A coefficient part of formula, $\ln(z/z_0)/\ln(z_{ref}/z_0)$, was measured and calculated at wind turbine site. The coefficient factors used in the simulation were 1.069 for Nordex wind turbine and 1.187 for Vestas wind turbine. The input time series is presented in Fig. 6.

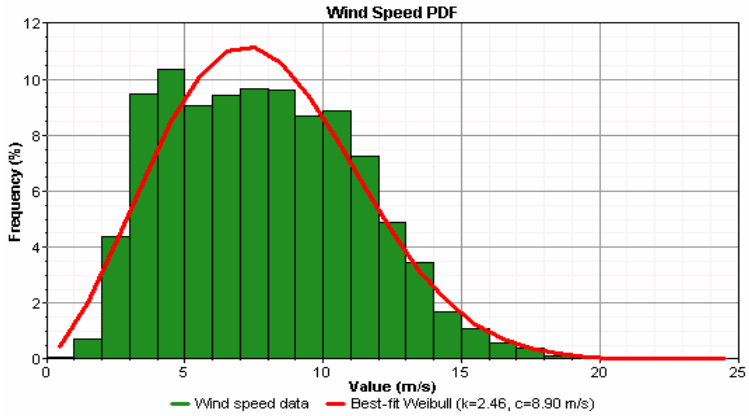

Fig. 5 Weibull Probability Density Function describes the Wind Speed on King Island

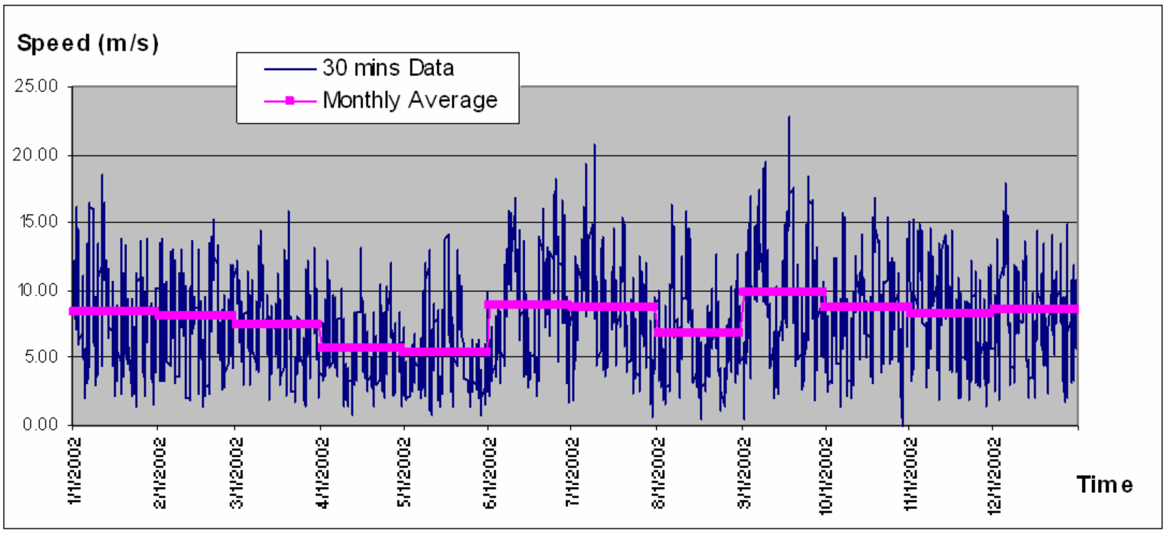

Fig. 6 Yearly Wind Speed Data and Monthly Average Used in Simulation

C. Load Profiles

A community of 300 residences on King Island includes houses and civic institutions such as hospital, district high school, museums, four churches, council chambers and town hall. There are golf, bowling, tennis and other sports facilities. The commercial centers include airline agencies, hotel, restaurants, and shops specializing in King Island food and the usual range of supermarket, newsagent's and pharmacist's outlets. Local industries are fishing, food processing, tourism and a kelp factory. A load profile from acquired data comprised of the residential variations and electrical usage patterns within all houses, commerce and industries located in the community.

Load data was collected hourly for a period of 1996-2003. Analysis of load data shows that, in a selected year (2002), demand of electricity varied between the minimum of 0.87 MW and the maximum of 3.0 MW. Power consumption is highest around 9:00 a.m. An average daytime load was about 68% of peak value, while an off-peak load was lower to 43%. An average daily load profile was used as a typical load profile for the model. Simulation program generated load value for different time of day by normalizing the typical profile on monthly basis. Statistical standard deviation was added to the generated values in order to make the fluctuation of load look realistic. The reference load profile and its confidential limit are presented in Fig. 7. Monthly average load and normalized ratios are shown in Fig. 8.

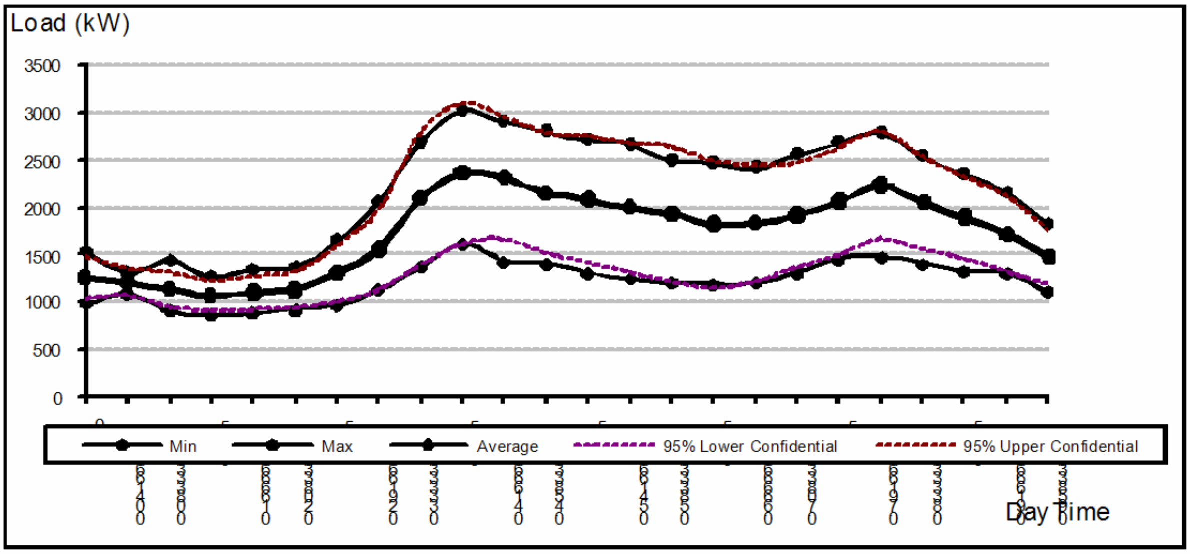

Fig. 7 Average Load Profile and Confidential Limits of Load

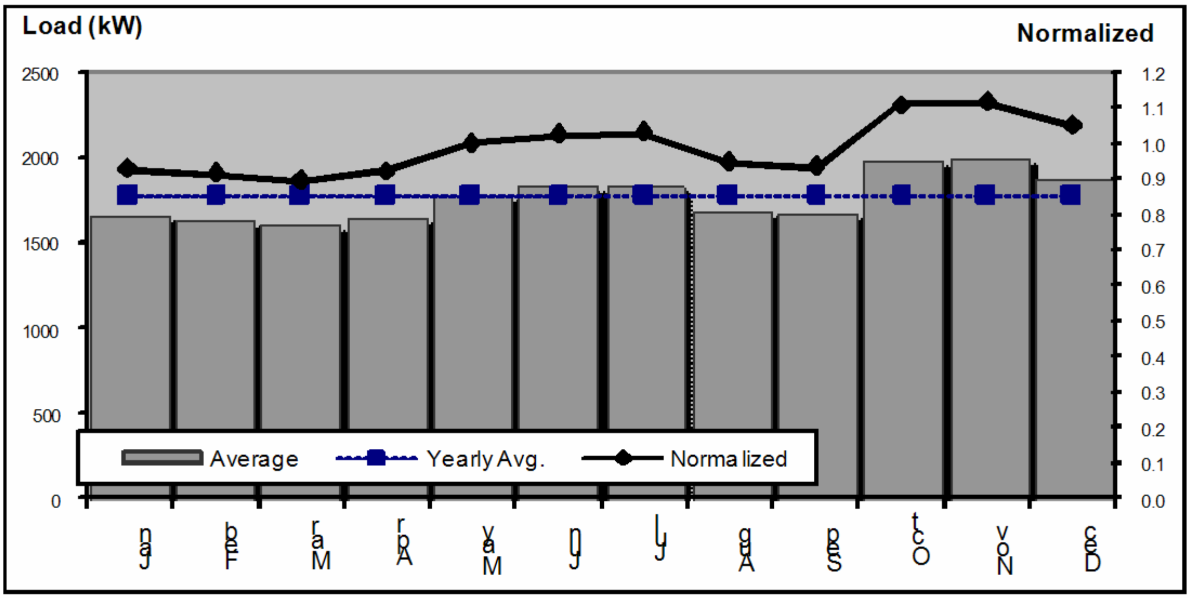

Fig. 8 Monthly Load Profile and Normalized Ratio

D. Diesel Generators

Diesel generator set is usually an integrated part of a remote power system since the areas are normally not connected to the grid supply. Diesel engine is ideal for operation in isolated and remote areas because it is simple and reliable [11]. However, the use of diesel engine has some drawbacks that they are inherently noisy and expensive to run, especially in the areas where the delivery costs of fuel is high. King Island employs a set of four 1500 kW diesel-driven generators, where diesel fuel consumption for this power plant is average at about 3.3 million liters per year.

To simulate a configuration for power balance on the island it is assumed that the diesel usage is a linear function of its electrical power output. An efficiency curve of the diesel engine, shown in Fig. 9, was used in the model. Simulation of diesel gensets were done by mapping the fuel usage ratio of the engines to the efficiency curve. Amount of diesel fuel used was calculated by interpolation of mapped efficiency curve to the percentage of required loading. For example: The percentage of diesel loading is 50%. The fuel usage ratio is 3.7 litres/Hr. Thus, the program simulates the usage of 0.37 litres in a time-step of 0.1 hour.

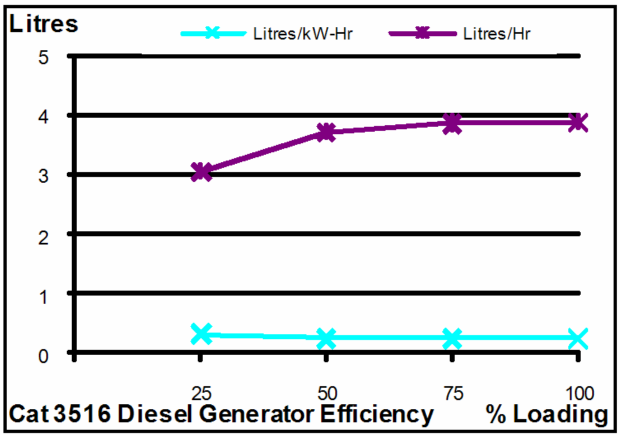

Fig. 9 Efficiency Curve for 1500kVA Diesel Generator on King Island

E. Components of Hydrogen System

The study of adding prototype hydrogen system to the remote island considered requires the estimation of the size and number of the system components. There are many different sizes of commercial hardware and configurations to be determined. Information of hydrogen components was gathered from various electric companies and manufacturers. The converters and inverters while responsible for efficiency losses were found to be not all that significant to the overall output of the designed configuration.

F. Electrolyser

An electrolysis process is only a practical and industrial process of splitting of water at the present time. Electrolysis involves passing an electric current through water. The current enters the electrolysis device through the cathode terminal, passes through the water, and leaves through the anode terminal. Hydrogen is separated and collected at the cathode and oxygen is separated and collected at the anode. Hydrogen can also be obtained from water by a variety of other methods that are not currently feasible for large-scale production.

Commercial electrolysers are normally designed to operate under steady conditions. The dynamic behaviour of the electrolyser is complex system for mathematical modelling [12]. None of experimental study about its response under unsteady conditions has been done. Modeling of electrolyser operation was simplified by using its conversion efficiency on an assumption that input power and conversion efficiency areconstant. Different sizes of commercial electrolysers were selected and simulated in this system by changing the input parameters which are input power, size of electrolyser, water usage, and conversion efficiency. Results were the estimation of hydrogen delivered, working hours, and water usage.

G. Hydrogen Internal Combustion Engine (H2ICE)

The use of Hydrogen ICE was considered to supplement the diesel engine in the power system. Thus, the Hydrogen ICE generator was selected for this study. A prototype of alternator running on hydrogen engine was developed by commercial companies, indicates electrical efficiency of nearly 30%. Some recent studies and researches indicated that the efficiency of hydrogen engine is estimated 25-35% more efficient than a typical gasoline engine [13]. An energy content ratio for hydrogen is 113,000 -134,000 Btu per Gallon, while it is 128,000 Btu per Gallon for No.2 diesel. In the combustion, hydrogen burns over a wide range of gas mixtures and water vapor is the byproducts. Heat of combustion is 2-3 times higher than other fuels [14]. This study assumes the efficiency of H2ICE to be 25% higher than that of a diesel engine. The H2ICE running condition and its usage of hydrogen gas were simulated by interpolation of efficiency curve to the amount of required power.

IV. Results of Simulation

The output from the configuration in terms of power should fully meet the demands on the island. If the demand is met for any configuration, the system said to be balanced. A simulation model, depicted in Fig. 10, programmed on Simulink was used to simulate the system. Simulation was performed at a time-step of 0.1 hour, running for a period of 8,760 hours (one year). An initial configuration of hydrogen components was previously added to the wind-diesel system. The initial configuration comprises of 1 MW Electrolyser, 1 MW Hydrogen Internal Combustion engine, 2 of 1.5 MW Diesel generators, and five existing wind turbines. Two of existing diesel generators were adjusted to use as backup generators, producing electricity when an electric load was higher than the capacity of wind turbines and H2ICE. The other two diesel generators were adjusted to use as an emergency generators. The comparison of the existing wind-diesel system and four different configurations was analysed. Followings are the different configurations simulated for load requirements and results. Table I shows the comparison of results from simulation models.

A. Case 1: Adding 1 additional Vestas V52 wind turbine to the initial configuration

This configuration was performed to study the effect of increasing more input power to the system. An additional wind turbine was added to the WECS. An average of wind power converted has increased by 426 kW on average. The additional wind turbine showed a strong effect on the performance of the system. The input power to an electrolyser was dramatically increased to 2,156 MWh per year while there was only a half of MWh on the simulation of the initial system. The amount of hydrogen delivered in this case was approximately 367,375 cubic metres. Diesel consumption was lower down to one and a half million litres, decreasing by 36% when compare with the wind-diesel system. All of hydrogen gas was used by the H2ICE in 1,672 working hours, producing 1,149 MWh of power output to the residential area. Diesel generators were still required in this configuration.

B. Case 2: Adding 2 additional Vestas V52 wind turbines to the initial configuration

Two additional wind turbines were designed to add to the system. In this case, the model simulated more excess power to hydrogen system. The average power output from the WECS increased by 852 kW to an average of 2,080 kW.

Electrolyser gained more power from wind turbines, and used 3,466 MWh to produce 466,000 cubic metres of hydrogen, while the H2ICE used all of hydrogen gas to produce 2,949 MWh of electricity in 1,986 hours. Diesel consumption was decreased by 16%, comparing to the configuration in case 1. However, the amount of spilled wind energy was also increased by 893 MWh in a year, and fed to the dump load. It can be concluded here that the second wind turbine added to system has slight effect on the performance of system.

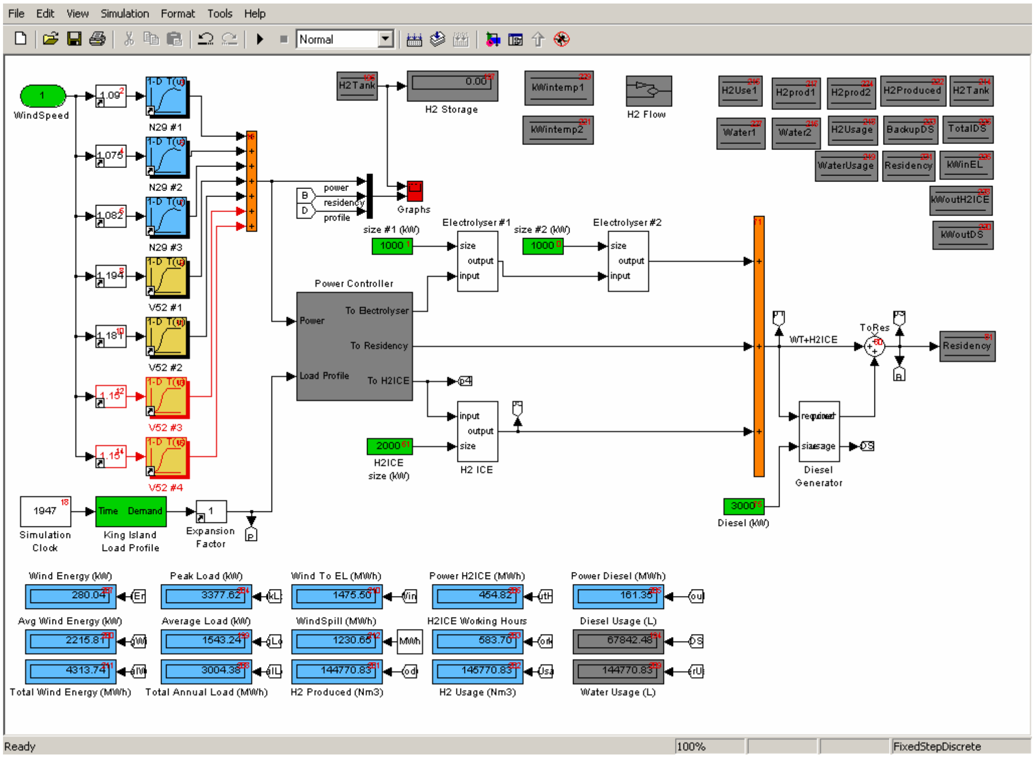

Fig 10 Simulink Based Simulation of H2-Wind System

C. Case 3: Adding 1 MW of electrolyser, 1MW of H2ICE, and 1 additional Vestas V52 wind turbine to the initial configuration.

In this case, another set of hydrogen components and an additional wind turbine were added to the initial configuration. The system gained more power from the additional wind turbine while the capacity of hydrogen production has increased. The result shows that power output from H2ICE increased slightly by 470 MWh per year comparing to case 1, and increased only 165 MWh comparing to case 2. The amount of hydrogen delivered was increased about 150,000 cubic metres per year while diesel consumption was slightly lowered down by 8% in comparison to case 1. It can be seen that adding of another set of hydrogen components required very high amount of excess power from wind turbines. Therefore, this configuration is not a practical design.

D. Case 4: Adding 1 MW of electrolyser, 1MW of H2ICE, and 2 additional Vestas V52 wind turbines to the initial configuration.

This configuration simulated more wind power to electrolysers and residency. Two of additional wind turbines were added to the initial configuration. The system consisted of two electrolysers and two H2ICE with totally 7 wind turbines. In this case, the average power of wind turbine increased to 2,080 kW. Electrolyser could produce a million cubic meters of hydrogen gas. The hydrogen generators generated 20% of total energy demanded by residencies. Diesel generators were still required in this system and consumed half a million of diesel fuel, approximately 21% of the required fuel in the wind-diesel system.

V. Conclusion

The simulation program that identifies the H2-wind configuration and associated parameter requirements to balance the system is shown in this paper. The program was modeled for various configurations of the stand-alone power systems. The comparison of simulation results for various configurations indicate that adding hydrogen system to the existing power system on King Island can significantly decrease the amount of diesel fuel consumed as shown in Table I. The system configuration that comprised of 1MW electrolyser, 1MW Hydrogen Internal Combustion Engine, 1 additional Vestas V52 wind turbine, and two of 1.5MW diesel generators are suggested for the prototype wind –hydrogen power system on this remote island. It has been shown that diesel consumption on the island can be reduced approximately by 32%. However, it is suggested that the analysis of future scenarios such as the expansion of community, the growth of energy consumption by residencies, change in behavior of energy users should be carried out for the need of grid reinforcements. The configuration suggested herein is suitable for the initial phase of a prototype wind-hydrogen power system on the King Island.

TABLE I
COMPARISON OF RESULTS FROM DIFFERENT CONFIGURATIONS

Case	Parameters	Existing system	Case 1	Case 2	Case 3	Case 4
		2x1.5MW DS Existing 5 W/Ts	*1MW EL 1MW H2ICE 2x1.5MW DS Add 1 V52/850*	*1MW EL 1MW H2ICE 2x1.5MW DS Add 2 V52/850*	*2x1MW EL 2MW H2ICE 2x1.5MW DS Add 1 V52/850*	*2x1MW EL 2MW H2ICE 2x1.5MW DS Add 2 V52/850*
Load	Total (MWh)	15,093	15,088	15,083	15,074	15,101
	Peak (kW)	3,936	3,953	4,071	3,873	4,138
	Average (kW)	1,723	1,722	1,722	1,721	1,724
Wind Energy	Total (MWh)	100,762	14,494	18,227	14,494	18,227
	Average (kW)	1,229	1,655	2,081	1,655	2,081
	Spill (MWh)	1,786	2,678	5,312	1,964	2,474
Electrolyser	Input (MWh)	0	2,156	3,466	2,486	5,063
	Working (Hrs)	0				
	H2 Prod (Nm3)	0	367,375	466,000	518,000	1,054,708
	Water Usage (L)	0	367,375	466,000	518,000	1,054,708
H2ICE	Output (MWh)	0	1,149	1,454	1,619	3,124
	Working (Hrs)	0	1,673	1,987	1,825	3,058
	H2 Usage (Nm3)	0	368,375	466,125	519,000	1,001,175
Diesel Gen.	Output (MWh)	6,115	3,885	2,949	3,410	1,286
	Working (Hrs)					
	Loading (%avg)					
	Diesel Usage (L)	2,494,652	1,586,540	1,206,822	1,395,911	522,875
System Balance		-	Fully Balance	Fully Balance	Fully Balance	Fully Balance

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