Modelling Renewable Energy at Race Rocks

by

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We accept this thesis as conforming
to the required standard

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ABSTRACT

This thesis presents a new model for the evaluation of energy systems based on renewable resources. The overall model incorporates stochastic predictive models for solar, wind and tidal resources and realistic models of energy storage, resource conversion technologies and demand loads. Race Rocks is used as a case study to both validate and determine the utility of the model. A tidal based energy system with an installed capacity of 100 kW and a 250 kWh hydrogen based storages system would be, technically, the best system to install for Race Rocks. Overall, the model provides exciting insights into renewable energy systems and design.

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1. Introduction

As eloquently stated by L. R. Wallis in his speech to the American Nuclear Society, the world will need to exploit energy resources in increasing amounts if we are to have any hope of bringing people in the developing world up to a reasonable standard of living [1]. As well, the UNDP projects that, even in the best case scenario where we try to conserve as much as possible without helping the developing world, the world energy demand will still nearly double by 2100 [2].

At the same time as our energy needs are increasing the Intergovernmental Panel on Climate Change (IPCC) has concluded that "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" [3]. Most of this warming is associated with the emissions of carbon dioxide into the atmosphere from the exploitation and burning of fossil fuel based energy resources. We therefore find ourselves in a situation where we need to carefully consider our energy resources.

Renewable energy is seen by many as a good resource to exploit. For example, the Earth Day Network claims that:

> Renewable sources of energy are virtually inexhaustible and are naturally and quickly replenished. … Switching to clean, renewable energy will bring us cleaner air and water, while improving human health and increasing energy security. [4]

However, others claim that renewable energy will never provide us with the energy we require. Vaclav Smil discusses the fact that running any city on renewable energy will likely have significant environmental consequences, if it is actually possible [5]. Smil also discusses the fact that most cities are located where there are no significant available renewable resources. Mark Mills of the Greening Earth Society discusses at length why the four "oft-repeated 'facts'" of renewable energy – "Renewable energy is abundant. Renewable energy is natural. Renewable energy is better. Renewable energy is free." – are just as applicable to conventional energy resources, and are not uniquely applicable to renewable resources [6].

Others even claim that fossil fuels are the only possible resource for our energy needs and imply that we should not bother looking elsewhere. For example, Skov states:

> Barring a significant technology breakthrough in either renewable-energy (technology) or cost (of nuclear power), fossil fuels appear to be the only real choice well into the next century. [7]

It is extremely rare for any of the expressed 'opinions' related to the energy available from renewable resources to contain concrete, quantitative and meaningful figures to backup their views.

The controversy doesn't only apply to the ability of renewable resources to provide us with energy, but also applies to the environmental aspects of these resources. The environmental impacts of renewable energy often seem to be ignored as non-existent by proponents of these technologies, as illustrated by the Earth Day Network quote. However, given the experience with bird kill of windmills [8], as well as the environmental impacts of tidal barrage energy systems [9], it seems ludicrous that we would consider renewable energy sources as non-invasive just by virtue of being renewable and non-fossil.

Carl Sagan, in his book "The Demon-Haunted World," expresses the need for scepticism and the critical evaluation of any proposed theory [10]. It would appear that renewable energy is in need of some scepticism and critical evaluation to determine where we can and cannot use these resources. This is not to say that renewable energy cannot provide us with reliable, clean sources of energy. However, it is high time that we quantify the advantages and costs of this resource so we can make informed decisions as to where and when renewable energy makes sense.

To be able to properly quantify the abilities of a renewable energy system installed operating demonstration systems in a variety of climates and configurations are essential. A number of such initiatives have already been developed around the world. For example, at the Université du Québec à Trois-Rivières, a system – consisting of a small wind turbine, a number of small photovoltaic panels and a storage system using hydrogen – has been installed [11]. In Russia, on the Black Sea, an integrated 6 kW hydrogen solar photovoltaic system has been in operation since before 1992 [12]. The main storage technology for both these systems was hydrogen with the associated electrolysers and fuel cells. However, the use of a small battery was required to smooth out short-term voltage fluctuations. Other installed systems exist or are being considered (see, for example, [13-17]) in places as varied as Germany, Saudi Arabia, the UK, Switzerland, Argentina, the US, Spain and Canada [18, 19]. All these systems provide valuable information but, to this point, have been restricted in their scope and have been mainly focussed on single source technologies.

The Institute for Integrated Energy Systems (IESVic) is working on taking the renewable energy system demonstration project one step further, with a 'renewable energy system laboratory' that is not restricted to a single resource nor a single technology for either resource extraction or storage. This laboratory would enable the evaluation of a variety of small to village-scale renewable resource extraction technologies and the associated storage technologies and enable the comparison of their ability to provide useful, reliable power.

For this initiative to be effective, a number of different criteria must be considered. First, a variety of renewable resources should be available to use as part of the system and a use for the energy produced must exist. As well, the location must derive benefits, both environmentally and economically from an installed system. A method of distributing the knowledge gained to a wide audience is also essential to the effectiveness of such a system. IESVic, in collaboration with Pearson College, has begun investigating the potential of Race Rocks, a small archipelago in the Juan de Fuca Straight, to provide the essential elements for a widely accessible, meaningful renewable energy systems laboratory.

Race Rocks, located just off the southern tip of Vancouver Island, is ideally suited to being developed into a renewable energy system laboratory. Being home to one of the most important navigational beacons for ships entering the Juan de Fuca Straight, the site requires energy to provide services for the two custodians who reside on the site. The current power source on the site is a 15 kW diesel engine, but with average wind speeds of 21.6 km/h, tidal currents of up to 4 m/s and being touted as one of the sunniest locations in Canada, the potential of installing a renewable energy system is exciting. As well, Pearson College has connected the site to the Internet (www.racerocks.com), making an installed system accessible to a wide audience.

Before we can install a system, we need to be able to accurately evaluate the potential systems that could provide power for Race Rocks and determine how each of these potential systems would operate on the resources available. A model of the potential energy systems out at Race Rocks would be the logical place to start our investigations. Since we are replacing the diesels with either solar, wind, or tidal energy, or a combination thereof, the model must include these resources and also the systems converting these resources into useful, reliable power for the site.

This thesis will discuss the development of a generic energy system model for the resources at Race Rocks and the advantages of such a model. Although there are other energy system models available, upon reviewing the available literature, a more generic model based on both generic technology and stochastic resource models has been developed. This system model provides us with a number of useful insights into renewable energy systems that cannot be obtained with currently available models. The application of this model to Race Rocks provides us with the ability to develop energy systems for Race Rocks and to compare the three resources available at Race Rocks under varying conditions.

Chapter 2 gives a brief outline of various energy system configurations, reviews the literature on renewable energy systems models, and develops the architecture of the model. Chapter 3 discusses the issue of storage, how this was modelled, and the integration of storage into the model. Chapters 4 through 6 discuss the resource and technology models for solar, tidal and wind. Chapter 7 discusses different load rules and models and concludes that there are no generally applicable rules that can be used for smaller systems and that the load model is therefore intricately dependant on the site.

Chapter 8 presents information on Race Rocks, the application of the model to Race Rocks and the resource assessment performed to determine the appropriate parameters for Race Rocks. The reader, by following through the process, can apply the model to any other site for which these resources are available.

Although the model provides the ability to create energy systems and evaluate how they perform, the criteria and numerical methods required to actually optimize systems is not trivial. Chapter 9 discusses these numerical methods and how optimizations are performed and provides details of the model implementation.

Having put together all the parts required for developing energy systems at Race Rocks, Chapter 10 presents some of the results obtained with the model and how they apply both to Race Rocks and to renewable energy systems, in general. Overall, this thesis shows the value of generic models and also the potential of Race Rocks to become a ‘renewable energy system laboratory.’

2. Energy System Model Development

To be able to effectively develop the structure for an energy system model we need to identify that renewable energy systems are significantly different than conventional energy systems. An evaluation of the literature on existing renewable energy system models provides insight into both what is required for systems and also where work needs to be done.

This chapter provides an overview of energy system configurations, discusses the sources of data that can be used in energy system modelling, reviews the literature on renewable energy system modelling identifying the areas that have not been investigated adequately, and concludes by describing the overall model configuration developed in this thesis.

2.1. Overview of Energy System Configurations

The general architecture of conventional grid-connected energy systems is significantly different from stand-alone renewable energy systems. This overview provides the background required to consider energy systems models and renewable energy systems models, in particular. As well, a comparison of the different systems architectures is given.

2.1.1. Conventional Energy Systems

A schematic of a conventional energy system is shown in Figure 1. From this figure, one can see that the system is, in general, quite simple. The resource has the ability to follow the demand and therefore requires no other components to function.

Both large-scale and small-scale systems have been developed in this manner. The major difference between large-scale and small-scale systems is the time constant that the systems operate on. A large-scale system, due to the “averaging” of the load from the many different devices on the system, does not need to respond rapidly to load changes. A small-scale system needs to respond quickly to changes in load. Conventional systems generally rely on fossil fuels, such as coal power plants, combined-cycle gas turbines and diesel generators. Nuclear power would also be considered a conventional power source.

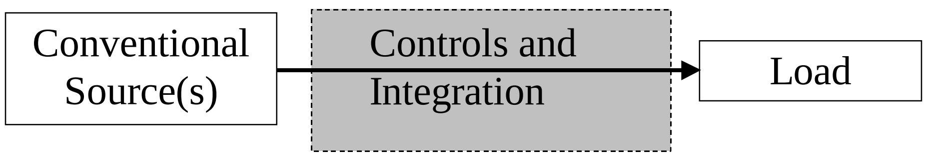

Figure 1: Conventional Energy System

2.1.2. Grid-Connected/Hybrid Renewable Energy

Renewable energy sources have been added to conventional energy systems, as shown in Figure 2. This configuration, if the renewable resource is less environmentally intrusive than the conventional resource it is replacing, has the ability to reduce the impact of our energy services. However, in this configuration, renewable resources will never exceed 12-25% of the energy generation capacity, as this would cause grid instabilities [18, 20, 21]. Often, forecasting of the renewable resource on times scales of between 1 minute up to a few days is required for adequate operation of such systems and for load scheduling. Although there has been much work on this, this is not a trivial task and research is ongoing in this area [22, 23].

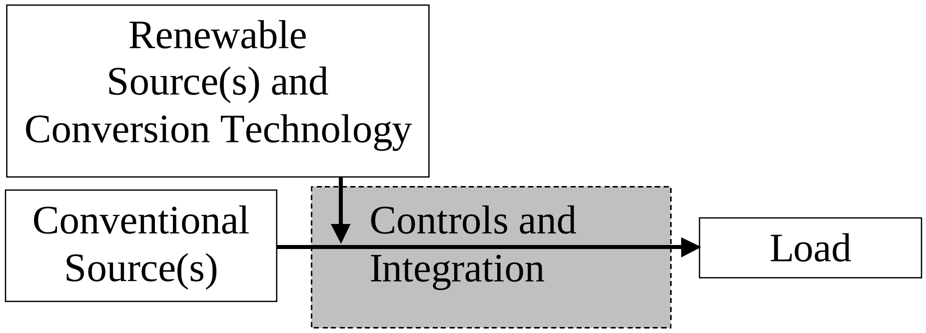

Figure 2: Grid-Connected Renewable Energy System

Grid-connected renewable energy is conceptually no different than adding a second conventional generator onto the grid as long as the penetration of the renewable resource does not exceed 15-25% of the load. Below this level, the grid can absorb the fluctuations in the renewable energy source by relying on the load following characteristics of the conventional resource. Above this load factor, the consideration of storage is needed to follow the load as conventional resources on a large scale have very slow response times. Such systems are similar to Stand-Alone Independent Renewable Energy Systems discussed in the next section. Diesel-hybrid systems, incorporating renewable energy, do not suffer from this limitation since small-scale diesel engines can respond to the load rapidly [24].

2.1.3. Stand-Alone Independent Renewable Energy Systems

Stand-alone, independent, renewable energy systems, which do not rely on any conventional energy sources, need some manner of matching the demand cycle with the resource cycle(s). This implies a need for some form of storage. Including storage into the energy system diagrams, we obtain the schematic of an integrated renewable energy system, as shown in Figure 3.

This system can be developed with either a conventional energy backup system, or the system can be installed without a backup, as shown. Most housing and/or village renewable energy installations, since they are replacing conventional energy installations, maintain the conventional energy as a backup until the renewable energy system is proven to work effectively. This is not the case for many telecommunications systems, which are often new installations and are therefore installed without any conventional backup system.

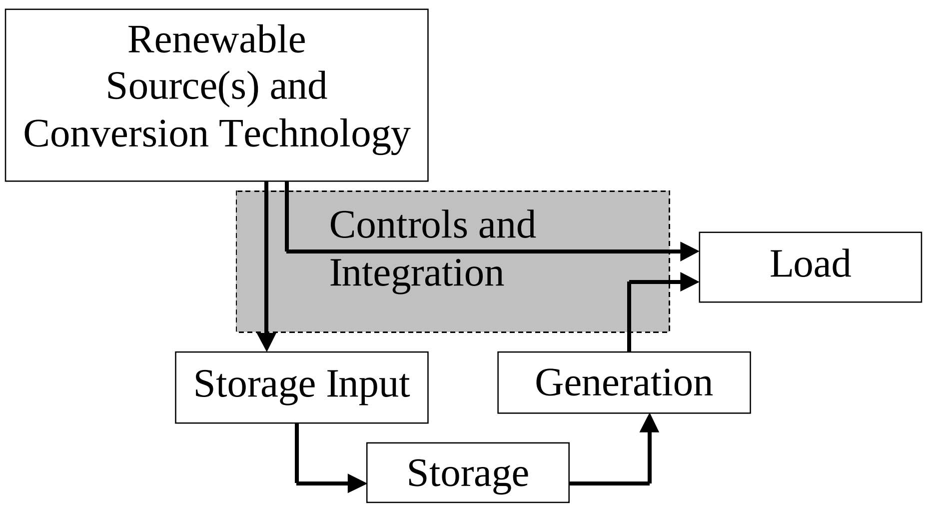

Figure 3: Renewable Energy System

For the purposes of this thesis, since we are trying to replace the diesel engines at Race Rocks, we will, from this point onwards, be primarily interested in stand-alone systems, and grid-connected renewable energy will not be discussed.

2.1.4. Systems Comparison

One way to compare the energy available from different resources is to use probability, or availability curves, as discussed by Sorensen [20]. Figure 4 shows the availability curves, as generated by the model developed in this thesis, for the three renewable resources at Race Rocks. The cumulative availability for the resources at Race

Rocks, not including any unscheduled maintenance outages, is 21.6% for wind, 41.6% for Tidal and 20.2% for Solar. In comparison, the availability for a wood waste fired plant in Williams Lake is over 95% [25] and the availability, including all scheduled maintenance, for a commercial coal gasification power plant in Terre Haute, Indiana is approaching 75% [26]. This availability for this plant would probably be closer to 95-100% if the scheduled maintenance were not included in the calculations.

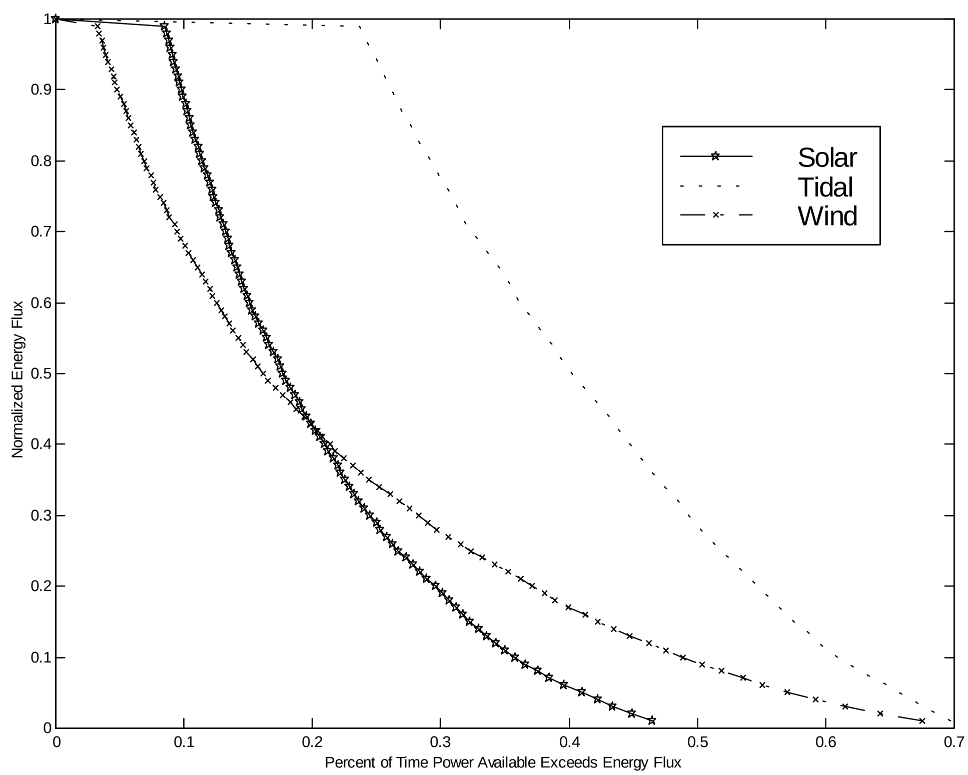

Figure 4: Energy Availability Curves

Using the availability of a renewable energy resource, we can calculate a basic installation size required for a specified amount of energy supplied. This calculation, although it can be used to calculate the energy supplied by grid-connected renewable energy, does not take into consideration the unique features of a stand-alone system. The time-dependence of the resource, the non-linearity of the storage system and the efficiency cost of the storage system all have significant effects on the operation of stand-alone systems.

Although renewable energy systems do require a storage system, which has a significant impact upon the overall efficiency and cost of the system, they are generally considered to have fewer environmental impacts than conventional energy sources, and definitely produce lower quantities of greenhouse gasses during operation.

2.2. Renewable Resource Data

The possibility of modelling a renewable energy system and gaining insight into the operation and potential of renewable energy has been presented. However, before a review of existing models, we need to have an idea of the different data sources used in these models. This section provides a brief review of the three different sources of data used in renewable energy system modelling: TMY data, gathered data and stochastically modelled data.

Typical Meteorological Year (TMY) data sets are compiled by Environment Canada, the United States Department of Energy, as well as international organizations. To create a TMY data set, the most typical month for a location, based on the statistics of the month, is chosen from a long-term data set for each month of the year. These typical months are concatenated to form a single 'typical' year of data. These data sets are static, and only one typical year is available for any given location.

The use of gathered data for a specific site allows for more detailed evaluation of the characteristics of the site, as well as the ability to use more than one year of data. Unfortunately, the ability to use gathered data is often limited by the accessibility to appropriate measurement devices and the time required to gather multiple years of data. Gathered data sets are also static entities, which will provide the same set of results, even if they were gathered during non-typical years.

The third type of data that can be used to model energy systems is stochastic data. The stochastic generation of data, although it does require computational power, does not have the same restrictions as either TMY or gathered data. A stochastically generated data set can be re-generated for any number of years, allowing for the long-term evaluation of system performance. The ability to run hundreds of years of data and examine the worst or best years allows for significant advantages over other data sets.

Overall, stochastic generation of data provides the most advantages with the required computer time being the only significant disadvantage.

2.3. Review of Existing Models

Significant work has been published on renewable energy systems models. This section gives an overview of this work and discusses the strengths and weaknesses of the different approaches, especially in terms of the ability to examine the effects of various parameters on the overall system designs. The factors identified in this section are taken into consideration in section 2.4, where we create the overall system model structure.

The different modelling efforts in the literature can be loosely categorised in many different ways. For example, McGowan and Manwell [27] discuss the separation of models for hybrid wind/diesel systems into four categories: 1. quasi steady state, 2. dynamic-mechanical, 3. dynamic-mechanical with steady-state electrical and 4. dynamic mechanical and electrical. The quasi steady-state models consider discrete time steps of, typically, 10 minutes or one hour and are used to develop the system characteristics of a stand-alone system and to perform economic analyses. The partial and full dynamic models are used to obtain information on the short-term performance and power balances of the system for control and stability considerations.

Since, in this thesis, we are interested not in the dynamic response of each of the components, but rather the overall operation of the energy system, we will restrict our review to only quasi-steady state models. The quasi-steady state models, themselves, break down into power balance models, where a simple power balance is used to determine the storage size, and time-step models, which, through stepping through, can include much of the non-linearity of integrated energy systems.

2.3.1. Power Balance Models

Power balance models use the power balance between the load and resource availability to determine the general overview of a proposed energy system. Kellogg et al. discuss the use of a simple power balance as shown in equation (1). In this equation, P represents the average power either generated or demanded over a chosen time period. This equation is integrated over time to create an energy curve as shown in equation (2) with W representing the energy balance [28].

$$\Delta P = P_{gen} - P_{dem} \tag{1}$$

$$\Delta W = \int \Delta P dt = W_{gen} - W_{dem} \tag{2}$$

The difference between the maximum and minimum energy balance is used to size the storage system.

In a similar manner, Spinadel et al. [29] discuss the use of areas between the demand and resource curves as an indication of the requirement for storage. They discuss a very simple efficiency based model for the conversion efficiency of the wind resource. The model they discuss is also a single day model, which does not allow for long-term determination of performance. Zahedi [30] discusses the use of a “power equation” for the evaluation of the performance of a system. Unfortunately, no information on the model is given other than that it uses these “power equations.” It is expected that this procedure is similar to the ones used by Kellogg et al. and Spinadel et al.

Lehman and Chamberlin [13] discuss the development and modelling of a photovoltaic/hydrogen-fuel cell energy system. The general design assumes that some form of backup power is used for a portion of the demand to keep costs down. Although there is no real information on the specifics of the model used, the strong implication is that an energy balance was used to create a solar array area to power between 75% and 90% of the load.

Ashari and Nayar [31] discuss the use of “set points” for the control of a PV-diesel-battery hybrid system. An optimization is used to calculate the most appropriate set points for these hybrid systems with various configurations. They use actual system data and use a form of energy balance to calculate the optimal set points.

The loss of load risk (LOLR) for renewable energy systems is evaluated by Al-Ahswal [32]. These calculations are performed using a probability function technique that, although not precisely a power balance, uses many of the same ideas. This technique is used by Al-Ashwal to evaluate the risk of loss of critical power systems for telecommunications equipment.

Manwell and McGowan [33] discuss the creation of a screening level model for wind-diesel systems. This model is also a probabilistic model similar to the LOLR model discussed by Al-Ashwal. This type of model is considered useful for determining if a system is economically viable and if the energy required is available where required. They discuss the fact that this model can be used prior to a time-series model since it uses much fewer computing resources and also does not need large quantities of data.

All of the power balance models discussed above are quite useful in getting a general idea of the required system and performing a cursory evaluation of the capacity of renewable energy required for a system. However, these systems are limited by the requirement of linearity between the resource conversion technology and the load. This requirement makes it difficult to include storage input and output efficiencies in the calculations and impossible to place a cap on the input and output power of the storage system or to allow for outages in the system performance. For many sites, the economic benefit of having a smaller system would outweigh the consequences of having the lights go out for a few hours. Loss of Load Risk models are even less able to take into account the time-series dependence of the system since they are based solely on probability functions, and do not consider the time series of the resource or load in any explicit manner. However, since we use the time-series in the case of a power balance approach, and the probability in terms of the loss of load risk approach, we can get an idea of the peak-to-peak power and use this to get a first-cut approach of the required storage system. Overall, power balance models provide only a cursory, first stage evaluation of renewable energy systems.

2.3.2. Time Series Models

Unlike the power balance models just discussed, time series models have the ability to take into account the time-series dependence of the storage system as well as the non-linearity due to storage losses, storage size and/or storage input and output ratings and efficiencies. While the Power Balance models give a general idea of the required specifications for a system, the time-series models provide a more quantitative analysis of the actual, time dependant, performance of the system and can identify weaknesses, trade-offs and potential benefits of over-designed systems. Manwell and McGowan [33] discuss that power balance models can be used at the screening level to determine if further research is warranted. The time-series models are the next step in this process that needs to be taken prior to installing a system.

The time-series models in the literature can be loosely categorized as hybrid system models, which include some form of backup power, or stand-alone systems, that rely solely on the renewable resource. This section discusses the literature on time series models, both hybrid and stand-alone, and some of the issues with these models. It will be noticed that each of the modelled systems requires that the technology being modelled, both for the resource extraction and the storage system, be chosen prior to constructing the model and evaluating the systems performance. Few of the systems use any stochastically generated weather data, which makes their application in long-term evaluation difficult.

Fiksel et al. [34] discuss the development of the TRNSYS transient simulation program and the continuing developments up to 1995. Although this program is not, specifically, a renewable energy system-modelling package, it has been used by various organizations to model such systems. There is a module for TRNSYS called PVHYDRO, which can be used to model photovoltaic systems components. Martin and Muradov of the Florida Solar Energy Center [35] use PVHYDRO with a simple control scheme to model a solar hydrogen system. Using both typical load data and Typical Meteorological Year (TMY) data, they provide both 7-day time series and yearlong time series of two systems with combined battery and hydrogen fuel cell/electrolyser storage system. The Desert Research Institute, under contract to the Department of Energy, used TRNSYS for modelling renewable energy systems for various locations in both Alaska and Nevada [36]. They present a general business case for such systems and do not go into details on the modelling systems used.

Gregoire Padró et al. [37] use Aspen+, a process simulator, for time-series studies based on TMY data. They use the “best and worst days” to determine the system requirements of both a photovoltaic-electrolysis-metal hydride-fuel cell and a wind-electrolysis-compressed gas-internal combustion engine energy system on an hourly basis. In Rio de Janeiro, Valente and Almeida [38] perform one-day simulations for an analysis of another diesel-photovoltaic system. This analysis is performed to determine the fuel savings and economics of such a system. Average solar radiation values are used for the analysis, making this approach a combination power balance and time-series model. Both these models, by performing the analysis only for a few days, ignore, the day-to-day sequences of the solar radiation and the effect this has on the storage system.

Bonanno et al. [39] have created a system model for hybrid diesel, photovoltaic, and wind systems. Using data files of wind, solar radiation and load, a case study of a small island in the Mediterranean has been performed. The only storage considered is a small battery system for the photovoltaic system connection, which would smooth out small voltage fluctuations, but not have a significant effect on the overall system.

Meibom et al. [40] compare the power exchange between hydro and wind-dominated energy systems. The analysis is performed using actual historical data on an hourly basis. The systems analysed are grid-connected systems where the goal is to share energy between Norway and Denmark to increase the utilization of the wind and hydro resources. Again, gathered data is used for the simulations and the concept of storage and the losses associated with storage are not considered.

Chan [21] developed a model of the use of hydrogen storage with renewable energy for the Canary Islands. This study used hourly data for the power available from the renewable resource and a smooth load profile since this was for a large system. Only one year of gathered data was used for this study and model details were not given.

The Saudi-German HYSOLAR project includes system layout and design activities. Dienhart and Seigel [41] discuss the activities within this project for a PV-Wind-Hydrogen autonomous energy system. The modelling project is being used to match the electrical load of an island community to the renewable resource. The effects of different climates are taken into account by using gathered data for three locations, but this does not make the model generally applicable. The PV/wind ratio is varied and the costs of energy from each system are considered.

Ding et al. [42] create an energy system model for a hybrid, PV-hydro-wind system for the Auckland Institute of Technology campus lighting system. They use 480 time steps for the system that models a full year of system operation. This amounts to just under a day for each time step, implying significant averaging of the resource. Unfortunately, this paper does not give details of the modelling system used or the specifics of the resource models. It does, however, seem that very simple resource models are used which models single days. A battery system is modelled to provide storage and it appears that all the energy produced by the system is cycled through the batteries, implying that an almost power-balance style approach is used. The cycling of all the power produced by the solar panels through the storage system implies an efficiency cost. For the campus lighting system discussed by Ding et al. where they know that the solar panels will not be producing power when then lights are on, this is not an issue. However, for general systems where this correlation does not exist, the cost of cycling all the energy through the storage system implies that a different control strategy is warranted.

Isherwood et al. [43] discuss the optimization of various wind-diesel systems using HYBRID2, a hybrid system simulation program developed by the National Renewable Energy Laboratory. All of these systems have significant diesel backup capabilities and an analytical optimization is used to calculate the cost benefits. The HYBRID2 code, discussed by McGowan et al. [44] as using gathered data, is not discussed in detail but economic payback periods are discussed for various scenarios. All scenarios use hydrogen storage systems with various storage technologies. In their system the diesel backup makes it a hybrid system with storage, rather than a stand-alone system.

McGowan, Manwell and Avelar [44] discuss the modelling effort of hybrid systems at the Renewable Energy Lab at the University of Massachusetts. They model hybrid systems including wind, photovoltaic, and diesel and discuss the applications in South America. They compare two different modelling systems, HYBRID2 and SOMES for these calculations and conclude that there are only small differences between the results, due to the different assumptions used by the models. Both models use hourly gathered data for the locations investigated. They conclude that there is no universal design tool for hybrid energy systems but that models can be used to define the major performance characteristics. As with Isherwoods work, above, this model is geared towards hybrid systems.

Nehrir et al. [45] discuss the creation of a Matlab/Simulink model for wind-PV systems with battery storage. Specific models for each of the conversion technologies are discussed and the model is used to develop general system configurations and performance characteristics of various energy systems. Nehrir et al. discuss that this system is a useful tool for the evaluation of stand-alone wind/PV generating systems. Although information is not given on the resource data, it is apparent from the paper that either gathered or TMY data, and not generated data, was used for the analysis.

All of the system models discussed in this section provide useful information on system configurations and the possibilities of renewable energy. However, these models also make the assumption that a specific technology will be used and there is no consideration of the potential of using different technologies. In the best case, two or three technologies are compared. This means that examining the effect of, say, the efficiency of the storage system cannot be performed with these models since the storage technology is defined at the outset with its associated characteristics. This prevents these models from being used as general renewable energy system design tools. The model developed in this thesis uses the most generic models for each resource, their associated conversion technologies, and a generic storage model. This allows us to perform a number of interesting investigations that are not possible with other models.

The reliance of the models discussed above on gathered or TMY data makes their use in the long-term performance evaluation of designed systems suspect. Although long-term data can be used for reliability analysis, the lack of easily available data records of any significant length makes it difficult to evaluate performance over more than 25-30 years. The use of stochastically generated data allows for the evaluation of the system performance for 50 or 100 years or longer, thereby allowing for a more detailed analysis of the reliability of the system. The model developed in this thesis uses stochastically generated data, thereby allowing for a more detailed analysis of system performance and reliability.

2.4. Model Architecture

Section 2.1.3 showed the general configuration required for utilising renewable energy in a stand-alone configuration, and the energy flows within this system. Although a model is trying to represent these energy flows, the actual data flows in a model do not follow these same paths. This section identifies the required components that need to be modelled and then develops the data flows required to obtain useful data from the model.

Any stand-alone renewable energy system requires a number of different components in the servicing of a load from a renewable resource. First, we need to be able to convert the energy from the renewable flux into a currency we can use, in this case electricity. This is performed with the resource conversion technology. Once we have this energy we need to either feed it directly to the load, if the right amount is available, feed it to the storage system, if there is excess, or take energy from the storage system if there is a deficit from the resource. If we have a model for each of these components, as well as the load and the resource, we can put together an energy system model.

The data flows through this model do not follow the same paths as the energy flows. The data does start at the renewable resource and goes through the conversion technology to obtain an available energy, but at this point, we subtract the load to get an energy balance before storage. Using this balance, we can determine if we need to add energy to the storage system, using the storage input function, or if we need to remove energy from the storage system, using the storage output function.

Figure 5 shows the data flows through the system model and each of the components that need to be modelled, including the resource and load models as functions of time and a random seed. These functions are different for each resource and are described in detail in later chapters. The data flow, and the application of the transfer functions to the data, is performed at each time step. It should be noted that the storage system, by applying a loss over time, has an associated time-shift. The dashed line in the figure shows this.

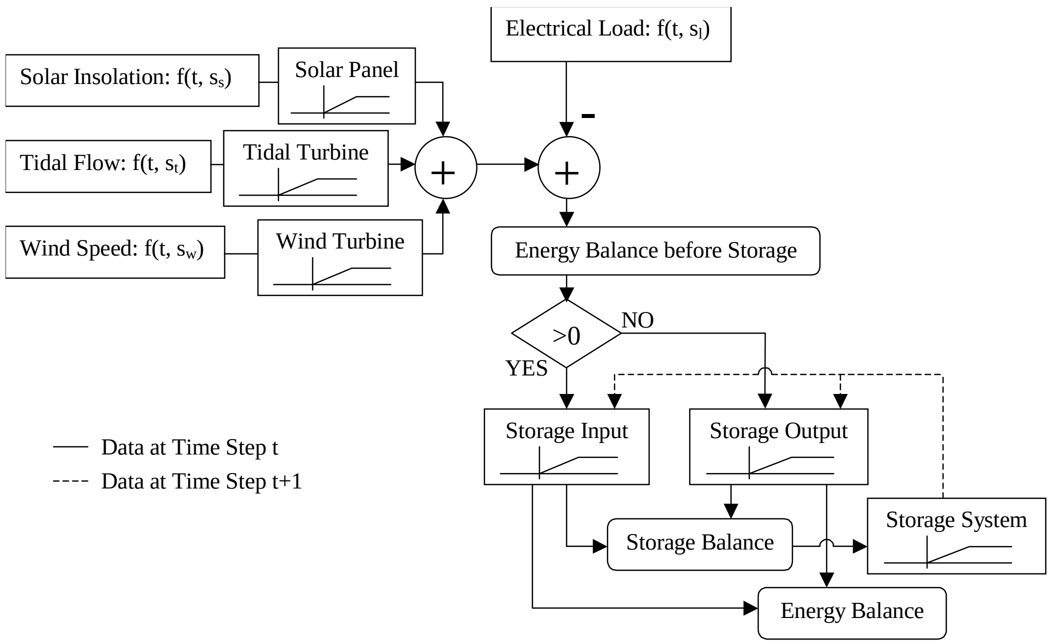

Figure 5: Energy System Model

In Figure 5 the outputs are shown in rounded boxes, each resource and the load model are shown as a function of time, t, and a random seed, s, and the transfer functions are shown as graph icons. Although the graph icons show only linear systems with limiting functions, the two turbine models are not linear functions. As well, the looping of the system and the limiting factors create significant non-linearity in the system.

Having developed the model architecture, the only item that has not been determined for the system is the time-step that the system needs to perform with. If a time step is chosen that is too long, such as a day, the averaging of the resource and load will provide systems that appear to perform adequately in the model but would not perform properly if installed. If the time-step chosen is too short, detailed information on the system is available, but due to the computational requirements, obtaining results will require significantly more resources. A time step of an hour is a nice compromise between these two.

To determine if a time-step of one hour is adequate, the short-term variability of the resources and its effect on the outcome of the results must be considered. For tidal flows, the variation happens over three or four hours and therefore one-hour averages are reasonable. As discussed by Cermak [46], the wind variability within the hour does not have a significant effect if the height and location effects are considered properly. The solar variation is therefore the only variation we need to consider in more detail, and this is discussed in section 4.5.

Having defined the model, the following chapters will provide the details for each component of the model, starting with the storage system, adding the various resources one at a time, and finishing with the load model.

3. Storage Modelling

In section 2.4 we discussed the flow of data through our model and identified a number of components that were used to model our system. The storage system was identified as a significant part of this system, and this chapter develops the storage system model in detail. Background material on storage system modelling is presented; the most appropriate input and output transfer functions and also the storage function are developed. A review of storage technologies available in the literature is given and appropriate parameters are identified for the system.

3.1. Background

The modelling of a generic storage system is inherently difficult due to the many different technologies available for energy storage. For example, there are storage systems employing such varied technologies as pumped hydro, compressed air, batteries, super-conducting magnets, hydrogen combined with fuel cells and electrolysers as well as flywheels [47-51]. Each of these systems has very different performance curves, which makes it difficult to model all of them with a single storage model.

If we look at specific storage models, we can find models for many different technologies. However, as an example of the complexity of using these models in a generic manner, we can look at one typical storage model presented in the literature. This model, developed by Vanhanen and Lund [50], is for a hydrogen storage system and they use this model to improve the performance of the overall energy system they are researching. However, this paper presents over 50 equations to illustrate the modelling of this single system and requires over 25 parameters to evaluate these equations. Although this does allow for the accurate development of hydrogen storage systems using the specific technologies they identify, it becomes difficult to evaluate the difference between various storage systems. As well, Vosen and Keller [52] discuss the use of hybrid storage systems, where multiple storage systems are incorporated into a single energy system. Some researches have found that the use of hybrid storage system is sometimes necessary to have adequately performing systems [11, 12]. The modelling of such combined systems becomes quite difficult if each storage technology model requires over 25 parameters, each of which must be estimated.

3.2. Energy Storage Model

As shown in section 2.4, the storage model consists of an input transfer function, an output transfer function, and a storage function. Each of these functions performs a specific role in the operation of the energy system. Even though this set of functions is most easily applied to a storage system consisting of hydrogen with the associated electrolyser and fuel cell, it can be applied to batteries and other systems as well.

If we look carefully at storage systems and the parameters given for the input and output, we see that the efficiency of the input and output play a significant role. As such, the storage input and output were modelled as simple efficiency based models that operate on the energy balance of the load and the resources. However, we cannot assume that our system will have infinite power available into and out of the storage system, and we therefore also implemented a limit on the power of the system. Equations (3) and (4) show the input and output transfer function for the storage system as implemented in the energy system model. The input transfer function is used when the balance between the resource(s) and load is positive and the output transfer function is used when this is negative. In these equations, E_S represents the storage balance, E_{B4} represents the energy balance before storage, η_i and η_o are the input and output efficiencies of the storage system, respectively, and S is the storage size.

$$E_S(t) = \min[\min\{\eta_i \times E_{B4}(t), R_i\} + E_S(t-1), S] \tag{3}$$

$$E_S(t) = \max[E_S(t-1) + \frac{\max\{E_{B4}(t), -R_o\}}{\eta_o}, 0] \tag{4}$$

Once we have added the energy to the storage system, we need to create our overall energy balance after storage. Applying equation (5) or (6) for the input and output to storage, respectively, gives us the energy balance, E_B.

$$E_B(t) = E_{B4}(t) - \frac{E_S(t) - E_S(t-1)}{\eta_i} \tag{5}$$

$$E_B(t) = E_{B4}(t) - [E_S(t) - E_S(t-1)] \times \eta_o \tag{6}$$

As well as the above equations, the model takes into account the possibility of storage loss over time, which can be significant for storage systems that are designed for short-term operation, such as flywheels. The loss of storage over time is, again, a function of the system configuration and the different components involved. However, we can model this as a simple percent loss during every time step. The overall storage loss between each time step can be modelled by equation (7) and equations (3) through (6) above will use E_{Sloss}(t), the storage balance after losses, instead of E_S(t-1), the storage for each system at the previous time step. In equation (7), τ represents the percentage loss for each period.

$$E_{Sloss}(t) = E_S(t-1) - E_S(t-1) \times \tau \tag{7}$$

This system, although a simplification of the operation of a real storage system, allows for the examination of the effect that each parameter has on the overall workings of the energy system. The ability to examine the use of high-cost high-performance storage versus lower-cost lower-performance storage allows for the comparison of the advantages and disadvantages of each. A generic storage system model also enables the evaluation of an entirely generic energy system, not based on any specified technology. This can be used to identify design targets for technology development.

To expand this system slightly, the ability to model multiple storage systems was also implemented. To implement multiple storage systems, a simple control scheme is needed to determine which system is used at which time. To keep things as simple as possible, and allow for multiple systems that work together, the storage systems were set-up to be used in the order the user specified them. This means that, if the user specified first a battery and then a hydrogen based storage system, the battery system would be filled and emptied before using the hydrogen-based system. This is consistent with the discussion of Vosen and Keller in relation to hybrid storage systems, in which they use two different control algorithms and state "Both algorithms use battery storage to provide much of the daily energy shifting and hydrogen to provide seasonal energy shifting, thus using each storage technology to its best advantage" [52]. Once this control scheme has been decided upon, we need to expand equations (3) through (6) to include multiple systems.

To expand these equations the variables that change between the update of each storage system need to be examined. A careful examination of these equations, with the realization that initial state of the storage system (as calculated by equation (7)) is defined separately for each system in the model, we realize that it is only the energy balance before storage, E_{B4}, that would be different for each storage step. After the first storage system, the energy balance available or required will be reduced, and this changed value will have to be fed to the following storage system. The overall balance for the whole system is then the balance out of the last storage system.

3.3. Storage Technologies

As mentioned in section 3.1, the large variation of storage technologies, and the complexity of modelling them interchangeably, has resulted in the use of storage input and output transfer functions and a storage loss over time. This section presents a table of the various parameters considered for the different storage technologies.

There are four different storage systems that have been considered in this section, electrolyser-hydrogen-fuel cell, battery, pumped hydro and flywheels. Each of these technologies, due to their unique characteristics, will have very different parameters. For example, flywheels are generally designed to be short-term storage systems, and will therefore have high loss over time, while hydrogen or battery based systems will have much lower loss over time.

Table 1 details the input and output efficiencies, as well as the storage loss, in percent per hour, for various storage systems found in the available literature. From this table it can be seen that the variation of each parameter for the various storage systems is quite large. It therefore becomes even more important to be able to model the effects of slight variations in these parameters and their effect on the system performance.

Storage System Type	Input Eff. (%)	Output Eff. (%)	Storage Loss (%/h)	Notes	Source
Battery (Lead-Acid)	80	100	Low	No info on loss with time is given.	[53]
Single-Stage Francis Turbine Pumped Hydro	90	90	Low	No info on loss with time is given. Typical head of 600m.	[54]
Electrolyser/Fuel Cell	70-80	40-50	Low	Input efficiency may be lower for liquid H_2.	[49, 54]
1.2 MW Flywheel	60	100	High	The loss with time is expected to be high, but is not given.	[51]

Table 1: Storage System Parameters

4. Solar Modelling

In section 2.4, we identified each resource as a function of a random seed and time, combined with a transfer function for the resource extraction technology. This section expands these items for solar energy, taking us from the solar insolation to an available energy from an installed solar energy technology.

There are, in general, three different components required to obtain energy from the sun. First, the insolation at a site will, obviously, have a significant impact on the available energy. The orientation of the collector to this insolation also has a significant effect, since solar insolation is highly directional. Finally, we realize that the actual technology used to convert the insolation to a useable energy form has a significant effect on the amount of energy available.

This chapter develops these three categories in more detail, starting with an overview of insolation models. A discussion of the different inclined plane models follows, allowing for the evaluation of the effect of the orientation of the collector. This is followed by a discussion of the implementation of the models for insolation and orientation. A review of the different solar energy technologies is presented, and typical parameters for these technologies are identified.

As discussed in section 2.4, our model will be averaging over one-hour periods and we need to evaluate the potential effects this may have on the solar energy available. The final section in this chapter discusses the literature on sub-hourly variations of the solar resource and the effect this may have on the results of the model.

It should be noted that, in general, two different methods of discussing solar radiation exist, that of discussing the irradiance directly, and that of discussing a clearness index. The clearness index, k, is defined as the ratio of the global horizontal irradiance at the surface and the global horizontal extraterrestrial irradiance as shown in equation (8) where H is the irradiance on the surface and H_0 is the irradiance outside the atmosphere.

$$k = \frac{H}{H_0} \tag{8}$$

For the purpose of this chapter, these different models are discussed on the assumption that the conversion between the clearness index and the irradiance is given. For a description of the calculation of the extraterrestrial irradiance refer to section 4.3.2.

4.1. Solar Insolation Models

Due to the dependence of solar insolation on a large variety of both stochastic and deterministic factors, the modelling of solar insolation sequences is quite difficult. For this reason, and the fact that gathering solar insolation data is both expensive and time-consuming, both the Canadian and United States governments have produce “Typical Meteorological Year” data. The Canadian TMY data, called CWEC or Canadian Weather for Energy Calculations, is available from Environment Canada’s Atmospheric Environment Service [55, 56]. The United States TMY data is available from the National Renewable Energy Laboratory [57].

These data files, provided free of charge from the respective agencies, give a typical year of data that is taken from a 30 year data set. Each “typical” year is extracted, month-by-month, from the 30-year data set using a number of different statistical criteria that are deemed appropriate for the specific purpose that the files are being developed for. The extracted months are then combined into a single 'typical' year. In the case of the TMY and CWEC data files, this is for building and solar energy calculations.

The use of this data, however, was found by Knight et al. [58] to be less accurate, and even less typical, than data generated by a stochastic approach, even when the statistics for the stochastic approach were taken from the TMY data. Gansler et al. [59] also found that using a stochastic weather generator was more effective than using any reduced data sets. With the current speed of computers, the modelling of stochastic insolation sequences is also no longer prohibitive and therefore, for this study, a stochastic insolation model was used.

A variety of stochastic methods exist for predicting solar insolation sequences. These models often require various different inputs and produce a large number of possible different outputs, depending on the purpose of the model. For example Graham et al. [60] and Aguiar et al. [61] both describe models that give daily average insolation values when given the monthly means. Since inclined plane models exist to convert from global horizontal to any arbitrary surface orientation and we are interested in the hourly average insolation, only the global horizontal models that give hourly averages were considered. For a detailed description of Inclined Plane models, refer to section 4.2.

Hourly average global horizontal irradiance models can be broken into a number of different categories. There are models that predict the insolation for a location with clear skies, those that use hourly cloud and other meteorological data to estimate irradiance, models that use an ARMA and/or Markov processes, and others that use various statistical and curve fit methods.

Biga and Rosa, Marathe et al. and Gueymard [62-64] all present different clear sky irradiance models. Biga and Rosa discuss the statistical properties of the insolation in Lisbon and discuss some correlations between the global and diffuse irradiance under clear sky conditions. Marathe et al. discuss the use of a simple model for the solar radiation given by sinusoidal equations. Very similar equations are used to calculate the extraterrestrial irradiance as discussed in section 4.3.2. These models are applicable only to clear sky conditions.

Gueymard discusses a model for clear sky irradiance given the solar elevation, the amount of precipitable water, the Angstrom turbidity coefficient and the stations pressure (or altitude). Again, as with the Biga and Rosa model and Marathe et al.'s model, this model is applicable only to clear sky conditions.

Cloud and sunshine observations are often used to estimate irradiance when such data is available. This method is used for many of the TMY data sets since many of the meteorological stations do not record insolation directly. Biga and Rosa [65] and Olseth and Skartveit [66] provided preliminary work in this area in 1980 and 1993, respectively. The methods presented in these papers are quite similar. Biga and Rosa estimate the amount of irradiance between two levels, G_n`` and $G_n$`. $G_n$`` is equivalent to the diffuse radiation incident during the one hour period while G_n` is the maximum possible irradiance for that level of cloudiness. The actual irradiance, D_n, is calculated from equation (9) given C_n, the amount of cloudiness and D_{on}, the amount of diffuse irradiance on a clear day. F_n represents the additional amount of diffuse irradiance contributed by the presence of clouds. [65]

$$D_n = (1 - C_n) D_{on} + F_n \tag{9}$$

Olseth and Skartviet [66] use a similar method but determine a clearness index, k_h, and use this clearness index, and a calculated extraterrestrial irradiance, to calculate the global irradiance. They define nine different cloudiness indices, c_h, and use these with empirical relationships to find k_h for each hour of the year.

Maxwell [67], in discussing the National Solar Radiation Data Base, presents a more detailed and expanded model for hourly solar irradiance given a more detailed weather database. Gul et al. [68] present two models for obtaining radiation from cloud cover and meteorological data, the Cloud Cover Radiation Model (CRM) and the Meteorological Radiation Model (MRM). These models are similar to the ones discussed above and again give the irradiance for each hour of the day.

The main problem with the clear sky and the cloud cover based models discussed above is that they require a clear sky or an estimate of the amount of cloud cover. Most locations do not, generally, have either predictably clear skies or hourly cloud data available. Stochastically modelling cloud cover is just as difficult as the stochastic modelling of irradiation sequences, so this approach does not provide any significant advantage.

A number of papers present the use of ARMA models and/or Markov Transition Matrix (MTM) models for solar irradiation estimation. Many of these models have been developed for the daily insolation sequences rather than the hourly insolation sequences due to the difficulty in having to transform the hourly sequences to remove the diurnal variations. Kamal and Jafri [69] note that ARMA models can only be used accurately for data sequences that have normal distributions. They note that insolation sequences do not have normal distribution even when representing daily values. For examples of the use of ARMA models for the prediction of daily irradiance see Callegari et al. [70], Brinkworth [71], Loutfi and Khtira [72], and/or Kamal and Jafri [69].

To expand the ARMA models to hourly sequences, Panek et al. [73] creates daily insolation sequences with an ARMA model and then uses a quadratic function to model the irradiance variation over the course of the day. Anand and Dief [74] use a similar procedure with a sinusoidal curve instead of a quadratic curve. Although these procedures obviously give an idea of the hourly insolation values, they do not give an accurate representation of the variation of the insolation throughout the day.

Siala [75] attempts to correct this deficiency by creating an hourly ARMA process which uses the data adjusted by the hourly means and standard deviations. Although this process works well and provides results that seem accurate this process cannot avoid averaging of the data unless multiple day variations are taking into account. The regression over multiple days, each of which requires 24 regression coefficients, makes for a cumbersome model. Hokoi et al. [76] used similar methods to model both solar radiation and outdoor air temperature and the same comments as applied to Siala's model apply to Hokoi et al.'s model.

Morf [77] presented the Stochastic Two-State Solar Irradiance Model (STSSIM) in 1998. This model uses an assumed two-state value for the insolation sequence. These two states correspond to the clouded states and the unclouded states. Using a sinusoidal function for both the clouded insolation and the unclouded insolation, a series of random numbers is used to calculate the length of the period where it is clouded or clear. Depending on the current state, the model either outputs the clouded or clear curve. The lengths of the periods of cloudiness and clearness, as well as the shapes of the curves, are determined from gathered data. Although this model gives the ability to theoretically produce data down to minute periods and shorter, it also requires some knowledge of the short-term insolation sequences to be able to obtain accurate time series. These short-term time sequences are, generally, not easily obtained. This model assumes that there are only two possible cloud covers, clear or cloudy, which is a significant simplification.

Knight et al. [58] present a model that takes into account both the non-normal distribution of the clearness index, and the correlation of these sequences over multiple days. This model was developed specifically to create accurate "typical" insolation data sequences. The general procedure used with this model is to pick a set of randomly generated sequences using the actual daily clearness index distribution. These daily clearness indices are then used with a sinusoidal function to obtain an hourly clearness index that is then modified to represent the expected variation in the insolation.

This model takes into consideration all the important factors that need to be considered for modelling solar insolation sequences for the purposes of this study and it was therefore the chosen model. Details of this model, and how it was implemented, are given in section 4.3, Model Implementation.

4.2. Inclined Plane Models

As was mentioned above, the orientation of the collector to the incoming insolation has a significant effect on the available energy from this insolation. Inclined plane models provide the ability to convert the insolation from one orientation to another, thereby allow this effect to be taken into consideration.

Hay and McKay [78] wrote an excellent article describing the state of the field of inclined surface irradiance models in 1985. In this work they state that "the calculation of inclined surface irradiance involves separate treatment of the three components of the incident solar radiation: the direct, the diffuse from the sky hemisphere, and the reflected from the ground surface within the field of view of the sloping surfaces." [78]

Of these three factors that need to be considered, the diffuse radiation from the sky hemisphere is, by far, the most difficult to calculate and models can be classified in terms of the method they use to calculate this portion of the irradiance [78]. Models for the calculation of the sky hemisphere can be classified into two categories: isotropic and anisotropic. Hay and McKay, while discussing isotropic models, state that there is "ample direct and indirect evidence of its inappropriateness" [78]. Reindl et al. [79] compare a number of different models, one isotropic and three anisotropic. They found that the isotropic model performed poorly and that the anisotropic models have comparable performance with each other. As such, we will focus our attention only on anisotropic models that Hay and McKay state can now provide realistic estimates of slope irradiance.

Perez et al. [80] published the Perez tilted surface irradiation model, an anisotropic model, in 1986. The simplified version of this model [81], published in 1987 and known as the simplified Perez model, has since become one of the most used models for inclined planes. The governing equation for this model is given by equation (10) where s is the plane tilt angle, a, c, F_1, and F_2 are coefficients found as given by the paper and D_h is the global horizontal irradiance. The coefficients a, c, F_1 and F_2 are related to the geometry of both the sun and the surface as well as the properties of the atmosphere.

Using this equation, the diffuse irradiance on any plane surface, D_c, can be calculated. To get the global irradiance the direct irradiance calculation discussed by Hay and McKay is added to this diffuse calculation. This calculation, however, requires knowledge of the direct normal or direct horizontal irradiance.

$$D_c = D_h \left[0.5(1+\cos(s))(1-F_1^{'}) + F_1^{'}(a/c) + F_2 \sin(s) \right] \tag{10}$$

This model has been extensively evaluated by various authors and found to perform well. Utrillas and Martinez-Lozano [82] found that the simplified version of the Perez model worked better than the original version of the model for experimental data from Valencia, Spain. Feuermann and Zemel [83] performs a similar evaluation of a number of different models, including the Perez model, for Sede Boqer, Israel and finds that the Perez model performs with errors that are similar to the measurement instruments. Vartiainen [84] found that the Perez sky model performed significantly better than other models for Turku, Finland.

Although the Perez model has been found to be accurate and applicable to many different locales, two other models have been published since and deserve consideration. For example, Olseth and Skartveit [85] discuss the modelling of the probability functions of irradiance on inclined planes. This procedure could be used with non-hourly probabilistic based system models such as those described by Al-Ashwal [32].

Olmo et al. [86] describe a model that requires only the global irradiance, and not the direct irradiance value to calculate the global irradiance on an inclined plane. They developed the model for Granada, Spain but verified the results of the model with a large set of data to validate it over a variety of conditions. In comparison with the Perez model, they found this model to produce similar results.

Although the Perez model is, by far, the most used model for calculating the irradiance on a tilted surface, the requirement for both the direct and diffuse components poses a problem. The stochastic modelling of both the global horizontal, and the diffuse irradiance, as discussed in section 4.1, is difficult due to the correlation between them that varies with cloud cover. The Olmo model requires only the global irradiance on a horizontal surface. The ability to model only a single stochastic variable and then be able to generalize this to any arbitrary surface makes the Olmo model a natural choice, especially since this model was shown to perform similarly to the Perez model. Since the Olmo model was used for this project, details on this model, and it's implementation for this project can be found in section 4.3, Model Implementation.

4.3. Model Implementation

There are two distinct stages to calculating the irradiance on an inclined surface. We first need to calculate the global horizontal irradiance, and then we need to convert this to a global irradiance on an inclined plane. This section discusses these two procedures and how they have been implemented. A section on the calculation of extraterrestrial irradiance, which is required for the hourly irradiance model, is included for reference.

4.3.1. Knight Hourly Irradiance Model

As discussed in section 4.1, the Knight et al. hourly solar insolation model [58] was chosen as the most appropriate model for this project. This section, based upon this work, details the model developed and gives details of its implementation for the purposed of this project. The model creates a sequence of clearness indices for each hour of the year, and then the extraterrestrial insolation, as discussed in detail in section 4.3.2, is used to obtain the global horizontal insolation using equation (8).

To generate a stochastic sequence of clearness indices, the model starts by calculating a daily clearness index for each day of each month. Knight et al. discuss the use of various statistical distributions presented in the literature but find that, although these distributions are applicable to the locations studied, their universality is questionable. The correlation used by Knight et al., and verified for Albuquerque, NM, Madison, WI and New York, NY is described by equation (11) with γ found from equation (12). $K_{t,min}$ was taken as 0.05 with $K_{t,max}$ given by equation (13).

$$f = \frac{\exp(\gamma K_{t,\min}) - \exp(\gamma K_t)}{\exp(\gamma K_{t,\min}) - \exp(\gamma K_{t,\max})} \tag{11}$$

$$\gamma = -1.498 + \frac{1.184\xi - 27.182\exp(-1.5\xi)}{K_{t,\max} - K_{t,\min}}$$
$$\xi = \frac{K_{t,\max} - K_{t,\min}}{K_{t,\max} - \overline{K}_t} \tag{12}$$

$$K_{t,\max} = 0.6313 + 0.267\overline{K}_t - 11.9(\overline{K}_t - 0.75)^8 \tag{13}$$

Using a random number seed, f, we can work backwards from equation (11) to find the daily clearness index, K_t. As well as discussing this method, Knight et al. discuss the fact that, if these distributions are not appropriate for a specific site, we can use the actual distribution of the clearness index directly to find a set of daily clearness indices. The comparison of the curves, for Race Rocks, is given in chapter 8.

Once a set of K_t values is calculated using the distribution, as discussed above, Knight et al. sequence these values for each month. The sequences chosen were generated to maintain the statistical correlation of the data. Table 2 shows the sequences developed by Knight et al. and the average value of the daily insolation, $\overline{K}_t$, required to determine which sequence to apply. The same sequences are applied for each month of the year with the starting point within the sequence randomly selected for each month using a random seed.

Average K_t, $\overline{K}_t$	Sequence Order
$\overline{K}_t < 0.45$	24, 28, 11, 19, 18, 3, 2, 4, 9, 20, 14, 23, 8, 16, 21, 26, 15, 10, 22, 17, 5, 1, 6, 29, 12, 7, 31, 30, 27, 13, 25
$0.45 < \overline{K}_t < 0.55$	24, 27, 11, 19, 18, 3, 2, 4, 9, 20, 14, 23, 8, 16, 21, 7, 22, 10, 28, 6, 5, 1, 26, 29, 12, 17, 31, 30, 15, 13, 25
$0.55 < \overline{K}_t$	24, 27, 11, 4, 18, 3, 2, 19, 9, 25, 14, 23, 8, 16, 21, 26, 22, 10, 15, 17, 5, 1, 6, 29, 12, 7, 31, 20, 28, 13, 30

Table 2: K_t Ordering Sequences [58]

The next step in finding an hourly clearness index is to produce a series of hourly mean clearness indices, k_{tm}. Applying either equations (14) through (16) or equation (17) creates this series. Knight et al. found that equation (14) gave lower deviations from the actual values when applied to long-term data sets. Also, they found that the application of equation (17) gave values of K_t for each day that varied significantly from the defined value depending upon the time of year. For the purposes of this study, equation (14) was used since this gives the best results. In these equations, ω is hour angle of the sun, ω_s is the sunset hour angle and θ_z is the solar zenith angle.

$$k_{tm} \approx K_t r_t \frac{H_0}{I_0} \tag{14}$$

$$r_t = (a + b\cos\omega)\frac{I_0}{H_0} \tag{15}$$

$$\begin{aligned} a &= 0.409 + 0.5016\sin(\omega_s - 60) \\ b &= 0.6609 + 0.4767\sin(\omega_s - 60) \end{aligned} \tag{16}$$

$$k_{tm} = K_t - 1.167 K_t^3 (1 - K_t) + 0.979 (1 - K_t) \exp\left[\frac{-1.141(1 - K_t)}{K_t \cos\theta_z}\right] \qquad (17)$$

The hourly mean clearness index, k_{tm} represents the long-term mean for that hour of the day for days with the given clearness index, K_t. This mean value, however, does not represent an actual value for k_t, the clearness index for that hour. k_t is found by applying equation (18), which is found by equating the k_t distribution with a normal distribution for a normally distributed variable, χ, with a mean of 0, variance of 1. The random variable χ can then be used to generate values of k_t for any given σ_{kt} as given by equation (19).

$$k_t = k_{tm} - \frac{\sigma_{kt}}{1.58} \ln\left[\frac{1}{0.5[1 + erf\,(\chi/\sqrt{2})]} - 1\right] \qquad (18)$$

$$\sigma_{kt} = 0.1557 \sin\left(\frac{\pi K_t}{0.933}\right) \qquad (19)$$

To include the correlation of the hourly clearness indices, the random variable χ is calculated from a first order autoregressive model, as given by equation (20). The lag one auto regression coefficient, ϕ_1 is taken to be 0.54 [58]. ε is a normally distributed random variable with mean 0 and variance 1.

$$\chi_t = \phi_1 \chi_{t-1} + \varepsilon \qquad (20)$$

Once the hourly series of k_t values is determined, it is a simple procedure to calculate the insolation using the extraterrestrial insolation and equation (8).

4.3.2. Extraterrestrial Irradiance

The calculation of the extraterrestrial irradiance requires consideration of the orientation of the surface with respect to the irradiance arriving from the sun as well as the consideration that the direct extraterrestrial solar irradiance varies with the day of the year. Randall [87] describes a relationship between the extraterrestrial direct solar irradiance and the solar constant dependent upon the day of year as described by equations (21) through (23).

$$TH = 2\pi Day / 365 \tag{21}$$

$$\left(R / R_0 \right)^2 = 1.000110 + 0.034221\cos(TH) + 0.001280\sin(TH) + 0.000719\cos(2TH) + 0.000077\sin(2TH) \tag{22}$$

$$D_x = D_0 \left(R / R_0 \right)^2 \tag{23}$$

In these equations, Day is the day of the year, TH represents the angle of revolution of the earth around the sun, R/R_0 represents the distance ratio for the solar constant D_x, and D_0 represents the solar constant. D_0 is commonly taken as 1377 W/m^2. Randall mentions that the maximum error in $(R/R_0)^2$ is less than 0.0001 [87].

To determine the extraterrestrial global radiation, Q_x, the quantity we are interested in, Randall [87] gives equation (24) with D_x as determined above and z as the zenith angle of the sun.

$$Q_x = D_x \cos(z) \tag{24}$$

4.3.3. Olmo et al. Tilted Surface Model

As discussed in section 4.2, the Olmo et al. [86] tilted surface model is the simplest and most easily applied tilted surface model that still maintains reasonable accuracy. This section presents the details of this model as published by Olmo et al. in 1999. The geometry used for the following discussion is shown in Figure 6 and Figure 7.

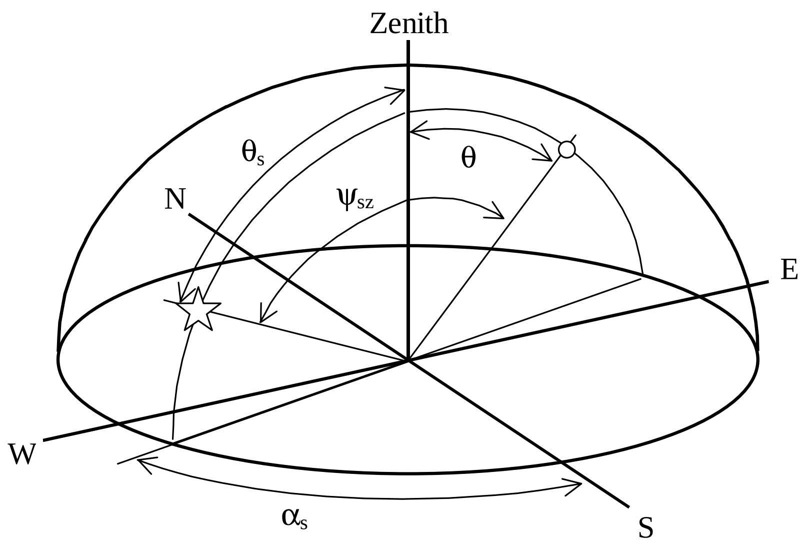

Figure 6: Solar Hemisphere w/ Normal in Solar Zenith Plane (After Olmo [86])

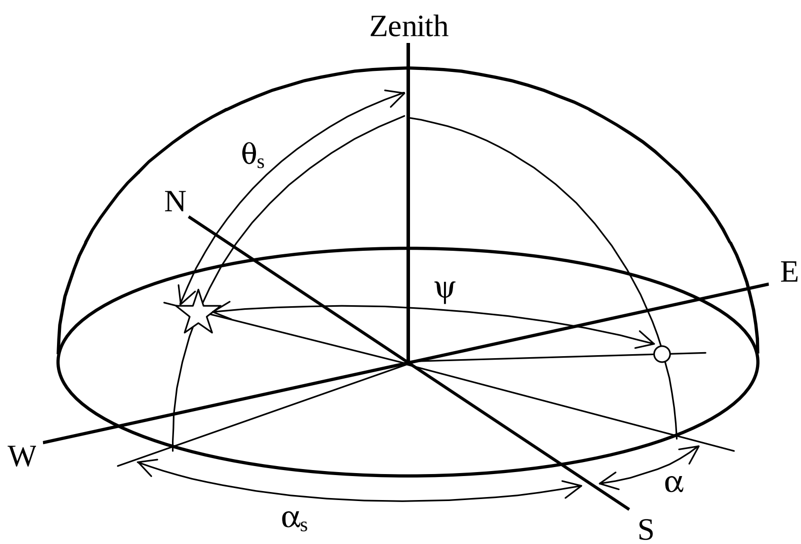

Figure 7: Solar Hemisphere w/ Normal not in Solar Zenith Plane (After Olmo [86])

The basic premise for this model is that an exponential relationship exists between the insolation on a surface perpendicular to the sun and an arbitrarily oriented surface, as shown by equation (25) and Figure 6 which relates G_n, the insolation on the plane perpendicular to the sunbeam, with a $G_{\psi zs}$, the insolation on the plane at angle ψ_{zs}, the angle, in radians, between the sunbeam and a perpendicular to any arbitrary surface.

$$G_{\psi zs} = G_n \exp(-k_t \psi_{zs}^2) \tag{25}$$

The k_t in this equation is the same k_t obtained from the Knight model, and takes into account the sky conditions. This same equation can be applied to the horizontal plane, to give the horizontal global insolation, G_H as shown in equation (26). ψ_H in this equation, as the angle between the sunbeam and the perpendicular to the plane, reduces to the solar zenith angle.

$$G_H = G_n \exp(-k_t \psi_H^2) \tag{26}$$

Combining equations (25) and (26) by equating G_n we obtain an expression for the global irradiance for any arbitrary surface as shown in equation (27). In this equation ψ is the orientation of the surface of interest relative to the sun, and ψ_H is the zenith angle of the sun as shown in Figure 6 and Figure 7. The determination ψ is a simple matter of geometry.

$$G_\psi = G_H \exp(-k_t(\psi^2 - \psi_H^2)) \tag{27}$$

To include the effect of reflection from the ground or other surface in front of the tilted plane, Olmo et al. include an adjustment factor, F_c, as shown in equation (28). In this equation, ρ represents the albedo of the underlying surface. After applying this adjustment factor, the overall model is shown in equation (29).

$$F_c = 1 + \rho \sin^2(\psi/2) \tag{28}$$

$$G_\psi = G_H \exp(-k_t(\psi^2 - \psi_H^2))F_c \tag{29}$$

4.4. Solar Energy Technologies

A variety of solar energy conversion technologies exist, ranging from large-scale thermal systems to small-scale photovoltaic panels. Although large-scale thermal systems achieve high efficiencies (up to 35%), the scale that these systems must be operated on to obtain such high efficiencies makes them inappropriate for small-scale and village systems. Solar photovoltaic panels, which convert photons from the sun directly into electricity, generally have lower efficiencies in the 5-15% range for direct conversion in practical systems. If concentrators are used, this efficiency can rise to over 30% [88]. However, no practical system with concentrators seems to be commercially available.

As well as a number of different solar energy conversion technologies, the actual conversion of energy for these systems depends on a variety of different parameters. The most common model for solar photovoltaic performance is PVFORM, developed by Sandia National Laboratories in the 1980s [89, 90]. This program, which has been used by a variety of studies (see, for example, Perez et al. [91], Walker and Price [92] and Rahman and Chowdhury [93]), requires both direct and global radiation, the ambient temperature and the wind speed to determine the available output of the solar panels. Although this program was found by many of its users to work effectively, the use of stochastically generated insolation sequences in place of the TMY data files, which include all the required parameters, makes such a model difficult to use.

To overcome the problem of using TMY data files, and to enable the modelling of a variety of different technologies, a simple solar panel model was developed which considers only the conversion efficiency of the panel, η_s, in relation to the insolation sequences generated and the maximum rated power of the panel, R_s. The power output of the panel can then be calculated as given by equation (30).

$$P(G_\psi) = \begin{cases} G_\psi * \eta_s & G_\psi * \eta_s \le R_s \\ R_s & G_\psi * \eta_s > R_s \end{cases} \quad (30)$$

Table 3 gives a listing of some commercially available and published solar panel efficiencies and rated powers.

Panel Manufacturer and Model or Published Technology	Rated Power (W/m^2)	Area Ratio	Conversion Efficiency (%)	Source
Arco/Siemens M75 Modules (~$0.52m^2$ each)	~92	N/A	8.1	[14, 15]
Siemens SR-90 Module (singlecrystal cell)	101	0.737	11.8	[94]
Siemens SP-75 Module (singlecrystal cell)	118	0.85*	13.6	[94]
Siemens ST-40 Thin-Film Module	94	0.95‡	10.45	[94]
Soltek SK-25 Module (singlecrystal cell)	105	0.95**	15.2	[94]
Unisolar USF-5 (flexible cell material)	36	0.95‡‡	7.6	[94]
Unisolar USF-32 (flexible cell material)	40	0.95‡‡	7.6	[94]

* Estimated since the geometry was not specified by the source.
‡ Thin film cells have only their edges not covered by cell material.
** Square cells cover nearly the whole surface, other than the edges.
‡‡ Similar to thin-film cells, only the edges are not covered.

Table 3: Characteristics of Commercially Available and Published Solar Technologies

In Table 3, the conversion efficiency is a combination of the cell efficiency and the area covered by the actual cells for this panel. For example, for the Seimens SR-90, there are 36 – 6 inch round cells in an area of 150 x 59.4 cm [94]. As such, the area covered by the panel, A_p, and the area covered by the cells, A_c, are calculated in equation (31). The overall efficiency of the panel, η_p, is therefore the cell efficiency, η_c, (16% for this type of cell [94]) multiplied by the area ratios of the cells to the panel, as calculated in equation (32).

$$A_p = 1.50cm \times 0.594cm = 0.891m^2$$
$$A_c = 36 \times \pi (3'' \times 0.0254m/inch)^2 = 0.657m^2 \qquad (31)$$

$$\eta_p = \eta_c \frac{A_c}{A_p} = 16\% \frac{0.657m^2}{0.891m^2} = 11.8\% \qquad (32)$$

The use of reflectors and concentrators to increase the output of a solar energy system does not, necessarily, increase the efficiency of the system, although it will definitely reduce the cost since the reflectors cost significantly less than the solar photovoltaic or thermal converters [95]. No commercial or installed systems were found that used concentrators.

The effect of tracking on the solar system does significantly affect the ability of the system to obtain energy [96]. The tracking ability is incorporated into the tilted surface model by allowing the model to calculate the maximum possible output when no tilt, no swivel angle (or neither) is specified for the system. In this way, the model can take into account both one and two axis tracking systems. The energy cost of the tracking system can either be included as an efficiency reduction for the solar panel or can be taken as an added load for the system.

4.5. Hourly Averaging of Solar Data

The averaging of solar radiation may have an effect on the results of the model. This section gives an overview of the literature that discusses intrahour variability of solar irradiance and the effect this has on system performance.

Skartveit and Olseth [97, 98] discuss the intrahour variability of solar irradiance and discuss that this would have an effect on the system performance. They however, state that the differences between the hourly and 5-minute distributions are “moderate, and may certainly be ignored in many cases.” Gansler et al. [99] also discuss the fact that there is a difference between using hourly averages and minute-by-minute data and counsel that, due to the non-linear effect of the system models, the use of minute-by-minute data does produce different results than hourly data. The overall difference was generally only a few percent, but was found to be over 30% in a few special cases, near sunrise and sunset. Although this seems high, the amount of irradiance at sunrise and sunset is already low, so a small difference would produce a high percent difference, and this difference would not have a major effect on the overall system performance. Hourly averages for solar are adequate for the model being developed, though consideration of this effect, and an evaluation with an installed system, would be interesting. As a starting point, if one was to try to model the intrahour variability of the irradiance, Suehrcke and McCormick [100, 101] provide models for the intrahour variability.

4.6. Conclusions

This chapter has identified the different components required for modelling a solar energy resource. These included the insolation model, providing the raw energy flux at a given location, the inclined plane model, allowing for different orientations of our collector, and a technology model, allowing for a variety of different technologies to be examined. Using these components the solar energy available for any site can be modelled as long as we have the average daily clearness index, $\overline{K}_t$, for each month of the year and have verified that the distributions for the clearness index is applicable to the site being studied. The application of this model, and the parameters required for Race Rocks, is discussed in detail in section 8.1.

Various technologies were identified that can be used for solar energy conversion and the parameters for these technologies were identified. Overall, solar energy conversion is a mature technology.

The effect of short-term variations in the insolation sequences were examined and it was found that these effects are not significant for a yearly model with hourly averaging.

5. Tidal Modelling

Tidal energy has been used for decades in tidal barrages, where an estuary is blocked to create a head for the turbines. Since the installation of tidal barrages in France and Russia, however, the popularity of tidal barrages has declined due to the significant environmental impacts of such systems on the estuary behind the barrage. The use of tidal stream energy, where a turbine is put in-stream and extracts kinetic energy from the flow, is relatively new. This technology will have a lower impact upon the environment although the amount of energy we can extract is also less. Since we are interested in lowering the environmental footprint of energy services, we will only concern ourselves with tidal stream energy in this thesis. This section will discuss the prediction of tidal currents and the use of tidal stream turbines to capture the energy in these currents to produce useable power. The models developed can then be used as the tidal components of the energy system model.

5.1. Tidal Current Modelling

In 1972 Godin published “The Analysis of Tides” [102] and provided us with the information needed to predict tides and tidal currents into the foreseeable future, if the harmonic constituents of the tidal stream are known. Although there is still work in this area, the main focus of the work is analysing the effect of small influences of celestial bodies other than the moon [103] or modifying the manner in which the constituents are calculated depending on the data available [104]. Overall, the analysis of tides is a well-known field, with very little uncertainty. The uncertainties that do exist are generally small, and are often related to ocean storms, which can have an effect on the tidal flow but cannot be accurately predicted.

Overall, tidal current prediction has been simplified into the task of identifying the harmonic components of the flow. Since data series are more common than lists of harmonic components, and the analysis of a data series produces the list of harmonics, the programs for tidal analysis and prediction include the conversion of these series into harmonic components.

Data series of tidal currents are, by convention, separated into north/south and east/west components. Although the analysis of two time-series does use more resources, the ability to also determine the direction of the flow with such an analysis makes it a convenient method. We can easily combine the two flows into a single, non-directional speed by calculating the resultant vector.

Mike Foreman of the Institute of Ocean Sciences created a set of tidal analysis and prediction programs using Fortran in 1978 [105]. These programs have become the standard for Tidal analysis and prediction. Rich Pawlowicz of the Woods Hole Oceanographic Institute ported these programs to Matlab in 2001 [106]. Details of these programs, and the numerical calculations performed, can be found in the "Manual for Tidal Currents Analysis and Prediction" [105] and the Manual for Tidal Heights Analysis and Prediction" [107]. The analysis is, essentially, a harmonic analysis assuming certain frequencies will be present, since these 'constituents' are common to all tidal flows.

These same sets of programs can be used to create a sample year of tidal current data. However, the time for each prediction needs to be specified. For the purpose of this thesis, since we want to obtain independent tidal flows for single years, we choose a random number between 2000 and 2100 to use as the year for prediction. The tidal analysis programs are then given the associated time series for each hour of the year chosen and the appropriate harmonic data to create a time-series of tidal currents.

5.2. Tidal Stream Energy Technologies

Tidal stream energy technologies, like wind turbine technologies, can be broken into two distinct categories: Vertical Axis Horizontal Turbines (VAHT) and Horizontal Axis Horizontal Turbines (HAHT) [108]. In the case of wind turbines the HAHT style turbine has many advantages, mostly due to the ability to place the turbine into a better wind regime by placing it atop a tower (See section 6.4). In the case of the tidal turbine, however, horizontal axis turbines do not maintain this advantage, since the tidal flow is highest near the waters surface. Therefore, there are both horizontal and vertical tidal stream technologies being investigated. This section discusses the developments in tidal stream technologies, details the model implemented for these turbines, and outlines the parameters for some turbines that have been presented in the literature.

The tidal stream technologies are still under significant development, with no known technology being at the commercial stage. There are, however, a couple of companies that are attempting to commercialize these technologies. Blue Energy Canada Inc. and Marine Current Turbines Ltd. of the UK are both working on tidal stream technologies. Blue Energy is working on the Davis turbine, a variant of the Darrieus turbine, a VAHT style turbine. They are focussing on larger scale systems of between 500 kW and 1 MW [109, 110]. Blue Energy’s work is based on the work of Davis, Swan and Faure in the early 1980s when they tested a number of prototypes at the National Research Council Hydraulics Laboratory [111-114].

Marine Current Turbines is also working on larger scale tidal turbines, on the order of a 300kW experimental prototype, but is developing a HAHT [115, 116]. The efforts of Marine Current Turbines is based on the work of Macnaughton et al. [117] who developed a proof of concept moored, 10kW tidal turbine in 1993.

A technology that is closely related to the Darrieus style turbine that Blue Energy is developing is the Helical Turbine invented by Alexander Gorlov [118]. Gorlov has taken the basic vertical blades of the Darrieus style turbine, and twisted them to obtain a helical configuration [119]. With this configuration, the advantages of the Darrieus turbine are maintained while the twisting of the blades reduces the power fluctuations of the system significantly [120]. This makes the turbine able to produce much smoother power cycles.

A number of university research groups have taken an interest in the generation of tidal stream energy. Tuckey et al. [121] from the Northern Territory University in Darwin, Australia placed a HAHT into the Apsley strait. They reported interesting results but there has been no further information on their progress published. Two research groups appear to be working on the Darrieus turbine in Japan. Gajanayake et al. [122] from Kyushu University in Fukuoko present a simulation of a Darrieus turbine for "Extra-Low Head Tidal Power Generation." Nihon University in Tokyo also has reported results with a Darrieus Turbine [123, 124]. They report good overall results but do not discuss the commercial viability of such a system.

As well as there being interest in the development of turbines for tidal stream energy conversion, there is also commercial interest in the development of small-scale run-of-river systems. These systems, though not directly applicable to the generation of power from tidal streams, use much of the same technology. There are a number of commercial systems that have been developed. The Amazon Aquacharger [125] provides 500 W at 1.5 m/s of water speed and starts producing useable power at 0.5 m/s. Tyson Turbine, a company in Australia, sells a 3 kW generating unit for US$6000, depending on the system configuration [126]. The Aquair Hydroelectric Generator [127], produced by Hydroshpere UK, Ltd., is a small 96 W system designed to provide power for auxiliary systems on sailboats. All of these systems are quite small in scale, but the general concepts are applicable in much larger scale systems.

To enable the modelling of a significant number of different turbines without the need to re-express the governing equations of the turbine each time, the model presented by Chou and Corotis for wind turbines [128] was also implemented for tidal turbines. This model, given by equations (33) through (36) with $v_m=(v_{ci}+v_r)/2$, gives the turbine output power as a quadratic function.

$$P(v)=\begin{cases}0 & v\le v_{ci}\\ A+Bv+Cv^2 & v_{ci}<v\le v_r\\ R & v_r<v\le v_{co}\\ 0 & v_{co}<v\end{cases} \tag{33}$$

$$B=R\frac{\left(\frac{v_m}{v_r}\right)^3\left(v_r^2-v_{ci}^2\right)-\left(v_m^2-v_{ci}^2\right)}{\left(v_r-v_{ci}\right)\left(v_r-v_m\right)\left(v_m-v_{ci}\right)} \tag{34}$$

$$C=\frac{R-B\left(v_r-v_{ci}\right)}{\left(v_r^2-v_{ci}^2\right)} \tag{35}$$

$$A = -Bv_{ci} - Cv_{ci}^2 \tag{36}$$

For details of this model, please refer to section 6.4, Wind Energy Technologies. Table 4 shows the parameters for this model for a number of published tidal turbine technologies.

Turbine Style and Author of Published Source	Diameter & Height* (m)	Rated Power (kW)	Rated Flow (m/s)	Cut-in Flow (m/s)	Cut-out Flow‡ (m/s)	Source
Darrieus Shiono et al.	0.3 by 0.2	0.018	1.4	0.4	2.8	[124]
Darrieus Kiho et al.	1.6 by 1.6	2.3	1.5	0.6	3	[123]
Gorlov Helical Turbine	1.01 by 0.84	2.1	8	2.1	16	[119]
VAHT (Model A-1) Davis et al.	0.813 by 0.625	5.33	4	1.1	8	[112]
Aquair Generator	0.312	0.096	4	1.1	8	[127]
Tyson Turbine	Not given	3	3.25	0.85	6.5	[126]
Amazon Aquacharger	1.8	0.5	1.5	0.5	3	[125]

* Height given for VAHT systems.
‡ Cut-out estimated at twice rated flow for all systems.

Table 4: Published Characteristics of Tidal Stream Turbines

5.3. Conclusions

This chapter has shown that tidal modelling is a well-known field, with very few unknowns and that, in general, tidal analysis and prediction was found to be an exercise in harmonic analysis. Given the harmonic components of a flow, the prediction of tidal flows is well known, with the only unknowns relating to the effects of storms and other such phenomena, which have only a small effect.

The technology used to convert tidal flows into usable energy was found to be in the development stage, with no commercial systems being available. However, a number of demonstration systems have been identified that provide enough information to allow for their use in the model.

6. Wind Modelling

This chapter identifies the models available for the wind resource, the adjustment of the resource for systems installed at different heights, as well as the technology models for extracting energy from this resource.

6.1. Wind Simulation Literature

Wind modelling algorithms fall into two distinct categories: forecasting and simulation. Wind forecasting techniques are used on minute, second, hourly and daily periods for weather forecasting and to enable the forecasting of the power output of wind energy systems to allow for control, especially of grid-connected systems. For a good review and comparison of wind forecasting techniques see Sfetsos [22].

Wind simulation techniques are used to simulate the wind regime for a location and try to replicate the different characteristics of the wind regime, namely the autocorrelation over time and the yearly and daily variations of the resource. The simulations of the wind resource are used for erosion and agriculture models and to simulate wind based renewable energy systems. This section gives an overview of the various wind simulation techniques in the available literature.

A number of papers present information regarding the stochastic modelling of hourly wind speed sequences. Most of these papers present some form of an Auto-regressive Moving Average (ARMA) model. These models are used to include the autocorrelation of the wind sequences. However, they are inherently based on normally distributed statistical sequences. Wind, which is not a normally distributed sequence, is therefore not necessarily best modelled using an ARMA model.

Daniel and Chen use an ARMA approach to model wind speed sequences by transforming the data from a Weibull distribution to a nearly gaussian distribution by finding a Weibull shape factor near 3.6 [129]. Billington et al. [130] use both a simple autoregressive model and a combined ARMA model for wind speed and report reasonable results. Nfaoui et al. [131] describe using ARMA models and employ the same transformation Daniel and Chen employ. Balouktsis et al. [132] transform the Weibull data by subtracting the mean and dividing by the standard deviation in an attempt to create a normally distributed sequence. Castino et al. [133] use a Markov Chain Method, which is closely related to the ARMA processes. However, their results do not indicate significant improvement over the regular ARMA models. As was mentioned above, a true ARMA process can only produce normally distributed data, which causes some concerns since the wind resource is not normally distributed, but follows a Weibull distribution.

Skidmore and Tatarko [134] use a different methodology. Their model uses a table lookup, where the daily wind speed is looked up in a table of wind speed probabilities for both direction and speed. The hourly wind speed is then calculated using a cosine function with a random perturbation to model the daily variation of the wind.

In 1981, Chou and Corotis [128] used a modified ARMA type process to model the wind speed sequences for an array of wind turbines. Their model was critiqued by Nfaoui et al. [131] as not having covered enough varied locations and by Billington et al. [130] as not taking into account the high autocorrelation of wind speed sequences. However, the model presented by Chou and Corotis can, by changing the lag-one autocorrelation, change the amount of autocorrelation of the wind speed sequences. The critique on the number of locations is really a function of not having tested the model for various locations, and is not, necessarily, an indication of the appropriateness of the model to a specific location. Overall, in the available literature, no model presented has shown significant advantages over Chou and Corotis's work.

6.2. Chou Wind Model

As stated above, the Chou and Corotis model [128] was the most appropriate for simulating the wind regime. This section, based on their work, gives details of the model as implemented.

The Chou and Corotis model takes into account the first order autocorrelation of the wind regime by using a modified ARMA type process, where the mean and the variance are re-calculated based on the previous values and are therefore auto-regressed. The actual values of the wind resource are determined using a Weibull distribution given this modified mean and variance.

The Weibull distribution, as shown in equation (37), provides the basis for the Chou and Corotis model. This distribution, with parameters K and c, the shape and scale parameters, respectively, has a mean and variance as given by equations (38) and (39). Γ represents the gamma function, given in equation (40).

$$f_v(v) = \left(K/c\right)\left(v/c\right)^{K-1} \exp\left[-\left(v/c\right)^K\right] \tag{37}$$

$$m_v = c\Gamma\left(1 + 1/K\right) \tag{38}$$

$$\sigma_v^2 = c^2\left\{\Gamma\left(1 + 2/K\right) - \left[\Gamma\left(1 + 1/K\right)\right]^2\right\} \tag{39}$$

$$\Gamma(\alpha) = \int_0^\infty x^{\alpha-1} e^{-x} dx \tag{40}$$

There is no closed-form inverse to the gamma function. It is therefore necessary, if one has a given mean and variance, to calculate the shape and scale parameters by numerically solving equations (38) and (39). The model uses this approach for each hour of each year, once a modified mean and variance are calculated based on the previous hour's value.

The initial mean and variance for the equations shown above are the day-hour mean for the month being modelled. To adjust the mean and variance, Chou and Corotis proposed the modification to the mean and variance as shown in equations (41) and (42) for the mean and (43) and (44) for the variance.

$$E[v_i] = m_i \tag{41}$$

$$\begin{aligned} E[v_i | v_{i-1}] &= (1-\rho)m_i + \rho\left(m_i + (m_{i-1} - v_{i-1})\frac{\sigma_i}{\sigma_{i-1}} \right) \\ &= m_i + \rho(m_{i-1} - v_{i-1})\frac{\sigma_i}{\sigma_{i-1}} \end{aligned} \tag{42}$$

$$V[v_i] = \sigma_i \tag{43}$$

$$V[v_i | v_{i-1}] = (1-\rho^2)\sigma_i \tag{44}$$

To run the model, the first hour of the year is calculated without any assumption of a previous value, given the mean and variance for that hour of the day and that month of the year. Each subsequent hour calculated for the rest of the year is then obtained by looking up the day-hour mean for the hour and month in question and using the adjustments given in the above equations for the calculation of new shape and scale parameters. The Weibull distribution is then used, with a random number, to determine the wind speed for that hour.

6.3. Wind Height Adjustment

Cermak [46] discusses that the installation height of the wind turbine has a large effect on the energy available from the system. The adjustment of the wind profile for height can be taken into account by using a height adjustment equation such as that proposed by Kellogg [28] and by Elliot [135] as shown in equation (45). In this equation, S represents the wind speed and H represents the height. The subscript 0 indicates the original height and wind speed and the non-subscripted variables represent the adjusted values.

$$\frac{S}{S_0} = \left(\frac{H}{H_0}\right)^{\alpha} \tag{45}$$

Kellogg describes alpha as a measure of surface friction and uses a value of 0.13 while Elliot uses a value of 1/7 (~0.14). The value of 1/7 seems to be the more realistic value, since in most locations where we want to install small-scale or village systems, there will be obstructions around such as buildings, etc.

6.4. Wind Energy Technologies

The installed capacity of wind energy systems has increased greatly over the last decade, with the installed capacity nearly doubling every three years [136] and the total increase between 1990 and 2000 being over five-fold [137]. This large increase in wind energy installations and systems has allowed wind energy extraction to become a mature technology. This section gives a brief overview of wind turbine technology, outlines the wind turbine model used for this study and gives a listing of some typical wind turbines for convenient reference.

Two main categories of wind turbines are possible, vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT). Most modern systems are horizontal axis systems since in this configuration the total area swept by the blades, compared to the actual blade area, is greater, creating a more solid turbine. This configuration can also be mounted on a tower, thereby putting the turbine in a higher speed wind regime [137]. Since the only commercially available wind turbines are HAWT, only this technology will be considered.

The towers that wind turbines are placed upon are generally one to one and a half the rotor diameter [137]. This means that, for a 50 m diameter rotor, the tower would generally be between 50 and 75 m high. The orientation of the turbine to the tower is also a variable, with most manufacturers opting for the rotor to be ahead of the tower to reduce the effect of the tower wind shadow. However, this configuration does require extra complexity to control the yaw of the wind turbine [137].

As well as the basic turbine designs, a number of different ideas have been considered to increase the output of wind turbines at specified wind speeds. For example, Bolcich [138] described the ducting of a wind turbine with a conical duct and found that this could be economically used to increase the output of the turbine. Weisbrich et al. [139] have developed an offshore wind power system that uses a variable diameter tower system with the turbine located at the high wind locations around this tower. They found that this system produced wind speeds in the vicinity of the turbine of up to 1.8 times the free stream wind speed. Although these technologies are interesting for the increase of the turbine output, they also increase the area the turbine system occupies and are therefore more of an economical than a technical or environmental advantage. As well, the turbine characteristics can still be modelled in the manner described below without any loss of accuracy.

To model wind turbines, a simple turbine model was used. This model matches the actual output of most wind turbines quite closely and, since we want to be able to evaluate a number of different possible system configurations with the model, the slight loss of accuracy is more than made up for by the increase of flexibility. Once a specific system is decided upon, the turbine model can always be adjusted to match the specific turbine in question.

Chou and Corotis [128] model the power output of a wind turbine with equation (46). A, B, and C in this model are given by equations (47) through (49) where v_{ci} is the turbine cut-in speed, v_{co} is the turbine cut-out speed and R the rated power at v_r, the rated wind speed. To obtain these equations, a third boundary condition is imposed at v_m, the median wind speed given by equation (50). At this wind speed, the output power of the turbine is taken as $R(v_m/v_r)^3$.

$$P(v) = \begin{cases} 0 & v \le v_{ci} \\ A + Bv + Cv^2 & v_{ci} < v \le v_r \\ R & v_r < v \le v_{co} \\ 0 & v_{co} < v \end{cases} \tag{46}$$

$$B = R\frac{\left(\frac{v_m}{v_r}\right)^3 \left(v_r^2 - v_{ci}^2\right) - \left(v_m^2 - v_{ci}^2\right)}{\left(v_r - v_{ci}\right)\left(v_r - v_m\right)\left(v_m - v_{ci}\right)} \tag{47}$$

$$C = \frac{R - B\left(v_r - v_{ci}\right)}{\left(v_r^2 - v_{ci}^2\right)} \tag{48}$$

$$A = -Bv_{ci} - Cv_{ci}^2 \quad (49)$$

$$v_m = (v_{ci} + v_r)/2 \quad (50)$$

Using these equations, the power output of a turbine can be modelled if the cut-in wind speed, cutout wind speed, the rated power and the rated with speed are known. Table 5 lists a number of commercially available wind turbines and the appropriate parameters to simulate each of these turbines with the model given above.

Turbine Manufacturer and Model	Turbine Diameter (m)	Rated Power (kW)	Rated Wind (m/s)	Cut-in Wind (m/s)	Cut-out Wind (m/s)	Source
Enron Wind 750i (50 m)	50	750	11.2	3.0	29.0	[140]
Enron Wind 900 (57 m)	57	900	14.0	3.7	25.0	[140]
Enron Wind 1.5 (77 m)	77	1500	11.8	3.1	20.0	[140]
Synergy Power Corporation S3000	2.7	0.325	4.5	2.0	9.0*	[141]
Synergy Power Corporation S20000	5.8	3	9.7	2.6	19.4*	[141]
Synergy Power Corporation SLG	13.2	30	11	3.5	14	[141]
Wind Turbine Industries 20kW Jacobs (29-20)	8.8	20	25.5	6	31	[142]
Wind Turbine Industries 10kW Jacobs (23-10)	7.0	10	25	5	30	[142]
Wind Turbine Industries 17.5kW Jacobs (26-17.5)	7.9	17.5	27	5	30	[142]
Bergey WindPower Excel	7	10	13.9	3.5	16.1	[143]

* Not given by source and estimated at twice the rated wind speed.

Table 5: Characteristics of Commercially Available Wind Turbines

6.5. Conclusions

This chapter reviewed the different wind simulation techniques published in the literature and found that the Chou and Corotis model was the most appropriate model. This model requires only the day-hour averages of the wind speed for each month of the year, as discussed for Race Rocks in section 8.3. The necessity of adjusting the resource for the height at which a turbine is installed was discussed and methods were presented. Wind energy technologies were found to be commercially available in a number of different configurations and the parameters for these systems were identified for use in modelling wind energy.

7. Load Modelling

The determination of load models is the last step in defining our energy system model, as described in section 2.4. This chapter reviews some load combination rules, the most common method of simulating load sequences. It is found that these rules, in general, are quite difficult to apply. The modelling of load sequences based on gathered data is therefore presented. Typical load profiles for coastal British Columbia are also included so that the model can be used for the evaluation of systems for a larger context than just Race Rocks.

7.1. Load Combination Rules

Load combination rules are used when the combined load for a system is not known, but the components of the load are well known. For example, the combination of a number of households into a typical load can be performed with these rules. This section presents a brief overview of some common load combination rules and discusses why they cannot be applied to Race Rocks.

L. Pham [144] discusses two different load combination rules: Turkstra's rule and the peak-load-factor method. Turkstra's rule states that the peak-combined load can be taken as the peak of one load and an arbitrary point-in-time value of the other loads. This is shown in equation (51) where Y is the combined load and X is the set of component loads. The ^ indicates the peak load.

$$\hat{Y} = \max_{k=1}^{n} \left\{ \hat{X}_k + \sum_{\substack{i=1 \\ i \neq k}}^{n} X_i \right\} \tag{51}$$

The peak-load-factor method is somewhat more complex as it takes into account the correlation between the loads to a certain degree. Pham discusses that both methods work well for Poisson load processes, which are by definition random, but notes that, when using actual loads from buildings, that the peak-load-factor method seems to work better since it can take into account the correlation between loads [144].

Since load combination rules require an accurate knowledge of the load cycles of each load on a system, it is difficult to implement such rules for a site with a large multitude of different loads which each have different cycles. Although obtaining this knowledge is theoretically possible, the actual gathering of this information is exceedingly difficult due to the requirement of measuring each device's power draw and characterizing each load.

7.2. Model Developed

As discussed above, the use of load combination rules becomes very difficult to apply to a site such as Race Rocks. Therefore, to obtain an accurate model for the loads on the Race Rocks site, a Power Measurement ION 8330 power meter was installed. This meter gathered data for a four-month period between March and July 2001. This data was used to develop a stochastic load model for the site.

From an examination of a the time series plot of the gathered data in Figure 8, it can be seen that there does not seem to be any long-term trend which would indicate a yearly cycle for the loads.

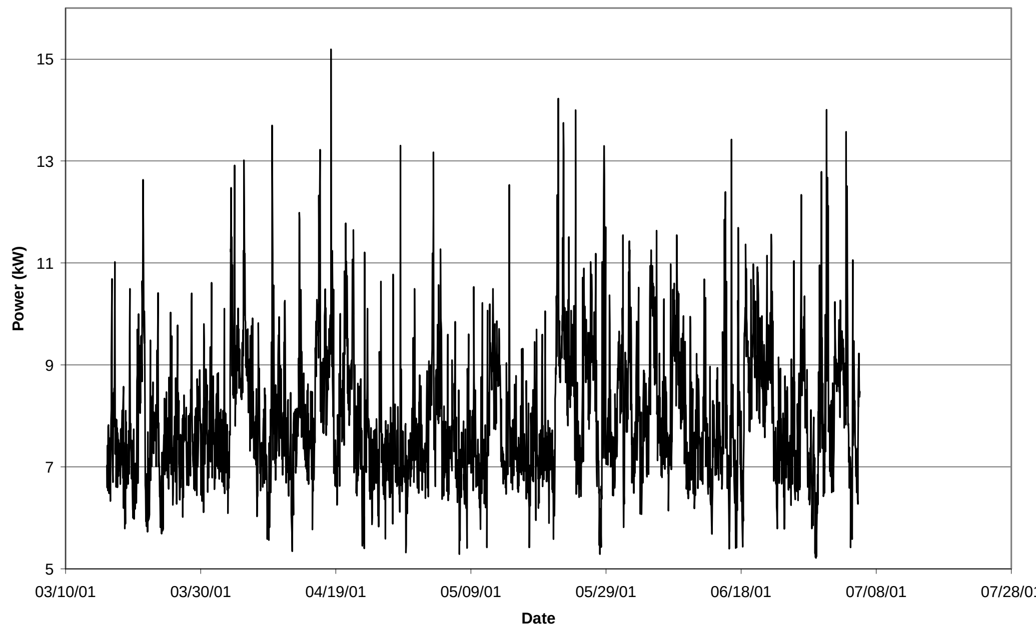

Figure 8: Race Rocks One-Hour Average Loads

There seem to be two distinct levels of load. To try to get an idea of the manner in which the loads vary between these two levels, a running average was used to determine when the load should be considered as a high-load period or a low-load period. The running average for a 12-hour and 60-hour periods are shown in Figure 9.

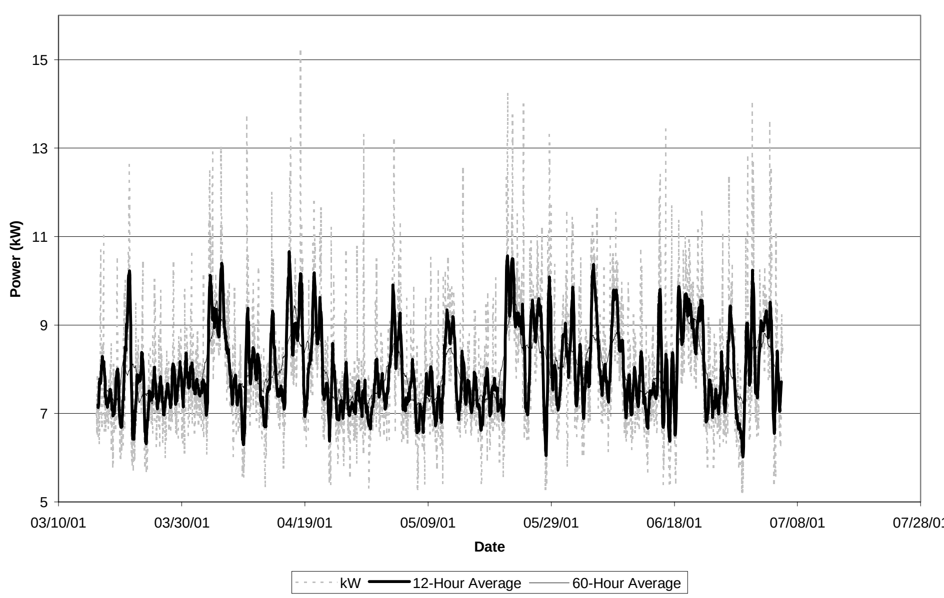

Figure 9: Race Rocks One Hour and 12 and 60 Hour Running Average Loads

From Figure 9 it would appear that the 12-hour averaging gives the most reasonable method of determining if the time period is a high-load or a low-load period. The distribution of the load for both the high and low load periods can be calculated if we define low loads as those where the 12-hour average is lower than the overall average, and high loads when the 12-hour average is above the overall average. Figure 10 shows the distributions of both the low and high loads as calculated from the gathered data.

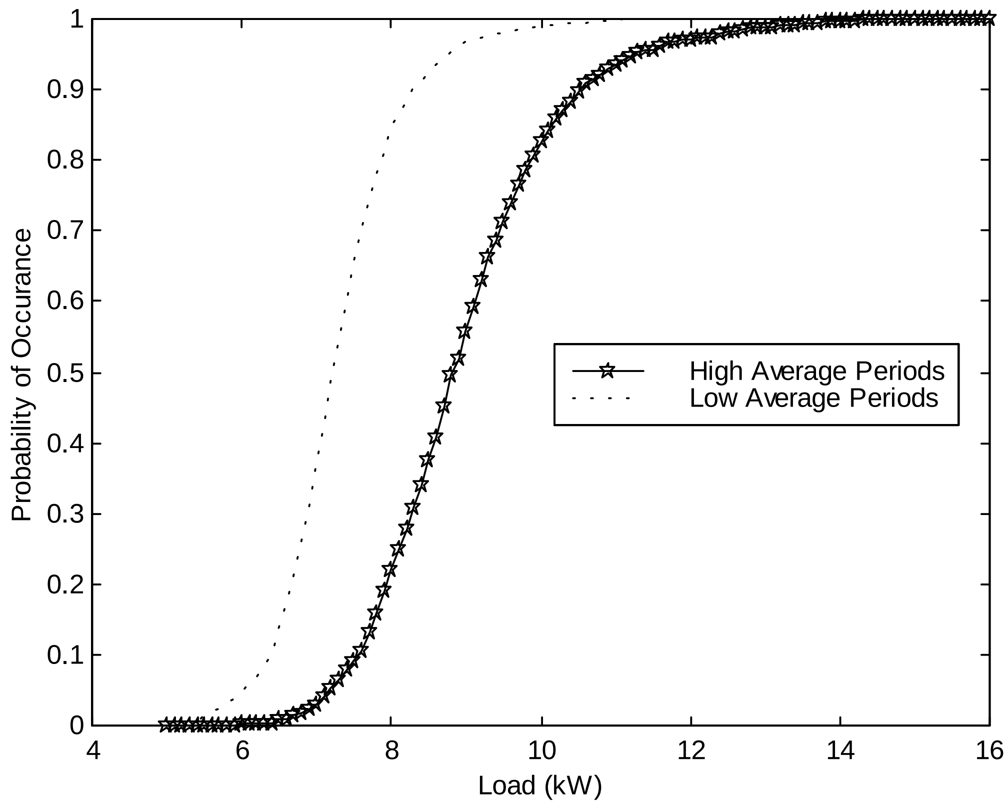

Figure 10: Load Distribution

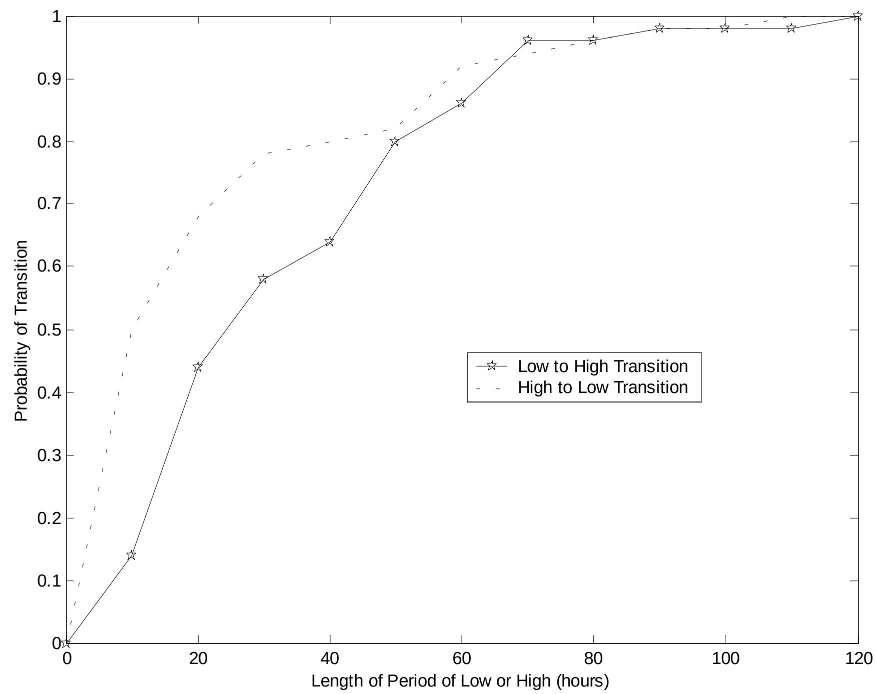

Figure 11: Load Transition Distribution

As well as needing the distribution of the actual loads for each regime, the time the load stays in a particular phase needs to be determined. Figure 11 shows the distributions for the time to transition for the loads.

To be able to model the loads stochastically, an attempt was made to fit various random variable distributions to the load data distribution. Figure 12 shows the residuals for each of the distributions that were considered for modelling the load.

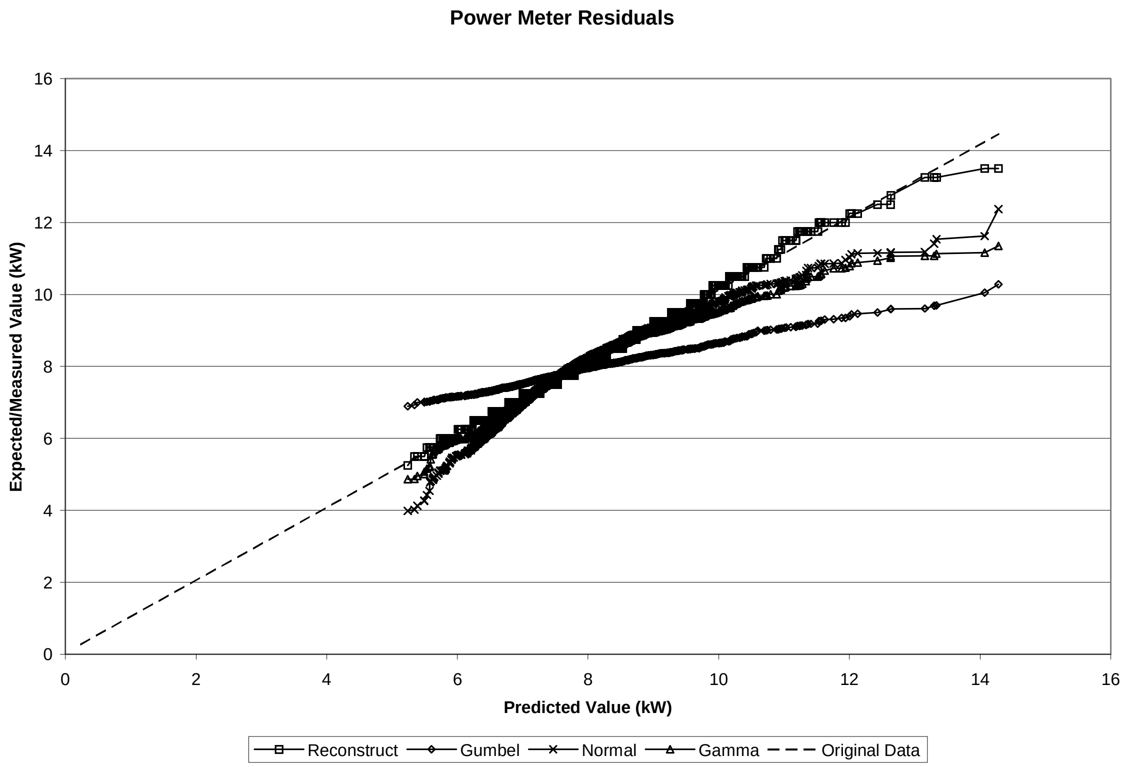

Figure 12: Load Probability Residuals

Figure 12 clearly shows that none of the distributions that were tested to fit the data obtained from the power meter. The only distribution that provides a linear correlation between the gathered data and the actual load is the Gumbel distribution. Given the linear relationship between this distribution and the gathered data, an attempt was made to use a linear transformation to match this correlation with the gathered data. Unfortunately, due to the nature of the distribution, this was found to be impossible.

Since none of the distributions tested in Figure 12 fit the data accurately, the actual distributions as shown in Figure 10 and Figure 11 were used as lookup tables, with a random number generator, to produce a typical year of load data. To obtain the two different load sequences, for high and low load, respectively, the time to transition was also looked up in a similar manner. The low load was then calculated for the number of hours determined from the time to transition, followed by the high load, and repeating until a full year of data was generated.

7.3. BC Hydro Typical Loads

For the purposes of evaluating energy systems for a number of different locations and scenarios, BC Hydro typical load profiles for coastal British Columbia were also include in these models. Plots of the time series for these load sequences are shown in Figure 13 and Figure 14. This can be useful if, say, we want to model 15 electrically heated, and 15 non-electrically heated homes to see how a renewable energy system would perform when providing electricity for a small village.

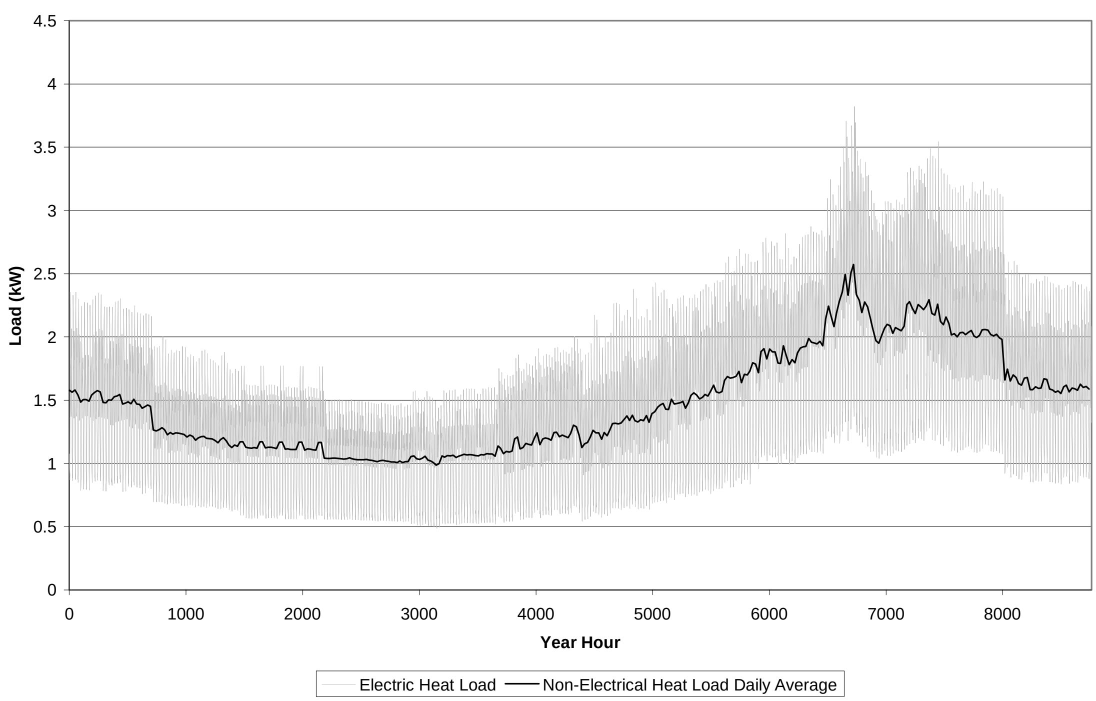

Figure 13: BC Hydro Non-Electrical Heat Typical Household Load Profile

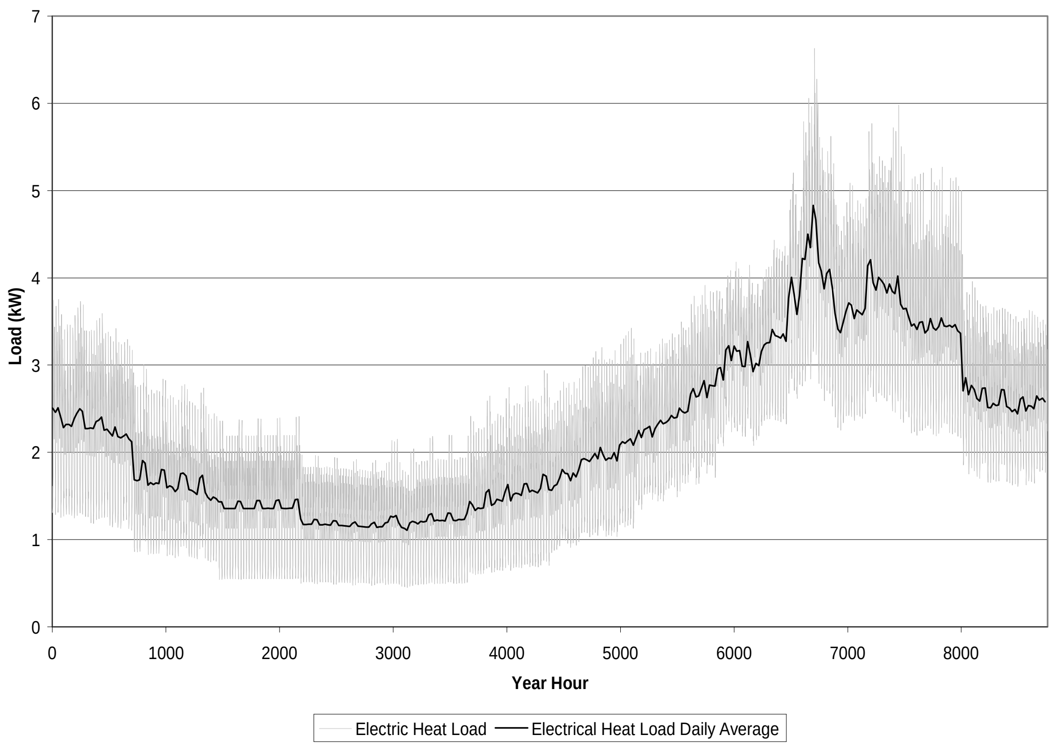

Figure 14: BC Hydro Electrical Heat Typical Household Load Profile

7.4. Conclusions

This chapter began by examining load combination rules for the load at Race Rocks. It was found that, although these rules perform well when each specific load cycle is known, the lack of knowledge about each load at Race Rocks makes it almost impossible to apply these rules. A stochastic model was therefore developed based on gathered data from the site.

BC Hydro typical loads were included in the model to allow for the evaluation of different energy system scenarios for various locations. It would be a simple procedure to include different load sequences into the model to allow for the application of the model to any system.

8. Race Rocks

As mentioned in Chapter 1, the purpose of this project is to evaluate renewable energy for Race Rocks. So far, we have developed the different components of an energy system model and provided the details of each component. This chapter discusses Race Rocks and, in particular, the data required to apply the energy system model to Race Rocks.

Race Rocks is a small archipelago located one mile off of the southern tip of Vancouver Island, in the Juan de Fuca Straight. Being home to seals and sea lions, as well as a nesting site for many migratory sea birds, it has been protected as a Marine Protected Area (MPA) and an ecological reserve. The main island, named Great Race Rock, is approximately 100 by 100 meters and is home to the two custodians. As well as being an interesting location in terms of the flora and fauna, Race Rocks is also a major navigational beacon, containing an important lighthouse for shipping to and from the ports of Vancouver and Seattle. Pearson College uses Race Rocks as a research station to enable their students to be exposed to a multitude of different ecosystems. As has already been discussed, Race Rocks has huge tidal flows (up to 4 m/s), a large wind resource (average winds of 21.6 km/h) and is considered one of the sunniest sites in Canada. Overall, Race Rocks is an exciting location for renewable energy.

The application of the energy system model developed in this thesis to Race Rocks, and the required parameters for the model are discussed in the remainder of this chapter.

8.1. Solar Resource

To apply the Knight et al. solar insolation model to a particular site, we need to determine two items. First, we need to determine the average daily clearness index for each month, $\overline{K}_t$, and then we need to determine if the K_t distributions presented by Knight et al. apply for the location in question.

To obtain $\overline{K}_t$ data for each month of the year, a CWEC data file was obtained from Environment Canada for Victoria International Airport [55] and a TMY data file was obtained for Quillayute, on the Olympic Peninsula from the US Department of Energy [57]. The average clearness index for each month, as obtained from these files, is shown in Table 6. Since these figures are relatively similar, and vary in a similar manner throughout the year, the figures for Victoria International Airport were used since this site is much closer to Race Rocks than Quillayute.

Month	Victoria Airport, BC	Quillayute, WA	% Above or Below Victoria
January	0.2940	0.3136	6.64
February	0.3648	0.3431	-5.95
March	0.4172	0.3675	-11.91
April	0.4594	0.4162	-9.41
May	0.5397	0.4570	-15.32
June	0.4892	0.4497	-8.09
July	0.5675	0.4733	-16.61
August	0.5826	0.4502	-22.73
September	0.5143	0.4626	-10.05
October	0.3987	0.4161	4.38
November	0.3476	0.3301	-5.05
December	0.2862	0.3599	25.76

Table 6: Average Montly K_t for Victoria International Airport and Quillayute

As well as determining the average clearness index applicable for Race Rocks, we need to evaluate the K_t distributions as given by Knight et al. and compare these to the actual distributions for the location. Figure 15 shows this comparison for four months of the year.

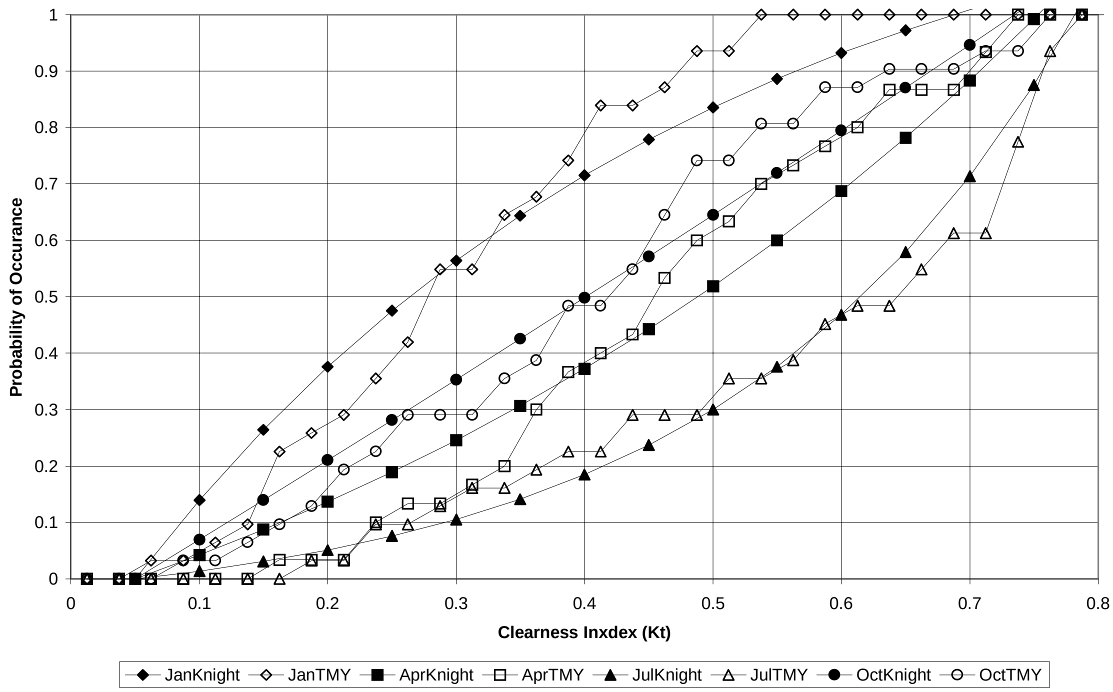

Figure 15: K_t, Daily Clearness Index Distribution Function

The statistical distribution used by Knight et al. do not differ significantly from the values for Victoria International Airport, close to Race Rocks. Therefore the distributions given by Knight et al. can be used since these are based on larger data sets and will therefore provide more realistic results.

Once we have applied the solar insolation model, the only other parameter required for the evaluation of solar energy for Race Rocks is the albedo in the vicinity of the collectors. Since the collectors will be installed on the main island, which is surrounded entirely by water, the abledo for water, as given by Iqbal in his book “Solar Resources” as 0.05, was used [145].

8.2. Tidal Resource

From the discussion in section 5.1, we know that we need to obtain the harmonic constituents of the tidal currents around Race Rocks for the prediction of these currents. Using data obtained from the Institute for Ocean Sciences for the flows in the passage between Great Race Rock and West Race Rock [146], the harmonic components of the tidal flow in this area were calculated. These components of the tidal stream can be used with the prediction program from Woods Hole to produce any arbitrary year of tidal flows. Both the East-West and North-South components were obtained separately and can be found in Appendix A.

To generalize the flows obtained from the current meter at Race Rocks, which was installed in the channel between Great Race Rock and West Race Rock, a tidal stream model developed by Crawford and Henry was used [147]. This model consists of a computational fluid dynamics grid for the area around Race Rocks and allows for the calculation of the relative currents around this area. Figure 16 shows the results of this model for the M2 component of the tidal stream. From this result, we can determine an appropriate multiplication factor for the tidal stream calculated, if we know the current meter was installed in a certain location. The Race Rocks current meter was installed between Great Race Rock and West Race Rock, with an M2 root mean squared value of 0.65 m/s.

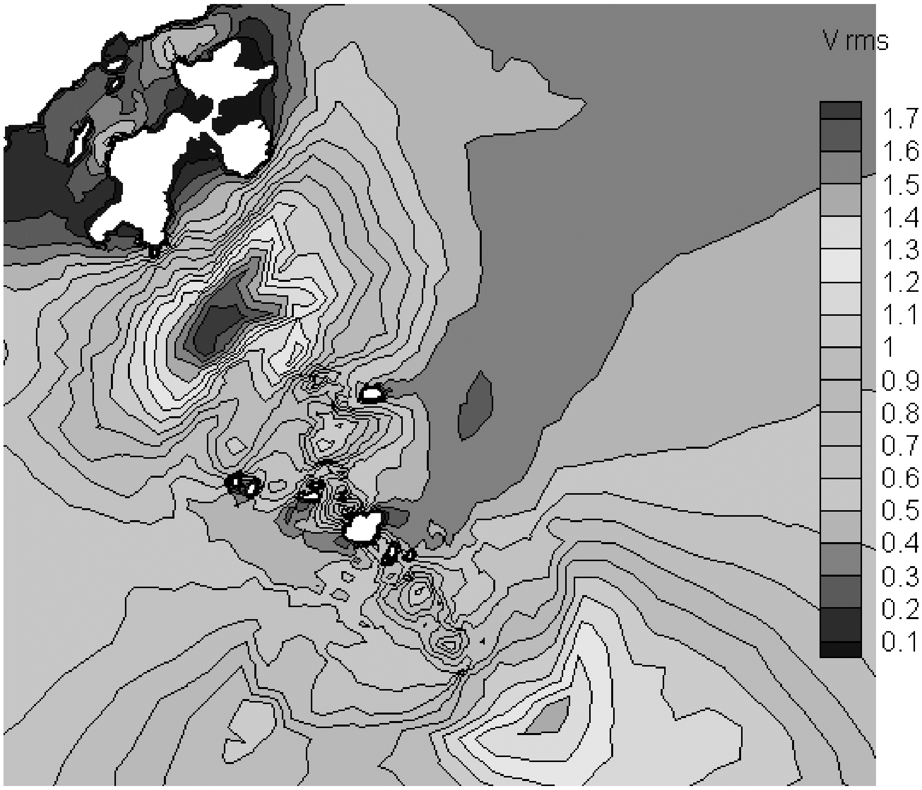

Figure 16: M2 RMS Tidal Component Flows Around Race Rocks [147]

Using this multiplication factor, we can easily see the effect of moving the system from the location of the current meter, between Great and West Race Rock, to a location with a different flow regime, and decide if the extra cost of laying a wire out to other locations is paid back by the greater amounts of energy produced.

8.3. Wind Resource

The Chou and Corotis [128] wind model, as discussed in section 6.2, requires the day-hour means for each month of the year. To calculate these values, five years of weather data were obtained from Environment Canada [148]. From this data, the day-hour means for each hour of the day for each month were calculated as shown in Figure 17.

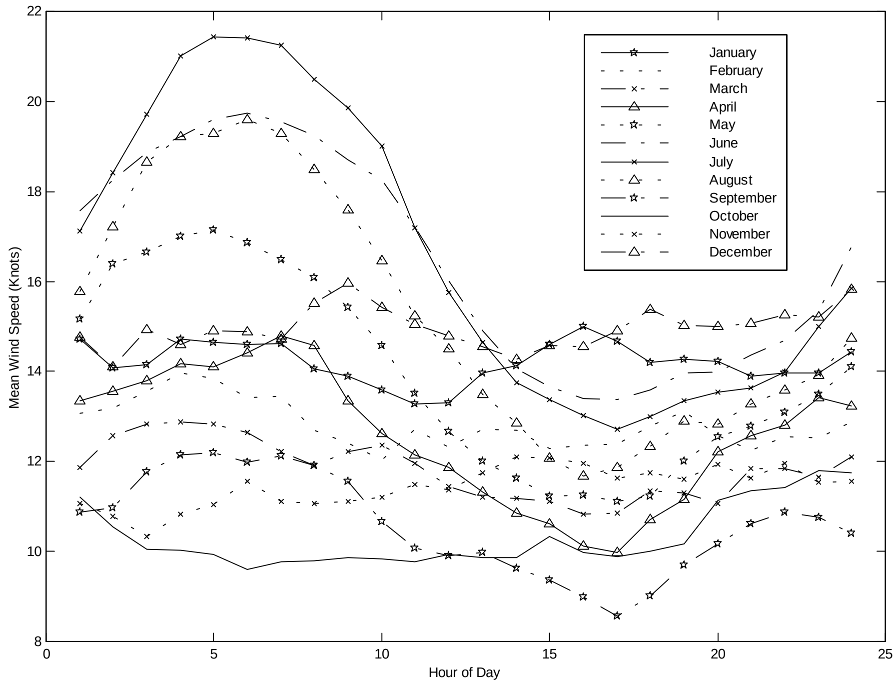

Figure 17: Monthly Day-Hour Wind Means for Race Rocks

As well as requiring this data, the wind height adjustment, as given by Elliott [135], requires the height of the wind meter. At Race Rocks, the wind meter is 25m above the ground surface [148].

8.4. Conclusions

This chapter has identified the various parameters required to apply the energy system model to Race Rocks. The average daily clearness index for each month was obtained from TMY data for Victoria International Airport, the closest location to Race Rocks for which data was available. The tidal constituents were obtained from data supplied by the Institute for Ocean Sciences and the day-hour mean wind speeds for each month were obtained from data obtained from Environment Canada. All the components are now in place to evaluate energy systems for Race Rocks.

9. Numerical Methods

This chapter provides details on the energy system model, how it was implemented, and also the numerical methods used to determine if system designs were appropriate.

9.1. Energy System Model

The energy system model was coded in Matlab 6.0, though it has been used interchangeably between Matlab 6.0 and 5.2. The random number generators within Matlab were used for any random number required and the random seed for these generators was re-set at the beginning of each resource model. This ensured that the resources were not dependant even if they were calculated in the same order at different times.

The model, as implemented in Matlab, used command line options to determine the system configuration. The first parameter for the model is used to determine if we need to reseed the random number generators or use a sample year that was previously generated. After this a number of variable length command line options allow for the configuration of an infinite number of different systems. Commas separate the options, and their parameters. Table 7 details the command line options, and the parameters required for each option.

Command Line Option	Parameters Required
'load'	Type – 1- Race Rocks; 2- Typical Non-Electrical Heat Load; 3- Typical Electrical Heat Load Multiplier – Multiplication factor for the load Base – Base load to add to the load sequence (kW)
'solar'	Size – Number of square metres of solar panels (m^2) Tilt – The tilt of the panel from the horizontal (degrees) Swivel – the swivel of the panel from south (degrees) Efficiency – The efficiency of the panel (0-1.0) Panel Rating – The peak power available from the panel (kW)
'tidal'	# units – the number of turbine units Cut-in flow – the flow rate the turbine starts to produce power (m/s) Cut-out flow – the flow rate at which the turbine shuts off to avoid damage (m/s) Rated Power – The peak power available from the turbine (kW) Rated flow – The flow rate at which we obtain the rate power (m/s) Multiplier – The flow rate multiplier
'wind'	# units – the number of turbine units Cut-in flow – the flow rate the turbine starts to produce power (m/s) Cut-out flow – the flow rate at which the turbine shuts off to avoid damage (m/s) Rated Power – The peak power available from the turbine (kW) Rated flow – The flow rate at which we obtain the rate power (m/s) Height – The hub height of the turbine (m)
'storage'	Input efficiency – The efficiency of the input technology (0-1.0) Input Rating – The maximum power into the storage system (kW) Size – The maximum storage size for the system (kWh) Output Efficiency – The efficiency of the output technology (0-1.0) Output Rating – The maximum power available from the installed technology (kW) Loss – the percentage of storage that is lost each hour Starting Level – the storage level that the system starts at. (kWh)

Table 7: Energy System Model Parameters

As mentioned above, the first command line option determines if we are to load a sample year from a file, or re-generate the resources for this run of the model. This option is used to enable the comparison of different technology configurations given a single resource year. In many cases, we want to evaluate the effect of a specified system parameter, but this cannot be done if the resource is also varying. The effect of the resource variance may obscure the effect of the parameter being studied.

Each of the other command line options enables the configuration of each resource conversion technology to the fullest extent possible. The actual system parameters for each resource model are stored in a file for each resource, which can easily be replaced if a different resource location is chosen.

Overall, there are 27 different parameters that need to be specified to run the energy system model, depending on the specific system being modelled and not including the parameters required for the resource models. This causes some concern over the ability to accurately define each parameter and to evaluate the effect each parameter has on the overall system. This number of parameters, however, is the simplest that could be modelled without losing significant detail on the overall configuration of the system.

9.2. System Optimizations

Although the energy system model, as discussed above, provides the opportunity to create any number of different energy systems, we need to be able to set some criteria to determine if a given system is appropriate for running the site. For Race Rocks, this criterion was set at having no more than 24 brownout hours each year. This allows for some outages, but ensures that, for most of the year, the systems will run smoothly. At least one brownout hour each year was required to ensure that we did not over-design our systems. The number of brownout hours is calculated by determining the number of hours the final energy balance goes below zero within a full year.

Although these criteria can be used to determine if a given system should be considered workable for Race Rocks, they do not allow for the optimization of systems. To enable the optimization of systems, a simple binary search algorithm was implemented. This algorithm, though it is slower than other numerical algorithms, is guaranteed to converge and also does not require us to differentiate the function being evaluated. Since the energy system model is a complex function, without the possibility of differentiation, we are restricted to simple numerical methods and the binary search method seems to be the best overall choice.

The process of implementing a binary search is simple. We first define both an upper and lower bound, and calculate the function at the middle point, namely (upper+lower)/2. If this value is higher than we require, we move the upper bound to the middle point, and re-run the system. If the value is lower, we move the lower bound, and again re-run the system. This loop is performed until we either reach the maximum number of iterations (we could not converge), or we have found a system that runs within the specified criteria. The only time a binary search does not converge is if the root of the equation is outside the original bounds. For this reason, one should consider results that are close to the bounds chosen as un-converged, and re-run the system with different bounds.

With the ability to optimize systems for a variety of parameters, we have a powerful tool for evaluating renewable energy systems.

10. Results

The development of a truly generic energy system model, that is not restricted to modelling only one technology or system, is a valuable contribution to the field of renewable energy systems modelling. As well, the integration of a number of different resources into a single model allows for the comparison of these resources and their potential contribution to an energy system.

This chapter details the results obtained using the energy system model. First, a number of simple energy system designs for Race Rocks are created. These are compared with the power balance approach described by Kellogg et al. Using these simple energy system designs, and looking at the yearly storage time-series of the different resources, we can design combined systems.

Once these designs were obtained, it was noticed that there are large variations in both the wind and the solar resource performance between multiple years. To get an idea of the performance of these systems over multiple years, each system was run for 100 years and histograms of the number of brownouts were obtained. From these histograms, a number of interesting features can be observed.

To evaluate the effect of storage efficiency on storage size, a parameter evaluation was performed. This parameter evaluation illustrated some interesting points about the relationship between storage size and storage efficiency, which have not been obtained with any other model.

10.1. General System Designs

This section provides details on a number of different systems that can be used to power Race Rocks. We will first design systems using the energy system model described in this thesis and then compare this with the power balance models, as discussed in section 2.3.1. The possibility of using our model to create combination systems, operating with both solar and wind power is also investigated.

10.1.1. Energy System Model

A number of different energy systems were designed by specifying the storage size and optimizing the size of the resource extraction technology as discussed in section 9.2. The storage sizes, specified arbitrarily as 2, 5, 14 and 30-day periods, corresponding to 384, 960, 2688 and 5760 kWh of storage, respectively, for an average 8kW load (8kW multiplied by 24 hours gives 192 kWh of storage per day required). Three different systems were chosen to perform the optimizations: a wind system employing Bergey Excel Turbines installed at a 25 m height above the ground, a tidal system employing Darrieus turbines as described by Kiho et al. in the stream at the location of the flow sensor used by IOS (a flow multiplication factor of 1) and a solar system using Siemens SP-75 Cells placed in a horizontal configuration on the ground. The storage system was modelled as an electrolyser-fuel cell system with input efficiency of 0.75 and output efficiency of 0.45 and no storage loss over time. The optimizations were performed for five different sample years to obtain a more accurate estimate of the actual installed capacity required.

Table 8 shows the results of these optimizations for each sample year. The kilowatt rating of installed capacity is shown for each sample year, and any years that did not converge to between 1 and 24 brownout hours are shown as a –. These systems could not, with up to 10 MW of installed capacity, power the load required.

System Installed	Storage Size (kWh)	Sample year installed capacity (kW)					Average Installed capacity (kW)
		Year 1	Year 2	Year 3	Year 4	Year 5	
Solar Panel (Siemens SP-75 Cells)	384	2286	2360	1770	1770	2065	2050
	960	1180	1180	590	885	885	944
	2688	479	479	479	479	442	472
	5760	350	303	368	387	350	352
Wind System (Bergey Excel Turbines)	384	–	–	–	–	–	–
	960	–	5000	5000	5000	–	6999
	2688	937	156	234	175	468	395
	5760	122	112	127	95	166	125
Tidal System (Kiho et al. Darrieus Turbines)	384	71.9	71.9	71.9	89.8	71.9	75.5
	960	44.9	44.9	40.4	44.9	44.9	44.0
	2688	35.4	35.4	34.8	35.9	35.4	35.4
	5760	33.4	33.3	32.4	32.8	33.0	33.0

Table 8: Energy System Designs

From this table a number of interesting items are immediately apparent. First, the installed capacity required for tidal energy systems, in all cases, is significantly smaller than the capacity required for either the wind or solar energy systems. This can be attributed to the known tidal flow each day as well as the higher overall availability of the tidal flow to produce energy. However, the ratios between the systems, which are orders of magnitude, cannot, entirely, be explained by the availability of the resources, which differ by no more than a factor of two.

It is expected that the time sequences of the resources have a significant impact on the systems required. The time sequence of the tidal resource is known to be available every six hours. Since this is not the case with either wind or solar energy, where we can have multiple days without significant available power, the results obtained corroborate what we would expect from such systems. However, it was not expected that the results would be an order of magnitude or more different. At this point, it appears that tidal energy would be the most appropriate system to install out at Race Rocks.

Another interesting feature of these results is the fact that the installed capacity for the wind system is smaller than that required for solar for high storage size systems, but becomes significantly greater at low levels of storage. This can be explained, at least partially, from an examination of the energy availability curves, as shown in section 2.1.4. The wind availability at low power values is higher than that for solar, implying that low level energy is available from the wind resource on a more regular basis. However, the availability at high powers is greater for the solar resource. This indicates that, with a larger storage system, the chance that we can produce a significant excess of energy to charge the storage system quickly is greater with the wind system for any given period of time. However, with a small storage system, where we rely on the low-level energy to charge our system, the chance that we cannot charge the system is greater for the wind system.

10.1.2. Power Balance Model

To enable a comparison of the energy system model to the simple power balance models described in section 2.3.1, a system was designed for each resource using the power balance model. Table 9 shows the results obtained with the simple power balance for both the storage size and installed capacity required. It should be noted that the ability to vary these two parameters to obtain the most cost-effective system is not possible with power balance models, and therefore only one system was designed for each sample year. We can also not include the possibility of brownout hours in these systems.

System Installed		Sample Year					Mean	Days of Storage
		1	2	3	4	5		
Solar Panel (Siemens SP-75 Cells)	Installed Capacity (kW)	39.0	37.9	37.9	37.7	36.9	37.9	
	Storage Size (kWh)	20419	18988	19055	18738	17704	18981	99
Wind System (Bergey Excel Turbines)	Installed Capacity (kW)	39.6	41.3	36.5	34.1	39.5	38.2	
	Storage Size (kWh)	8583	10224	8644	12053	8510	9602	50
Tidal System (Kiho et al. Darrieus Turbines)	Installed Capacity (kW)	19.0	18.9	18.6	18.7	18.9	18.8	
	Storage Size (kWh)	2107	2190	2576	2397	2228	2299	12

Table 9: Simple Energy Balance System Designs

Table 9 clearly shows that the installed capacities obtained using power balance models are significantly lower than those obtained with our model. As well, the storage sizes, except for the tidal system, are much larger than required for any system designed for Race Rocks using the energy system model. To compare these systems with the results from the energy system model, the systems were run for the five sample years used to design the systems in Table 8. The number of brownout hours for each system is shown in Table 10. From this table, it is obvious that simple power balance models cannot be used to accurately evaluate the performance of renewable energy systems.

System Design (Installed Cap. and Storage Size)	Number of brownouts for each sample year					Average # Brownouts
	Year 1	Year 2	Year 3	Year 4	Year 5	
Solar (37.9 kW, 18981 kWh)	3460	3509	3540	3531	3563	3521
Wind (38.2 kW, 9602 kWh)	3351	3273	3260	3161	3228	3525
Tidal (18.8 kW, 2299 kWh)	3425	3437	3390	3364	3385	3400

Table 10: Number of Brownout Hours for Power Balance Systems

We can conclude that our energy system model is significantly more useful in evaluating energy systems than a simple power balance model. Our system allows for the consideration of the losses in the storage system and the possibility of having systems that are not quite balanced, and therefore significantly smaller.

10.1.3. Combined Systems

If we examine the yearly variation in the storage system, insight into the possible synergies between the different resources can be obtained, possibly allowing for a combined system to be specified. This section examines the yearly variation of the stored energy for the different resources and uses this information to design some combined energy systems. The results show that combined systems have significant potential compared to single resource systems.

Figure 18 and Figure 19 show typical storage balances for the solar and wind systems developed in section 10.1 for a storage size of 5760 kWh. Examining Figure 18, it can be seen that the lowest portion of the solar storage system is in the first 1000 hours of the year. This indicates that there is a significant energy shortage at the cusp of the year and an energy surplus just after year hour 1000. From examination of Figure 19 the lowest storage level for the wind system is between year-hour 7000 and 8000, indicating an energy shortage around year-hour 7000 and an energy surplus around year-hour 8000. If we combined these two systems, we could see that the energy surplus from the solar energy system could be used to compensate for the energy shortage of the wind system and vice-versa. In this way, a smaller, and therefore less expensive system could be designed.

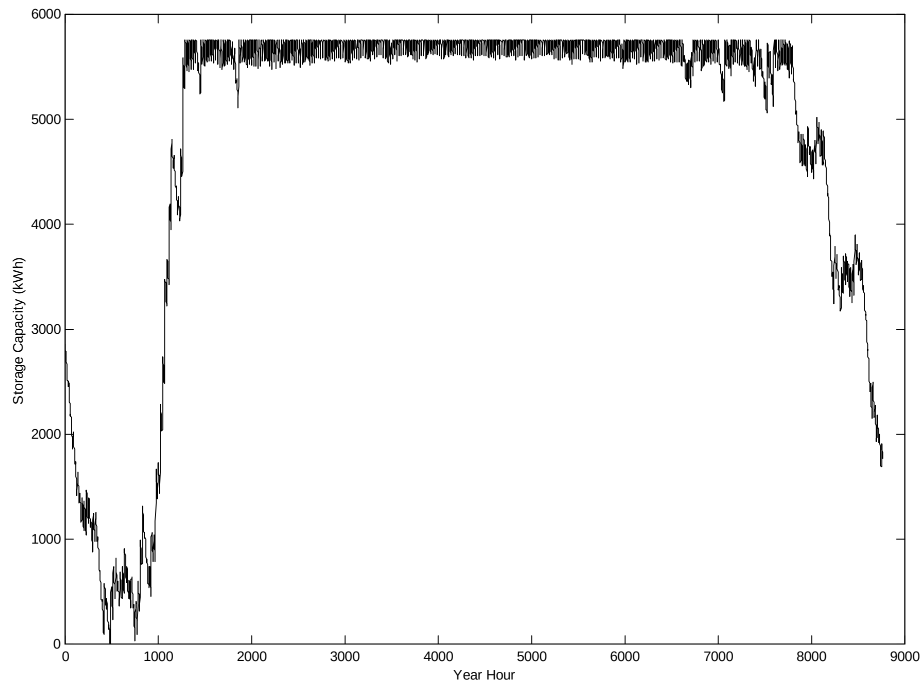

Figure 18: Typical Storage Year for Solar Powered System with 5760 kWh of Storage (Sample Year 1)

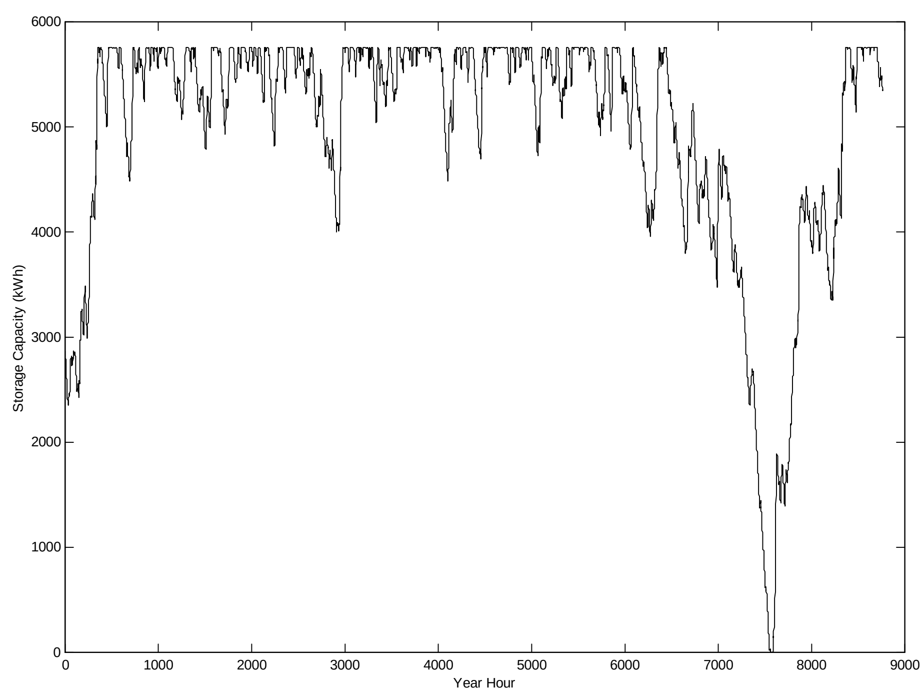

Figure 19: Typical Storage Year for Wind Powered System with 5760 kWh of Storage (Sample Year 3)

Table 11 shows the results of combining the solar and tidal systems for 5760 kWh of storage for each sample year. The storage balance for sample year #1 for this system is shown in Figure 20. In comparison, the installed capacity required for a solar-only system at 5760 kWh of storage was found to be 352 kW, and for the wind-only system was found to be 125 kW. From these results, it can be seen that the combined systems could have significant potential.

Combined System Design	Installed Capacity (kW) for each sample year					Average (kW)
	Year 1	Year 2	Year 3	Year 4	Year 5	
Solar Installed	56.25	63.28	49.80	45.70	48.63	52.73
Wind Installed	56.25	63.28	49.80	45.70	48.63	52.73
Total Installed	112.5	126.6	99.6	91.4	97.3	105.5

Table 11: Installed Capacity for Combined System

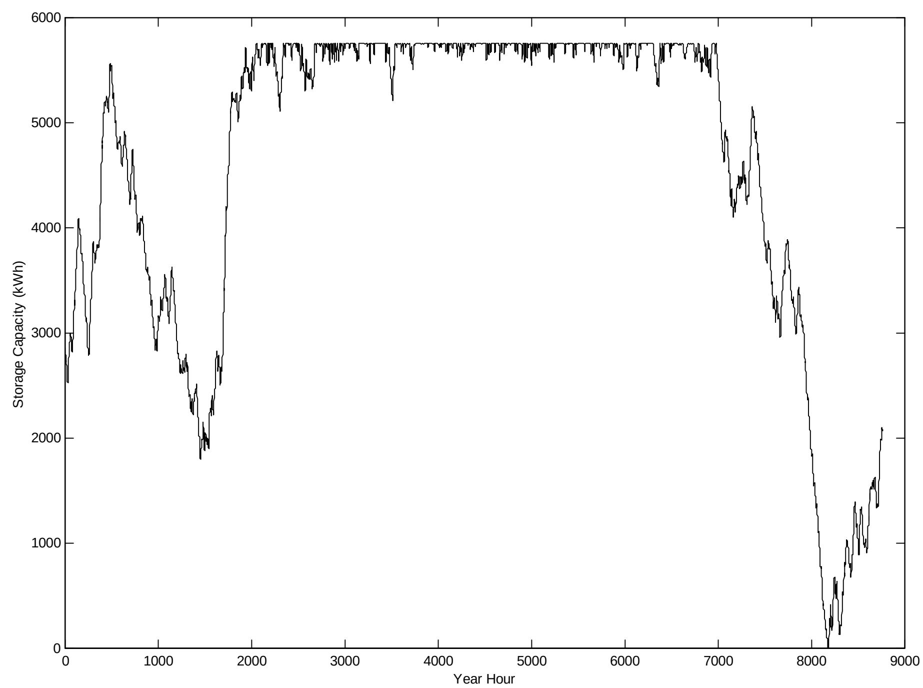

Figure 20: Typical Storage Year for Combined System with 5760 kWh of Storage

The other optimization that was performed with a combined system involved taking half the installed capacity of both the wind and solar system designed. The storage requirement for this system, with 176 kW of solar and 62.5 kW of wind, was then optimized. Figure 21 shows the storage balance for one of these optimizations on the same scale as Figure 18 through Figure 20. Table 12 shows the storage required for each sample year.

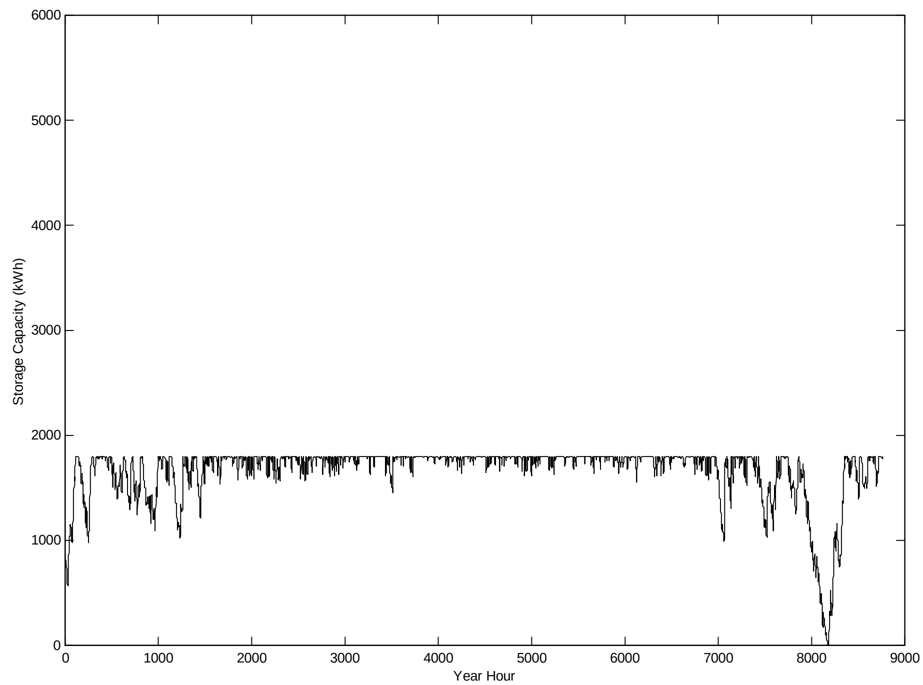

Figure 21: Typical Storage Year for Combined System with Storage Optimized

Storage (kWh) required for each sample year					Average (kWh)
Year 1	Year 2	Year 3	Year 4	Year 5	
1800	2160	1080	1080	720	1368

Table 12: Storage Size for Combined System

Again, from this result, the potential of combined systems is exciting, as the required storage has dropped from 5760 kWh to 1368 kWh.

10.2. Resource Variance

From Table 8 we can see that the installed capacity required for each separate sample year varies. In an attempt to get an understanding of the manner in which the resources vary, and the effect this has on the performance of the system, each system in Table 8 was run for 100 different resource years. Figure 22 through Figure 25 show histograms of the number of brownout hours obtained for each of these 100 years of data for 384, 960, 2688, and 5760 kWh of storage.

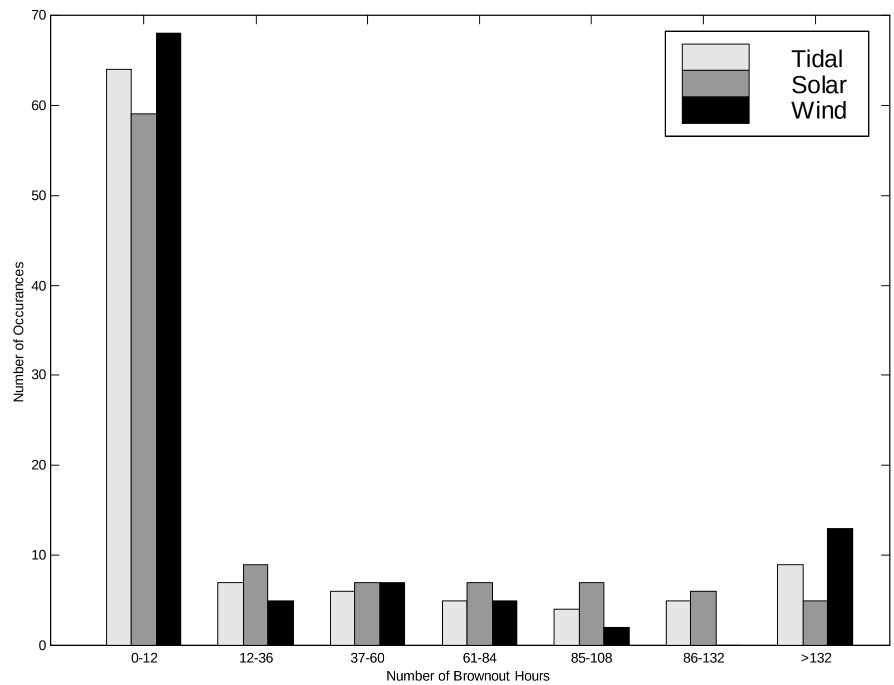

Figure 22: Brownout Hours Histogram for 5760 kWh Storage

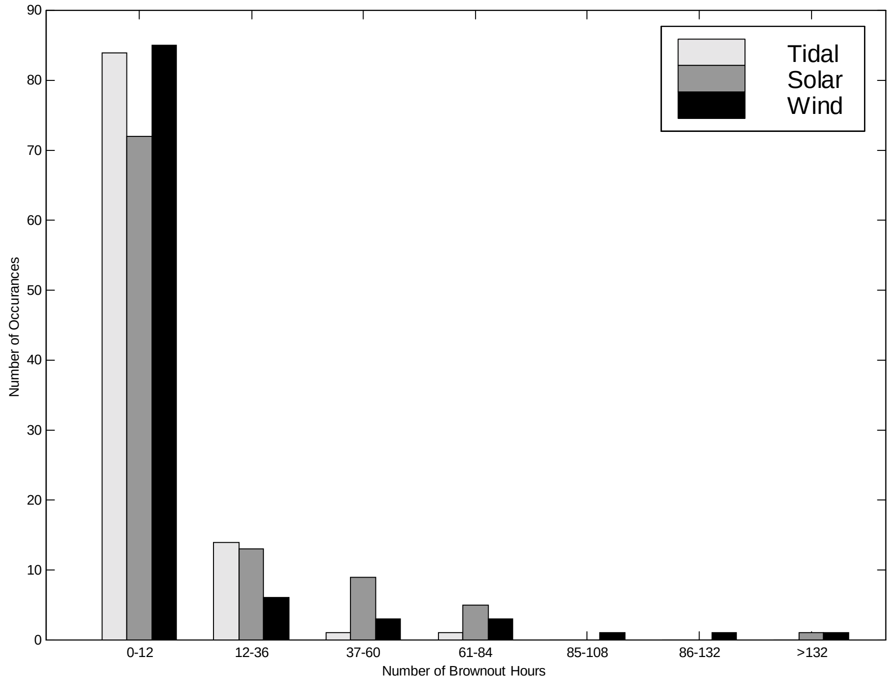

Figure 23: Brownout Hours Histogram for 2688 kWh Storage

Starting with Figure 22, we notice that each of the installed systems provides less than 12 brownout hours 65-70% of the time. As well, each system has a very similar distribution of the number of brownout hours. This implies that each system performs, over the long term, in a similar manner. Moving to Figure 23, we see a similar result with, in this case, tidal dropping off rapidly and solar dropping off much less rapidly. However, the systems still perform adequately, with only solar and wind having a significant number of years with more than 36 brownouts.

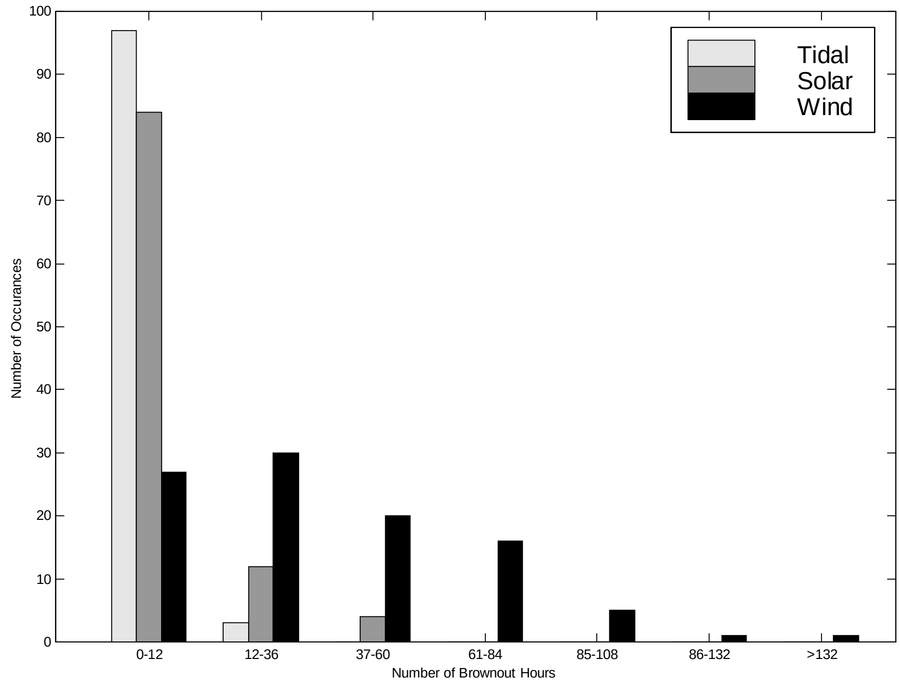

Figure 24: Brownout Hours Histogram for 960 kWh Storage

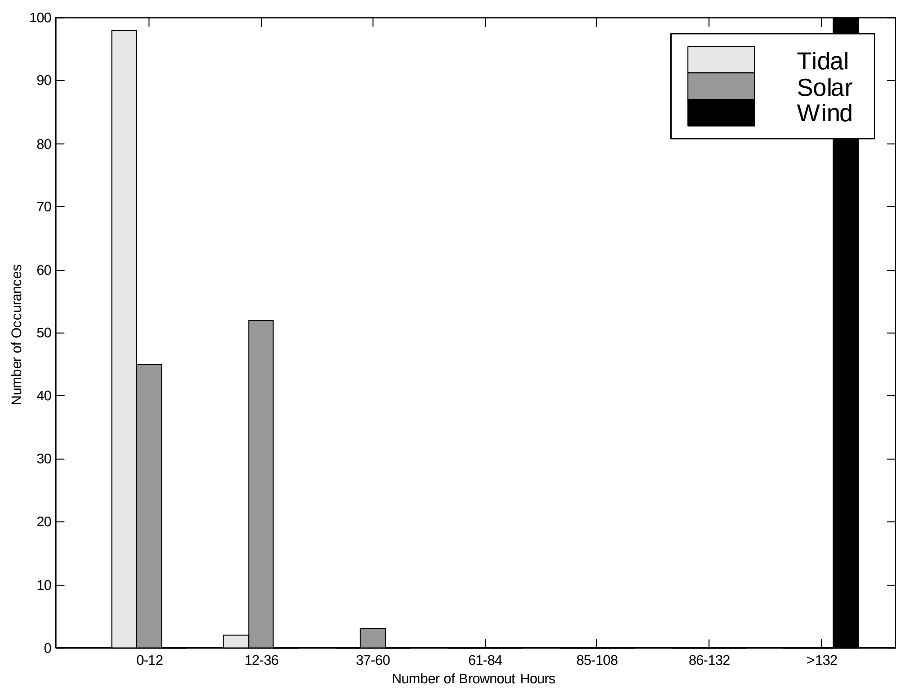

Figure 25: Brownout Hours Histogram for 384 kWh Storage

Figure 24 starts showing more interesting results. In this figure, the tidal system has over 95% of its years with less than twelve brownout hours, and just a few years with between 13 and 36. The solar system performs almost as well, having over 80% of the years falling with less than 12 brownout hours. However, the remaining years are more spread-out, with some years falling into the 37-60 range. The wind system in this figure is shown to be near its limit, as it has brownout hours spread almost evenly between 0 and 85, with some years falling throughout the whole range.

Looking at Figure 25, we see the most interesting results. In this figure, the tidal system has around 98% of its years falling with less than 12 brownout hours. The solar energy system did not fair as well, with the years spread nearly evenly between 0-12 and 13-36 brownout hours. The wind system, in this figure, is seen to be doing extremely badly, with all the systems running with more than 132 brownout hours each year. This was to be expected since, when the systems were designed, the wind system did not provide an adequate system even with 9999 kW of installed capacity for any of the five sample years.

These results indicate a significant effect of the storage size on the ability of various systems to provide effective long-term performance.

10.3. Storage Efficiency vs. Storage Size

To examine the effect of the storage efficiency on the storage size required, a number of systems had their storage size optimized at specified input and output storage efficiencies for a number of different installed capacities of resource conversion technologies. Since there are potentially an infinite number of different systems that could be optimized in this way, systems were chosen that would illustrate some specific points. Tidal systems were optimized for 15 and 30 turbines (installed capacity of 34.5 and 69 kW), and wind systems were optimized using 10 and 20 turbines (installed capacity of 100 and 200 kW).

Figure 26 shows the storage size required for a system with 30 turbines for a variety of storage input and output efficiencies. From this figure, one can see that the storage size seems to vary exponentially with the storage efficiency, as would be expected. However, what is interesting about this figure is the low slope of the storage size vs. efficiency for even medium efficient systems. For example the dotted line with the star markings is for an output efficiency of 50%, corresponding to a well running, optimized fuel cell system. The line for the output efficiency of 40%, shown as a solid line with the triangle markings, is not significantly higher for this system.

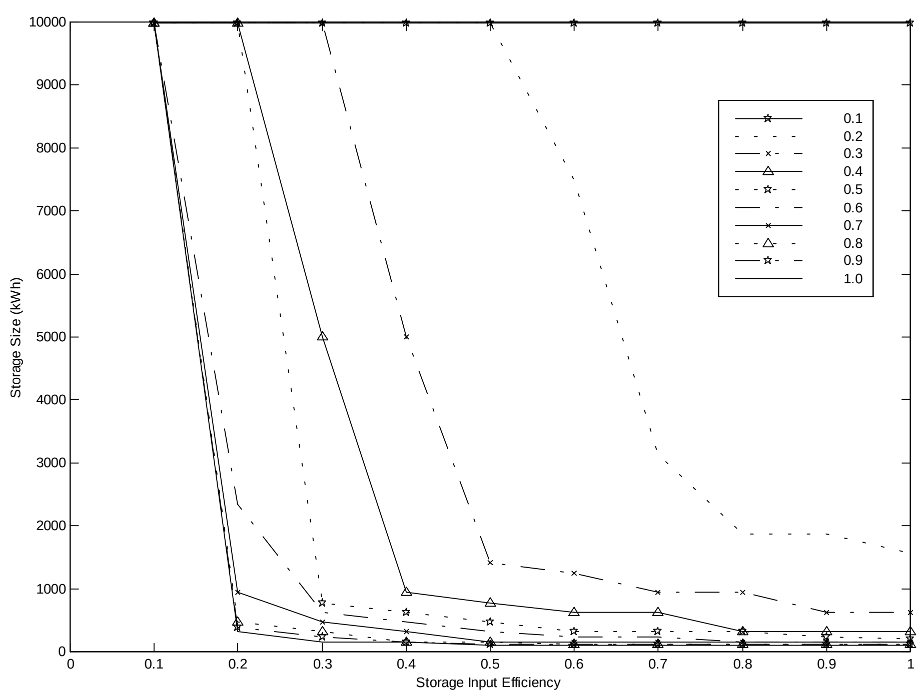

Figure 26: Storage Size vs. Storage Efficiency with 30 Kiho Tidal Turbines

Such a low slope on these lines at medium to high input efficiency and the closeness of these lines to each other indicates that the system storage size required is not significantly affected by a change in the storage input or output efficiency. This means that in the design and manufacture of storage systems, the input and output efficiencies are not the appropriate place to focus. As well, when considering a storage system for Race Rocks, the advantage of a battery system of having significantly higher throughput efficiency may not be significant.

When we look at a system with a smaller installed capacity, the results are similar, but the effect of efficiencies in the medium range is more significant. Figure 27 again shows the storage size required for a variety of storage input and output efficiencies, but this time for only 15 tidal turbines. This figure shows that the effect of reducing the storage output efficiency from 0.5 to 0.4 at an input efficiency of 0.8 has a small effect, but at an input efficiency of 0.7, the storage requirement nearly doubles. However, even with such a small installed capacity of only 34.5 kW, the system still does not require storage systems more than a few multiples of those required for the larger system with 69 kW of installed capacity.

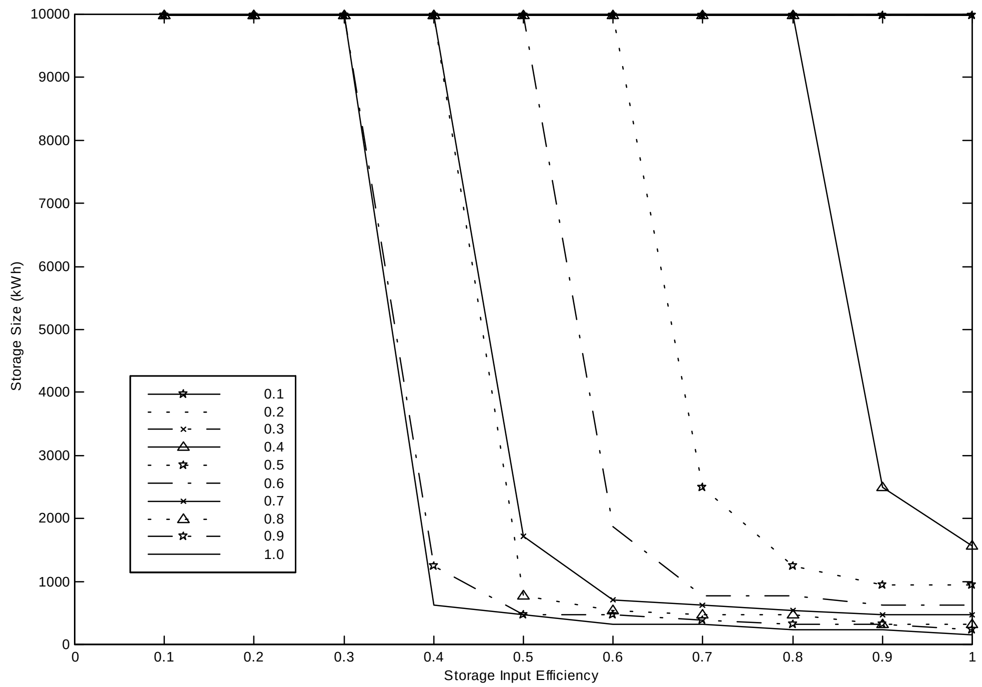

Figure 27: Storage Size vs. Storage Efficiency with 15 Tidal Turbines

Figure 28 and Figure 29 show the same results as the previous two figures but this time for 10 and 20 Bergey Excel wind turbine systems. As expected, for these systems, the same general pattern observed with the tidal turbines is visible. However, for these systems, even though the 10-turbine system has an installed capacity of 100 kW, much greater than even the 30-turbine tidal system with a capacity of 69 kW, the storage required is much higher in all cases. As well, the insensitivity to storage efficiency, which is quite clear in even the 15 tidal turbine case, is not apparent for the 10 wind turbine system, although it does begin to appear for the 20 turbine system.

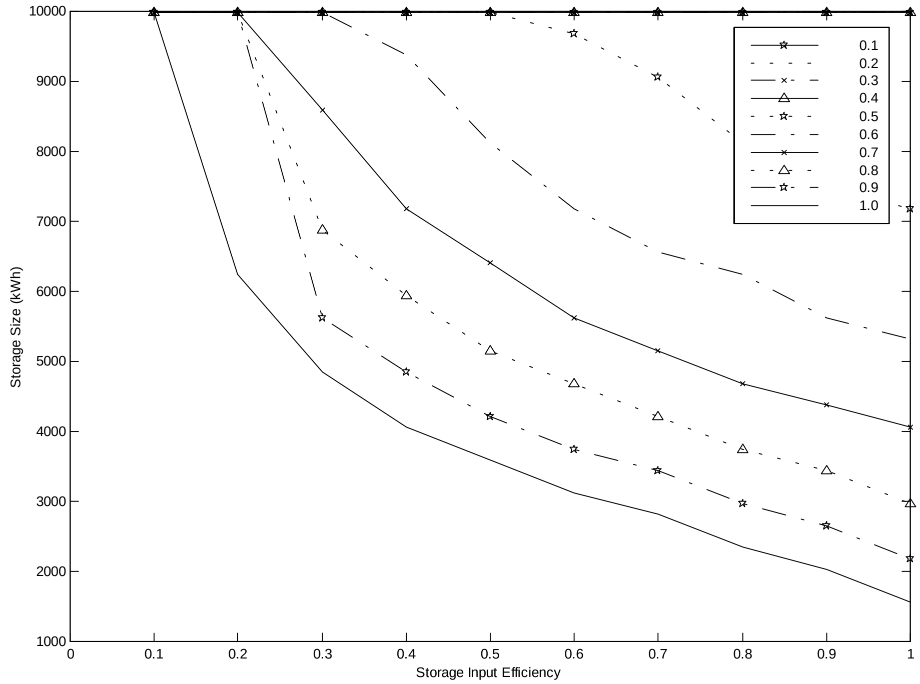

Figure 28: Storage Size vs. Storage Efficiency with 10 Bergey Excel Wind Turbines

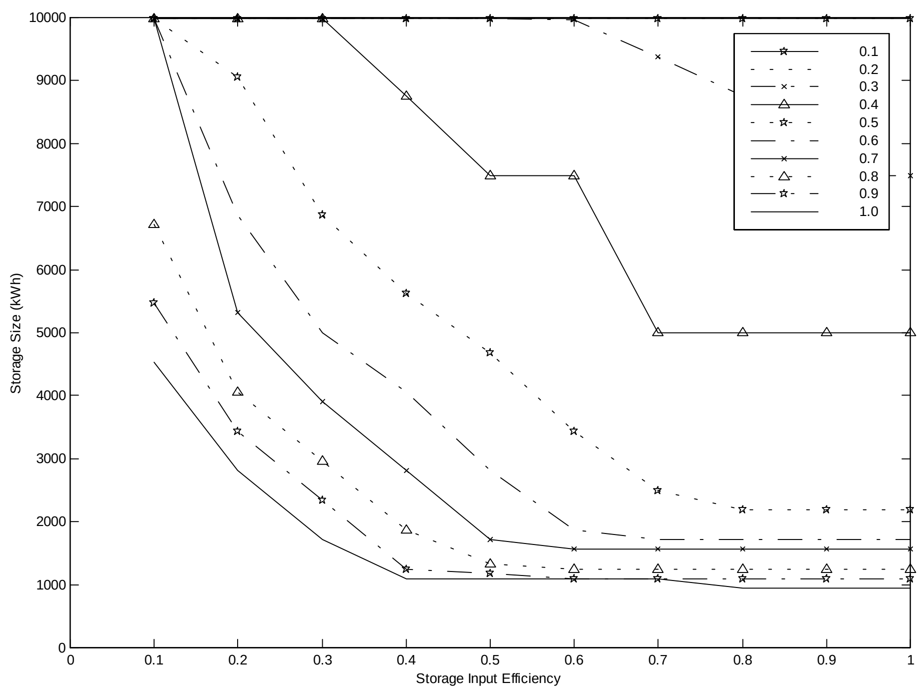

Figure 29: Storage Size vs. Storage Efficiency with 20 Bergey Excel Wind Turbines

10.4. Tidal Energy System Design

Since the above results indicate that tidal power is the most appropriate for Race Rocks, a more detailed evaluation of tidal power was performed. Figure 30 shows the effect of varying the storage size on the required installed system capacity. From this figure it can be seen that the installed capacity is incredibly large up to a storage level of about 240 kWh, and then the capacity drops quite suddenly, and remains low for storage capacities above 250 kWh. It can be seen that a system with storage of 250 kWh and installed capacity of 100 kW would be, technically, optimal. Increasing the storage past this point has very little effect on the installed capacity required, and increasing the installed capacity required, has very little effect on the storage system size.

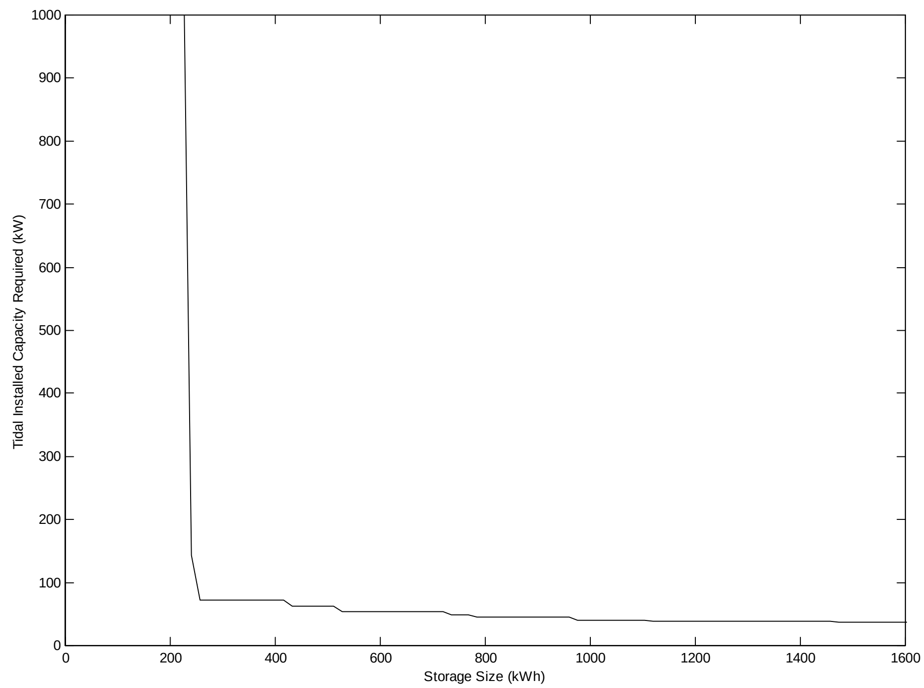

Figure 30: Tidal Installed Capacity vs. Storage Size

In this figure, the choppiness of the curve is an artefact of the optimization used. This comes about since we have a large bound for convergence and will therefore obtain a large number of systems that operate effectively at a certain level. With a binary search algorithm, we do not continue if we find a system that has converged. The figure, however, still indicates the effect of storage size on installed capacity required.

10.5. Environmental Considerations

So far, this chapter has shown that a tidal energy system with 250 kWh of storage and an installed capacity of 100 kW would be the most appropriate system for Race Rocks. As well, we have shown that the model developed, and the use of this model to design energy systems for Race Rocks, provides useful insights into both renewable energy system modelling and also into renewable energy for Race Rocks. However, the one item that we have not considered is the environmental aspects of installing a renewable energy system out at Race Rocks.

Race Rocks is a Marine Protected Area and an ecological reserve. This means that the site is both ecologically sensitive and that there are significant numbers of birds, marine mammals, and other flora and fauna on the site. The installation and operation of any energy system, including renewable energy systems, will require significant effort and impacts upon the site.

As well as considering the impact of the renewable energy systems on the site where they are installed, the impact of the system outside of the site may be significant. Even the actual energy balance of renewable energy systems needs to be evaluated to ensure that we are installing systems that provide a significant positive energy balance.

Unfortunately, the assessment of the environmental impact of renewable energy is beyond the scope of this thesis. This assessment is therefore left as future work.

11. Conclusions

This thesis started by looking at the controversy over renewable energy and the difficulty in evaluating the differing claims related to renewable energy. We saw that the opinions on renewable energy range from looking at them as our only hope for a sustainable future to looking at them as an expensive as well as environmentally costly alternative to traditional energy sources. To be able to evaluate these claims, IESVic is working towards a renewable energy laboratory where we can install and assess renewable energy systems in operation. Race Rocks, located one mile off the southern tip of Vancouver Island, is an ideal location for such a laboratory due to the large tidal fluxes, high winds as well as good insolation.

As a starting point in establishing such a laboratory, a modelling effort was commenced to assess the renewable energy potential at Race Rocks. Upon review of the current literature of renewable energy systems models, it was found that there were two types of models that have been used to model renewable energy system long-term performance, power balance and time-step models. Power balance models evaluate the power balance at each time point in the year and, upon integrating this balance, obtain an energy balance that can be used to estimate storage requirements. These models, however, do not allow for over-designed systems or storage losses, which can significantly affect the economics of the overall system. Time-step models allow for over-designed systems and storage losses, but it was found that none of the models presented in the literature were able to develop systems with a variety of generic storage systems or with multiple storage systems. Most of these models were based on specific technology choices, especially related to storage, and would not be useful in evaluating the potential of different technologies. None of these models used stochastic generation of the resource being assessed, which causes some concern over the long-term applicability of the model.

In light of this lack of an appropriate modelling tool, this thesis developed an energy system model with a generic storage system, generic resource models and generic resource conversion technologies that allow for the investigation into the effect of different parameters on system performance. The storage model takes into account the possibility of multiple storage technologies and allows for the evaluation of a number of different parameters' effects on the overall system performance.

Each resource was modelled stochastically using the best models presented in the literature and technology models were developed that represented the most general form of resource extraction technologies. It therefore becomes possible, for example, to evaluate the effect of solar panel efficiency on the overall system or to evaluate the effect of varying the storage efficiency on a variety of systems.

To both verify the model and investigate the potential of Race Rocks as a 'renewable energy system laboratory' a resource assessment was performed. This resource assessment identified the required parameters for the solar, tidal and wind resource at Race Rocks.

A number of preliminary results were obtained with the model, including an evaluation of some potential renewable energy systems for Race Rocks. A large number of different possibilities can be examined relatively quickly with the model, which aids in the evaluation of the different possible energy systems. From these results it was clear that the installed capacity of a tidal energy system at Race Rocks would be significantly lower than that required for either a wind or solar energy system.

It was noticed that the required installed capacity for solar was greater than that for wind at low storage levels and that this was reversed at high storage levels. It appears that this is related to the availability curves for these resources. This observation may allow the availability curve of a renewable energy resource to be used to perform some preliminary evaluations on the most appropriate system for a specified location. Further work in this area could shed light on the applicability of the availability curve to the design of renewable energy systems.

A comparison of the yearly variation in the storage balance between systems was performed. This analysis allowed us to create a combined system with both wind and solar resources that performed as well as the single-source systems, but at significantly lower installed capacity. The possibility of using combined systems to decrease the installed capacity or the storage size required is interesting and points the way towards developing truly integrated, multiple source renewable energy systems.

The generation of histograms for the number of brownouts for each system designed for each of 100 years allowed for the evaluation of the long-term performance of the different systems. It was found that systems with higher storage had much less steady performance, and that systems with lower storage had much more predictable performance with the exception of systems which ended up being under-designed at low storage levels. Overall, in all cases, the tidal systems performed significantly better than the other systems at all storage levels.

A sensitivity analysis was performed on the storage efficiency of the system and the effect that this had on the required storage size. This investigation pointed towards the possibility that the storage efficiency would not significantly affect the storage size if a system were properly designed. This has significant implications for developers of battery and storage technologies, where often efficiency is one of the major research foci. These results indicate that other areas in terms of storage technologies may be more important than efficiency, such as the storage density, which would have a significant effect on the cost. Further investigations into this effect would be interesting.

For Race Rocks, all these results indicate that a tidal energy system would be the most appropriate. The trade off between installed capacity and storage size would have to be based on economic considerations and the environmental impact that the installation and operation of such a system would have. However, results indicate that a tidal system with an installed capacity of 100 kW and a hydrogen based storage system of 250 kWh would be the technically most appropriate system. A detailed environmental analysis of all three renewable energy technologies, their overall lifetime energy balance, and the environmental impacts they would have should be performed prior to the installation of any system out at Race Rocks. However, it would be expected that a tidal powered energy system would be the least intrusive and provide the most reliable power of any of the systems installed.

Overall, it can be concluded that the generic energy system model allows for investigation of the effect of different parameters on the required system. For example, the effect of storage efficiency on storage size has, to this point, not been investigated in the literature. As well, the stochastic modelling of the renewable resources allows for an investigation into the reliability of systems that could not be performed if using long-term or typical meteorological year data. This ability, which was not available in any other models, is a significant improvement and can be used to evaluate the best areas to focus research on renewable energy and storage technologies.

A number of different areas were identified that would be interesting to investigate further. These include investigations into the use of the energy availability curve to draw conclusions about the installed capacity required for the different resources, the use of the variance between multiple years to evaluate the reliability of installed systems and the effects of storage efficiency on storage size. Other areas that could be investigated with this model include looking into the required storage size for specified installed capacities of each different renewable resource, the effect of a varying versus static storage efficiency and the possibility of testing the model against real-world results. Each of these investigations would provide useful insights into the prospects for renewable energy.

The model developed in this thesis has been shown to provide useful insights into renewable energy systems. These results, and results obtained upon further investigation, will enable more informed, and therefore more appropriate, decisions to be made in regards to renewable energy. Renewable energy has a bright future. However, if we let ourselves get blinded to its limitations or to its possibilities and accept the claims others have made, we will end up making uninformed and damaging decisions. This thesis provides one small part of the understanding of renewable energy that we require on our path to a brighter future.

Bibliography

[1] Wallis, L. R., “Through the Energy Looking Glass,” *Vital speeches of the day*, vol. LX, pp. 381, 1994.

[2] Goldemberg, J. Ed., *World energy assessment: energy and the challenge of sustainability: overview*. New York, NY: United Nations Development Programme, 2000.

[3] Intergovernmental Panel on Climate Change, “IPCC WGI Third Assessment Report Summary for Policymakers Draft,” IPCC, Shanghai, 2001.

[4] Earth Day Network, “Earth Day Network: Worldwide Campaign: Energy Basics,” Earth Day Network, Web Resource http://www.earthday.net/goals/basic.stm Accessed: 8/21/01.

[5] Smil, V., “Renewable energies: how much and how renewable?,” *The Bulletin of the atomic scientists*, vol. 35, pp. 12-19, 1979.

[6] Mills, M. P., “Renewable Energy & the Laws of Nature,” Greening Earth Society, Web Resource http://www.fossilfuels.org/Electric/nature.htm Accessed: 2/5/01.

[7] Skov, A. M., “National health, wealth, and energy use,” *JPT, Journal of Petroleum Technology*, vol. 51, 1999.

[8] Bradley, R. L. J., “Policy Analysis: Renewable Energy: Not Cheap, Not "Green",” Cato Institute, Washington, DC, Cato Policy Analysis No 280, 1997.

[9] Parker, D. M., “Environmental implications of tidal power generation,” *IEE Proceedings, Part A: Science, Measurement and Technology*, vol. 140, pp. 71-75, 1993.

[10] Sagan, C., *The Demon-Haunted World*. New York: Ballantine Books, 1996.

[11] Agbossou, K., “Renewable Energy Systems Based on Hydrogen for Remote Areas,” presented at 11th Canadian Hydrogen Conference, Victoria, BC, June 17-20, 2001.

[12] Bortnikov, Y., Z. Karichev, V. Titov and Y. Zenochkin, “Utilization of Hydrogen for Electrical Energy Storage in a Nonpolluting Self-Contained Power Plant,” presented at Hydrogen Energy Progress IX, Paris, France, June 22-25, 1992.

[13] Lehman, P. A. and C. E. Chamberlin, “Design of a Photovoltaic-Hydrogen-Fuel Cell Energy System,” *International Journal of Hydrogen Energy*, vol. 16, pp. 349-352, 1991.

[14] Lehman, P., C. Chamberlin, G. Pauletto and M. Rocheleau, "Operating Experience with a Photovoltaic-Hydrogen Energy System," presented at 10th World Hydrogen Energy Conference, Cocoa Beach, FL, June 1994.

[15] Moerner, S., W. Beckman and S. Klein, "Comparison of Simulations of a Photovoltaic-Hydrogen System with Measurements from the Schatz Solar-Hydrogen Project," presented at 10th World hydrogen energy conference, Cocoa Beach, FL, June 1994.

[16] Dimitrov, B. and K. Zmbov, "Analysis of an integrated solar - hydrogen energy system," presented at 11th World Hydrogen Energy Conference, Stuttgart, Germany, June 1996.

[17] Barthels, H., W. A. Brocke, K. Bonhoff, H. G. Groehn, G. Heuts, M. Lennartz, H. Mai, J. Mergel, L. Schmid and P. Ritzenhoff, "PHOEBUS-Julich: an autonomous energy supply system comprising photovoltaics, electrolytic hydrogen, fuel cell," *International Journal of Hydrogen Energy*, vol. 23, pp. 295-301, 1998.

[18] Altmann, M. and F. Gamallo, "Design of an Isolated Wind-Hydrogen Energy Supply System," presented at 12th World Hydrogen Energy Conference, Buenos Aires, June 1998.

[19] Schucan, T. H., E. Skolnik, M. Bracht and C. E. G. Padro, "Development of Hydrogen Technology Component Models for Systems Integration," presented at 12th World Hydrogen Energy Conference, Buenos Aires, June 1998.

[20] Sorensen, B., "Renewable energy: a technical overview," *Energy policy*, vol. 19, pp. 386-391, 1991.

[21] Chan, W. M., "Feasibility Study on Hydrogen Storage with Intermittent Renewables on Islands -- Case Study of the Canary Islands," MSc and/or DIC, Imperial College of Science, Technology and Medicine, London, UK, 2000.

[22] Sfetsos, A., "Comparison of various forecasting techniques applied to mean hourly wind speed time series," *Renewable Energy*, vol. 21, pp. 23-35, 2000.

[23] Mohandes, M. A., S. Rehman and T. O. Halawani, "Neural networks approach for wind speed prediction," *Renewable Energy*, vol. 13, pp. 345-354, 1998.

[24] McGowan, J. G. and J. F. Manwell, "Hybrid wind/PV/diesel system experiences," *Renewable Energy*, vol. 16, pp. 928-933, 1999.

[25] Kozak, C., "Williams Lake Generatin Station, British Columbia, Canada," NW Energy (Williams Lake) Corp., Web Resource http://www.westbioenergy.org/lessons/les12.htm Accessed: 10/4/01.

[26] Keeler, C. G., "Wabash River in its Fourth Year of Commercial Operation," presented at 1999 Gasification Technologies Conference, San Fransisco, CA, October 17-20, 1999.

[27] McGowan, J. G., J. F. Manwell and S. R. Connors, "Wind/Diesel Energy Systems: Review of Design Options and Recent Developments," *Solar Energy*, vol. 41, pp. 561-75, 1988.

[28] Kellogg, W. D., M. H. Nehrir, G. Venkataramanan and V. Gerez, "Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems," *IEEE Transactions on Energy Conversion*, vol. 13, pp. 70-75, 1998.

[29] Spinadel, V. W., F. Gamallo and E. Spinadel, "Mathematical Model for Determining the Accumulated Hydrogen Reserve in Wind-Generated Electricity at Distant Sites," presented at 12th World Hydrogen Energy Conference, Buenos Aires, June 1998.

[30] Zahedi, A., "Entirely Renewable Energy Based Electricity Supply System for Remote and Isolated Areas (System Design)," presented at 34th Annual Conference of the Australian and New Zealand Solar Energy Society, Darwin, Australia, October 1996.

[31] Ashari, M. and C. V. Nayar, "An optimum dispatch strategy using set points for a photovoltaic (PV)-diesel-battery hybrid power system," *Solar Energy*, vol. 66, pp. 1-9, 1999.

[32] Al-Ashwal, A. M., "Sensitivity analysis of stand alone PV systems," *Renewable Energy*, vol. 8, pp. 432-436, 1996.

[33] Manwell, J. F. and J. G. McGowan, "Wind diesel system simulation: A screening level model," *International Journal of Solar Energy*, vol. 17, pp. 223-240, 1995.

[34] Fiksel, A., J. W. Thornton, S. A. Klein and W. A. Beckman, "Developments to the TRNSYS simulation program," *Journal of Solar Energy Engineering, Transactions of the ASME*, vol. 117, pp. 123-127, 1995.

[35] Martin, E. and N. Muradov, "Modeling of Integrated Renewable Hydrogen Energy Systems for Remote Applications," in *Advances in hydrogen energy*, C. E. Grégoire Padró and F. Lau, Eds. New York: Kluwer Academic/Plenum Publishers, 2000, pp. 175-190.

[36] Rambach, G., "Integrated Renewable Hydrogen/Utility Systems," Desert Research Institute, Reno, Nevada, DOE Contract DE-FC36-98GO10842, 1999.

[37] Padro, C. E. G., V. L. Putsche and M. Fairlie, "Modeling of Hydrogen Energy Systems of Remote Applications," presented at 12th World Hydrogen Energy Conference, Buenos Aires, June 1998.

[38] Valente, L. C. G. and S. C. A. de Almeida, "Economic analysis of a diesel/photovoltaic hybrid system for decentralized power generation in Northern Brazil," *Energy*, vol. 23, pp. 317-323, 1998.

[39] Bonanno, F., A. Consoli, S. Lombardo and A. Raciti, "A logistical model for performance evaluations of hybrid generation systems," *Ieee Transactions On Industry Applications*, vol. 34, pp. 1397-1403, 1998.

[40] Meibom, P., T. Svendsen and B. Soerensen, "Advantages and disadvantages in exchange of power between a hydro- and a wind-dominated electricity supply system," presented at 3rd International Hydropower Conference, Trondheim; Norway, June 1997.

[41] Dienhart, H. and A. Siegel, "Hydrogen Storage in Isolated Electrical Energy Systems with Photovoltaic and Wind-Energy," presented at 9th World Hydrogen Energy Conference, Paris, France, June 22-25, 1992.

[42] Ding, J. J., A. M. Al-Jumaily and B. A. Tapp, "Design considerations and modeling of a hybrid energy system," *American Society of Mechanical Engineers, Advanced Energy Systems Division (Publication) AES*, vol. 39, pp. 365-372, 1999.

[43] Isherwood, W., J. R. Smith, S. M. Aceves, G. Berry, W. Clark, R. Johnson, D. Das, D. Goering and R. Seifert, "Remote power systems with advanced storage technologies for Alaskan villages," *Energy*, vol. 25, pp. 1005-1020, 2000.

[44] McGowan, J. G., J. F. Manwell, C. Avelar and C. L. Warner, "Hybrid wind/PV/diesel hybrid power systems modeling and South American applications," *Renewable Energy*, vol. 9, pp. 836-847, 1996.

[45] Nehrir, M. H., B. J. La Meres, G. Venkataramanan, V. Gerez and L. A. Alvarado, "Approach to evaluate the general performance of stand-alone wind/photovoltaic generating systems," *IEEE Power Engineering Review*, vol. 20, pp. 79, 2000.

[46] Cermak, J. E., "Applications of Wind Data and Definition of Needs," presented at Workshop on Wind Climate, Ashville, NC, November 12-13, 1979.

[47] "Electric-energy storage hinges on three leading technologies," *Power*, vol. 139, pp. 42-45, 1995.

[48] Mikkonen, R., A. Korpela, J. Lehtonen, J. Paasi and J. Vuorinen, "Design of a 0.2 MJ conduction cooled Nb3Sn SMES system," *IEEE Transactions on Applied Superconductivity*, vol. 10, pp. 784-787, 2000.

[49] Smith, W., “Role of fuel cells in energy storage,” *Journal of Power Sources*, vol. 86, pp. 74-83, 2000.

[50] Vanhanen, J. P. and P. D. Lund, “Computational approaches for improving seasonal storage systems based on hydrogen technologies,” *International journal of hydrogen energy*, vol. 20, pp. 575, 1995.

[51] Tarrant, C. D., “The Use of Flywheel Energy Storage in Electrical Energy Management,” in *Renewable energy storage : its role in renewables and future electricity markets*, Institution of Mechanical Engineers. Research and Technology Committee., Ed. Bury St Edmunds: Professional Engineering Pub. Ltd. for the Institution of Mechanical Engineers, 2000, pp. 35-44.

[52] Vosen, S. R. and J. O. Keller, “Hybrid energy storage systems for stand-alone electric power systems: Optimization of system performance and cost through control strategies,” *International Journal of Hydrogen Energy*, vol. 24, pp. 1139-1156, 1999.

[53] Power Beat.com, “High Density Energy Storage Systems,” Power Beat International, Web Resource http://powerbeat.com/Tech/Articles/Modular.htm Accessed: 7/13/00.

[54] Jensen, J. and B. Sørensen, *Fundamentals of energy storage*. New York: Wiley, 1984.

[55] Environment Canada, “Canadian Weather for Energy Calculations (CWEC Files),” Watson Simulation Laboratories, University of Waterloo, Waterloo, ON, 1995.

[56] Siurna, D. L., L. J. D'Andrea and K. G. T. Hollands, “Canadian Representative Meteorological Year For Solar System Simulation,” presented at Proceedings - SESCI '84 Calgary, 10th Annual National Conference of the Solar Energy Society of Canada, Calgary, Alberta, 1984.

[57] Marion, W. and K. Urban, “User's Manual for TMY2s Typical Meteorological Years,” National Renewable Energy Laboratory, Golden, CO, DOE Contract Number DEAC36-83CH10093, 1995.

[58] Knight, K. M., S. A. Klein and J. A. Duffie, “Methodology for the synthesis of hourly weather data,” *Solar Energy*, vol. 46, pp. 109-120, 1991.

[59] Gansler, R. A., S. A. Klein and W. A. Beckman, “Assessment of the accuracy of generated meteorological data for use in solar energy simulation studies,” *Solar Energy*, vol. 53, pp. 279-287, 1994.

[60] Graham, V. A., K. G. T. Hollands and T. E. Unny, “Time Series Model for Kt with Application to Global Synthetic Weather Generation,” *Solar Energy*, vol. 40, pp. 83-92, 1988.

[61] Aguiar, R. J., M. Collares-Pereira and J. P. Conde, “Simple Procedure For Generating Sequences of Daily Radiation Values Using a Library of Markov Transition Matrices,” *Solar Energy*, vol. 40, pp. 269-279, 1988.

[62] Biga, A. J. and R. Rosa, “Contribution to the Study of the Solar Radiation Climate of Lisbon,” *Solar Energy*, vol. 23, pp. 61-67, 1979.

[63] Marathe, H. Y. and S. Rahman, “Microcomputer Model For Photovoltaic Energy System Performance Analysis,” presented at IEEE Southeastcon '86., Richmond, Va, 1986.

[64] Gueymard, C., “Mathematically integrable parameterization of clear-sky beam and global irradiances and its use in daily irradiation applications,” *Solar Energy*, vol. 50, pp. 385-397, 1993.

[65] Biga, A. J. and R. Rosa, “Estimating Solar Irradiation Sums From Sunshine and Cloudiness Observations,” *Solar Energy*, vol. 25, pp. 265-272, 1980.

[66] Olseth, J. A. and A. Skartveit, “Characteristics of hourly global irradiance modelled from cloud data,” *Solar Energy*, vol. 51, pp. 197-204, 1993.

[67] Maxwell, E. L., “METSTAT - the solar radiation model used in the production of the National Solar Radiation Data Base (NSRDB),” *Solar Energy*, vol. 62, pp. 263-279, 1998.

[68] Gul, M. S., T. Muneer and H. D. Kambezidis, “Models for obtaining solar radiation from other meteorological data,” *Solar Energy*, vol. 64, pp. 99-108, 1998.

[69] Kamal, L. and Y. Z. Jafri, “Stochastic modeling and generation of synthetic sequences of hourly global solar irradiation at Quetta, Pakistan,” *Renewable Energy*, vol. 18, pp. 565-572, 1999.

[70] Callegari, M., R. Festa and C. F. Ratto, “Stochastic modelling of daily beam irradiation,” *Renewable Energy*, vol. 2, pp. 611-624, 1992.

[71] Brinkworth, B. J., “Autocorrelation and Stochastic Modelling of Insolation Sequences,” *Solar Energy*, vol. 19, pp. 343-347, 1977.

[72] Loutfi, H. and A. Khtira, “Stochastic analysis and generation of synthetic sequences of daily global solar irradiation: rabat site (Morocco),” *Renewable Energy*, vol. 2, pp. 129-138, 1992.

[73] Panek, A., Y. Lee and H. Tanaka, “Simulation of solar radiation heat flux data for energy calculation,” *Journal of Solar Energy Engineering, Transactions of the ASME*, vol. 118, pp. 58-63, 1996.

[74] Anand, D. K. and I. N. Deif, “Solar Cooling Performance Predictions Via Stochastic Weather Algorithms,” *Energy (Oxford)*, vol. 4, pp. 537-548, 1979.

[75] Siala, F. M. F., “Stochastic design of solar energy systems,” *Applied Energy*, vol. 52, pp. 141-152, 1995.

[76] Hokoi, S., M. Matsumoto and M. Kagawa, “Stochastic models of solar radiation and outdoor temperature,” presented at Annual Meeting of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, St. Louis, Mo, June 10-13, 1990.

[77] Morf, H., “Stochastic two-state solar irradiance model (STSIM),” *Solar Energy*, vol. 62, pp. 101-112, 1998.

[78] Hay, J. E. and D. C. McKay, “Estimating Solar Irradiance on Inclined Surfaces: A Review and Assessment of Methodologies,” *International Journal of Solar Energy*, vol. 3, pp. 203-240, 1985.

[79] Reindl, D. T., W. A. Beckman and J. A. Duffie, “Evaluation of hourly tilted surface radiation models,” *Solar Energy*, vol. 45, pp. 9-17, 1990.

[80] Perez, R., R. Stewart, C. Arbogast, R. Seals and J. Scott, “An Anisotropic Hourly Diffuse Radiation Model for Sloping Surfaces: Description, Performance Validation, Site Dependency Evaluation,” *Solar Energy*, vol. 36, pp. 481-497, 1986.

[81] Perez, R., R. Seals, P. Ineichen, R. Stewart and D. Menicucci, “A New Simplified Version of the Perez Diffuse Irradiance Model for Tilted Surfaces,” *Solar Energy*, vol. 39, pp. 221-231, 1987.

[82] Utrillas, M. P. and J. A. Martinezlozano, “Performance Evaluation of Several Versions of the Perez Tilted Diffuse Irradiance Model,” *Solar Energy*, vol. 53, pp. 155-162, 1994.

[83] Feuermann, D. and A. Zemel, “Validation of models for global irradiance on inclined planes,” *Solar Energy*, vol. 48, pp. 59-66, 1992.

[84] Vartiainen, E., “A new approach to estimating the diffuse irradiance on inclined surfaces,” *Renewable Energy*, vol. 20, pp. 45-64, 2000.

[85] Olseth, J. A. and A. Skartveit, “Probability Density Model For Hourly Total and Beam Irradiance On Arbitrarily Orientated Planes,” *Solar Energy*, vol. 39, pp. 343-351, 1987.

[86] Olmo, F. J., J. Vida, I. Foyo, Y. Castro-Diez and L. Alados-Arboledas, "Prediction of global irradiance on inclined surfaces from horizontal global irradiance," *Energy (Oxford)*, vol. 24, pp. 689-704, 1999.

[87] Randall, C. M. and R. Bird, "Insolation Models and Algorithms," in *Solar resources*, R. Hulstrom, Ed. Cambridge, Mass.: MIT Press, 1989, pp. 61-141.

[88] Lillington, D., H. Cotal, J. Ermer, D. Friedman, T. Moriarty and A. Duda, "32.3% Efficient triple junction GaInP2/GaAs/Ge concentrator solar cells," presented at Proceedings of the Intersociety Energy Conversion Engineering Conference, Las Vegas, NV, July 24-27, 2000.

[89] Menicucci, D. F., "Pvform - a New Approach to Photovoltaic System Performance Modelling," presented at Eighteenth IEEE Photovoltaic Specialists Conference, Las Vegas, NV, 1985.

[90] Menicucci, D. F. and J. P. Fernandez, "User's Manual for PVFORM: A Photovoltaic System Simulation Program for Stand-Alone and Grid-Interactive Applications," Sandia National Laboratories, Albuquerque, NM, SAND85-0376 - UC-276, 1988.

[91] Perez, R., J. Doty, B. Bailey and R. Stewart, "Experimental evaluation of a photovoltaic simulation program," *Solar Energy*, vol. 52, pp. 359-365, 1994.

[92] Walker, H. A. and S. K. Price, "Model validation and optimization of a hybrid photovoltaic-generator system using a modified version of PVFORM," presented at ASME International Solar Energy Conference, Washington, DC, 04/04-09/93.

[93] Rahman, S. and B. H. Chowdhury, "Simulation of photovoltaic power systems and their performance prediction," *IEEE Transactions on Energy Conversion*, vol. 3, pp. 440-446, 1988.

[94] Soltek Solar Energy Ltd., "Soltek Solar Energy Home Page," Soltek Solar Energy Ltd., Web Resource http://www.soltek.ca Accessed: 10/09/01.

[95] Huq, A.-u., M. I. Hossain and M. M. Rahman, "Effect of flat reflectors on the performance of photovoltaic modules," presented at Intersociety Energy Conversion Engineering Conference, Las Vegas, NV, July 24-27, 2000.

[96] Helwa, N. H., A. B. G. Bahgat, A. M. R. El Shafee and E. T. El Shenawy, "Maximum collectable solar energy by different solar tracking systems," *Energy Sources*, vol. 22, pp. 23-34, 2000.

[97] Skartveit, A. and J. A. Olseth, "Probability density and autocorrelation of short-term global and beam irradiance," *Solar Energy*, vol. 49, pp. 477-487, 1992.

[98] Skartveit, A. and J. A. Olseth, “Intrahour variability of solar irradiance,” *Energy Sources*, vol. 15, pp. 105-116, 1993.

[99] Gansler, R. A., S. A. Klein and W. A. Beckman, “Investigation of minute solar radiation data,” *Solar Energy*, vol. 55, pp. 21-27, 1995.

[100] Suehrcke, H. and P. G. McCormick, “Distribution of average instantaneous terrestrial solar radiation over the day,” *Solar Energy*, vol. 42, pp. 303-309, 1989.

[101] Suehrcke, H. and P. G. McCormick, “Frequency Distribution of Instantaneous Insolation Values,” *Solar Energy*, vol. 40, pp. 413-422, 1988.

[102] Godin, G., *The analysis of tides*. Toronto, ON: University of Toronto Press, 1972.

[103] Zetler, B. D., E. E. Long and L. F. Ku, “Tide Predictions using Satellite Constituents,” *International Hydrographic Review*, vol. LXII, pp. 135-142, 1985.

[104] Foreman, M. G. G. and E. T. Neufeld, “Harmonic Tidal Analyses of Long Time Series,” *The International hydrographic review*, vol. LXVIII, pp. 85-108, 1991.

[105] Foreman, M. G. G., *Manual for tidal currents analysis and prediction*. Sidney, B.C.: Institute of Ocean Sciences, 1978.

[106] Pawlowicz, R., “Rich Pawlowicz's Matlab Stuff,” Rich Pawlowicz, Web Resource http://www2.ocgy.ubc.ca/~rich Accessed: 2001/11/01.

[107] Foreman, M. G. G., *Manual for tidal heights analysis and prediction*. Sidney, B.C.: Institute of Ocean Sciences, 1977.

[108] Bullen, D. J., “Tidal stream energy,” *International Water Power and Dam Construction*, vol. 46, pp. 12-14, 1994.

[109] Blue Energy Canada, “Ocean Energy: A High Density Renewable Energy Source Perfect for British Columbia,” Blue Energy Canada Inc., Vancouver, BC, Brochure, 2001.

[110] Blue Energy Canada Inc., “Blue Energy Canada Inc. - The Future of Renewable Energy,” Blue Energy Canda Inc., Web Resource http://www.bluenergy.com/index2.html Accessed: 07/10/01.

[111] Davis, B. V., B. V. Davis, Nova Energy Limited, Hydraulics Laboratory (National Research Council Canada), Institute for Mechanical Engineering (Canada) and Coastal Zone Engineering, *Water turbine model trials to demonstrate the feasibility of extracting kinetic energy from river and tidal currents*. Halifax, N.S.: Nova Energy Ltd., 1980.

[112] Davis, B. V., D. H. Swan, K. A. Jeffers, B. V. Davis, Nova Energy Limited and Hydraulics Laboratory (National Research Council Canada), *Ultra low head*

hydroelectric power generation using ducted vertical axis water turbines. Dartmouth, N.S.: Nova Energy Limited, 1982.

[113] Swan, D. H., B. V. Davis, B. V. Davis and Hydraulics Laboratory (National Research Council Canada), *Commissioning and testing of a 100 kW vertical axis hydraulic turbine (model B2)*. [Ottawa]: The Laboratory, 1985.

[114] Faure, T. D., Hydraulics Laboratory (National Research Council of Canada) and Division of Mechanical Engineering (National Research Council of Canada), *Experimental results of a Darrieus type vertical axis rotor, in a water current*. [Ottawa]: Division of Mechanical Engineering National Research Council Canada, 1984.

[115] Fraenkel, P., "Production Turbines NOT YET FINISHED," Marine Current Turbines, E-Mail June 16, 2001.

[116] Michael, P., "Technology Status Report: Tidal Stream," ETSU (for DTI Renewable Energy Programme), U.K., 2001.

[117] Macnaughton, D., P. L. Fraenkel, O. F. Paish and A. Derrick, "Tidal stream turbine development," presented at Conference on Renewable Energy - Clean Power 2001, London, UK, November 17-19, 1993.

[118] Gorlov, A. M., "Unidirectional helical reaction turbine operational under reversible fluid flow for power systems," United States Patent Number 5,451,137 1995.

[119] Gorlov, A. M., "Helical turbines for the Gulf Stream: Conceptual approach to design of a large-scale floating power farm," *Marine Technology*, vol. 35, pp. 175-182, 1998.

[120] Gorlov, A. and K. Rogers, "Helical turbine as undersea power source," *Sea Technology*, vol. 38, pp. 39-43, 1997.

[121] Tuckey, A. M., D. J. Patterson and J. Swenson, "Kinetic energy tidal generator in the Northern Territory - results," presented at IECON (Industrial Electronics Conference), New Orleans, Louisiana, 1997.

[122] Gajanayake, P. A., A. Furukawa and K. Okuma, "Applicability of Darrieus-type turbine for extra-low head tidal power generation," presented at International Offshore and Polar Engineering Conference, Montreal, PQ, May 24-29, 1998.

[123] Kiho, S., M. Shiono and K. Suzuki, "Power generation from tidal currents by darrieus turbine," *Renewable Energy*, vol. 9, pp. 1242-1245, 1996.

[124] Shiono, M., K. Suzuki and S. Kiho, “Experiments on the characteristics of Darrieus turbine for the tidal power generation,” presented at International Offshore and Polar Engineering Conference, 1999.

[125] Marlec, “Amazon Aquacharger,” Marlec, Web Resource http://www.marlec.co.uk/products/prods/amozon.htm Accessed: 6/8/00.

[126] Tyson Turbine, “Tyson Turbine,” Tyson Turbine, Web Resource http://www.ozemail.com.au/~tysonturbine/home.html Accessed: 6/8/00.

[127] Hydrosphere UK Ltd., “Hydrosphere UK Ltd: "AQUAIR" Hydroelectric Generator,” Hydrosphere UK Ltd., Web Resource http://www.hydros.demon.co.uk/aquair/aquair.htm Accessed: 5/3/01.

[128] Chou, K. C. and R. B. Corotis, “Simulation of Hourly Wind Speed and Array Wind Power,” *Solar Energy*, vol. 26, pp. 199-212, 1981.

[129] Daniel, A. R. and A. A. Chen, “Stochastic simulation and forecasting of hourly average wind speed sequences in Jamaica,” *Solar Energy*, vol. 46, pp. 1-11, 1991.

[130] Billinton, R., C. Hua and R. Ghajar, “Time-series models for reliability evaluation of power systems including wind energy,” *Microelectronics and Reliability*, vol. 36, pp. 1253-1261, 1996.

[131] Nfaoui, H., J. Buret and A. A. M. Sayigh, “Stochastic simulation of hourly average wind speed sequences in Tangiers (Morocco),” *Solar Energy*, vol. 56, pp. 301-314, 1996.

[132] Balouktsis, A., D. Tsanakas and G. Vachtsevanos, “Stochastic Simulation of Hourly and Daily Average Wind Speed Sequences,” *Wind Engineering*, vol. 10, pp. 1-11, 1986.

[133] Castino, F., R. Festa and C. F. Ratto, “Stochastic modelling of wind velocities time series,” *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 74-76, pp. 141-151, 1998.

[134] Skidmore, E. L. and J. Tatarko, “Stochastic wind simulation for erosion modeling,” *Transactions of the ASAE*, vol. 33, pp. 1893-1899, 1990.

[135] Elliott, D. L., “Adjustment and Analysis of Data for Regional Wind Energy Assessment,” presented at Workshop on Wind Climate, Ashville, NC, November 12-13, 1979.

[136] Ackermann, T. and L. Soder, “Wind energy technology and current status: a review,” *Renewable & Sustainable Energy Reviews*, vol. 4, pp. 315-374, 2000.

[137] McGowan, J. G. and S. R. Conners, "Windpower: A turn of the century review," *Annual Review of Energy and the Environment*, vol. 25, pp. 147-197, 2000.

[138] Bolcich, J., "High Efficient Wind-Hydrogen Facility," presented at 11th Canadian Hydrogen Conference, Victoria, BC, June 17-20, 2001.

[139] Weisbrich, A. L., W. Smith, D. L. Rainey and G. Weisbrich, "e-Sea Warp(tm): An Offshore Wind Power System With Integral Fuel Cells," presented at 11th Canadian Hydrogen Conference (preprint), Victoria, BC, June 17-20, 2001.

[140] Enron Wind, "Enron Wind Home Page," Enron Wind, Web Resource http://www.wind.enron.com Accessed: 10/8/01.

[141] Synergy Power Corporation, "Synergy Power Corporation Home Page," Synergy Power Corporation, Web Resource http://www.synergypowercorp.com Accessed: 10/8/01.

[142] Wind Turbine Industries Corporation, "Wind Turbine Industries Corporation Home Page," Wind Turbine Industries Corporation, Web Resourcwe http://www.windturbine.net Accessed: 10/8/01.

[143] Bergey Windpower, "Bergey Windpower Home Page," Bergey WindPower, Web Resource www.bergey.com Accessed: 10/8/01.

[144] Pham, L., "Comparison of Stochastic Load Combination Rules," presented at ACMSM 8: Proceedings of the Eighth Australasian Conference on the Mechanics of Structures & Materials., Newcastle, Australia, 1982.

[145] Iqbal, M., *An introduction to solar radiation*. Toronto: Academic Press, 1983.

[146] Foreman, M., "Race Passage Data," Institute for Ocean Sciences, E-mail June 2, 2000.

[147] Crawford, W. R. and R. F. Henry, "Detailed Tidal Grid of Race Rocks," , Personal Communication April 26, 2001.

[148] Green, W., "Race Rocks Wind Data," Environment Canada, E-mail March 12, 2001.

Appendix A: Tidal Constituents at Race Rocks

Constituent Name	Frequency (Hz)	Constituent (mm/s)	95% Constituent Confidence Interval	Phase (degrees)	95% Phase Confidence Interval
SA	0.00011407	41.879	16.2951	14.0776	22.2937
SSA	0.00022816	12.7151	16.2951	40.0769	73.4277
MSM	0.0013098	3.4174	16.2951	261.7691	273.2019
MM	0.0015122	28.4935	16.2951	241.7684	32.7667
MSF	0.0028219	29.3047	16.2951	349.3405	31.8596
MF	0.0030501	51.5816	16.2951	172.0267	18.1002
ALP1	0.034397	8.5626	6.1862	315.2513	44.9469
2Q1	0.035706	2.7212	6.1862	211.2516	140.4487
SIG1	0.035909	22.473	6.1862	26.5229	17.4501
Q1	0.037219	31.3669	6.1862	275.9628	12.3942
RHO1	0.037421	13.5903	6.1862	241.7437	29.3758
O1	0.038731	254.843	6.1862	326.3917	1.5527
TAU1	0.038959	32.4502	6.1862	190.2981	9.602
BET1	0.04004	11.7883	6.1862	354.4032	34.1524
NO1	0.040269	27.8331	6.1862	69.0535	11.7764
CHI1	0.040471	9.881	6.1862	14.0243	39.6241
PI1	0.041439	7.1556	6.1862	49.1292	49.2983
P1	0.041553	144.4475	6.1862	95.2147	2.4382
S1	0.041667	44.2008	6.1862	39.8918	11.1801
K1	0.041781	511.2552	6.1862	98.9341	0.73878
PSI1	0.041895	7.2817	6.1862	35.6577	49.2406
PHI1	0.042009	13.4872	6.1862	94.1644	25.9647
THE1	0.043091	0.86547	6.1862	274.8219	442.031
J1	0.043293	19.0472	6.1862	153.1284	19.6619
SO1	0.044603	30.7506	6.1862	15.8163	12.8834
OO1	0.044831	20.1725	6.1862	159.0372	22.8571
UPS1	0.046343	6.8615	6.1862	191.4758	69.7996
OQ2	0.075975	6.3198	5.5284	173.7631	43.1397
EPS2	0.076177	9.9375	5.5284	53.8135	30.0848
2N2	0.077487	34.6543	5.5284	262.18	8.3532
MU2	0.077689	33.7295	5.5284	155.5983	9.0943
N2	0.078999	202.0021	5.5284	307.1981	1.5275
NU2	0.079202	48.8395	5.5284	323.232	6.3176
H1	0.080397	47.2249	5.5284	173.3106	6.4726
M2	0.080511	1087.4274	5.5284	30.7153	0.28454
H2	0.080625	27.5094	5.5284	56.0931	11.3624
MKS2	0.08074	19.3004	5.5284	124.9236	19.0341
LDA2	0.081821	17.3662	5.5284	127.1463	17.7442

L2	0.082024	50.6439	5.5284	115.2521	6.6472
T2	0.083219	30.4964	5.5284	126.5415	10.3866
S2	0.083333	274.0352	5.5284	147.6317	1.1573
R2	0.083447	4.6733	5.5284	9.2481	54.735
K2	0.083561	89.8507	5.5284	168.8516	4.1806
MSN2	0.084845	6.5519	5.5284	56.8894	46.0568
ETA2	0.085074	5.5459	5.5284	133.9998	66.7396
MO3	0.11924	41.9911	5.5236	155.5371	8.219
M3	0.12077	1.0968	5.5236	229.3947	278.706
SO3	0.12206	10.201	5.5236	251.0931	34.6765
MK3	0.12229	13.3302	5.5236	198.2134	24.7131
SK3	0.12511	14.4364	5.5236	50.5951	23.389
MN4	0.15951	13.386	4.9453	337.5609	20.1411
M4	0.16102	51.6318	4.9453	54.8502	5.2363
SN4	0.16233	2.699	4.9453	336.4358	102.3867
MS4	0.16384	14.7236	4.9453	133.148	18.8206
MK4	0.16407	38.4561	4.9453	238.8437	8.535
S4	0.16667	2.6632	4.9453	173.7636	106.6478
SK4	0.16689	10.5074	4.9453	64.1666	32.0169
2MK5	0.2028	52.6873	8.2169	337.4716	9.0858
2SK5	0.20845	2.2424	8.2169	255.9094	224.2718
2MN6	0.24002	12.4566	4.7325	184.9211	20.2327
M6	0.24153	34.2355	4.7325	295.2314	7.3822
2MS6	0.24436	33.5337	4.7325	47.5764	7.7248
2MK6	0.24458	18.8957	4.7325	336.6336	16.2376
2SM6	0.24718	8.8721	4.7325	120.6915	29.9256
MSK6	0.24741	6.776	4.7325	147.7412	46.4109
3MK7	0.28331	22.4997	3.1437	32.4545	7.9513
M8	0.32205	7.9944	2.5208	289.9494	16.4488

Table 13: Race Rocks East-West Tidal Components

Constituent Name	Frequency (Hz)	Constituent (mm/s)	95% Constituent Confidence Interval	Phase (degrees)	95% Phase Confidence Interval
SA	0.00011407	39.3912	10.782	43.3488	15.6828
SSA	0.00022816	9.8499	10.782	71.0958	62.7179
MSM	0.0013098	4.038	10.782	261.0345	152.986
MM	0.0015122	19.5341	10.782	239.7428	31.6249
MSF	0.0028219	19.4375	10.782	11.9391	31.7821
MF	0.0030501	31.8851	10.782	166.2081	19.3747
ALP1	0.034397	6.0958	4.4232	305.6771	45.142
2Q1	0.035706	1.1356	4.4232	205.3397	240.6301
SIG1	0.035909	16.1167	4.4232	24.7641	17.3976
Q1	0.037219	25.8107	4.4232	284.6598	10.7695
RHO1	0.037421	9.4209	4.4232	262.9607	30.2995
O1	0.038731	214.7584	4.4232	329.105	1.3174
TAU1	0.038959	19.3474	4.4232	190.2367	11.515
BET1	0.04004	10.5818	4.4232	339.2569	27.2031
NO1	0.040269	25.0875	4.4232	74.1204	9.3417
CHI1	0.040471	5.9887	4.4232	62.3952	46.7451
PI1	0.041439	6.1352	4.4232	57.0673	41.1112
P1	0.041553	128.0983	4.4232	98.7674	1.9658
S1	0.041667	41.6003	4.4232	31.7121	8.4935
K1	0.041781	432.031	4.4232	103.4764	0.6251
PSI1	0.041895	11.4858	4.4232	26.4535	22.3205
PHI1	0.042009	5.5769	4.4232	96.4728	44.8971
THE1	0.043091	2.102	4.4232	70.7571	130.1326
J1	0.043293	19.168	4.4232	168.4468	13.9697
SO1	0.044603	19.6533	4.4232	18.7186	14.4131
OO1	0.044831	10.927	4.4232	157.1755	30.1708
UPS1	0.046343	3.8897	4.4232	187.591	88.0373
OQ2	0.075975	3.4668	5.1579	181.393	73.3715
EPS2	0.076177	4.6012	5.1579	63.3382	60.6214
2N2	0.077487	27.8421	5.1579	264.2168	9.7003
MU2	0.077689	21.4631	5.1579	167.9827	13.3341
N2	0.078999	168.8238	5.1579	309.3623	1.7052
NU2	0.079202	39.653	5.1579	333.8113	7.2598
H1	0.080397	42.078	5.1579	181.8579	6.7775
M2	0.080511	897.752	5.1579	32.2771	0.32156
H2	0.080625	24.0181	5.1579	29.7511	12.142
MKS2	0.08074	15.7663	5.1579	157.0764	21.7393
LDA2	0.081821	15.8158	5.1579	138.3816	18.178
L2	0.082024	39.3984	5.1579	115.8094	7.972

T2	0.083219	28.2734	5.1579	132.2539	10.4525
S2	0.083333	229.7332	5.1579	149.7264	1.2879
R2	0.083447	5.9009	5.1579	322.3698	40.4434
K2	0.083561	63.8125	5.1579	169.7251	5.492
MSN2	0.084845	4.2012	5.1579	45.2402	67.0137
ETA2	0.085074	2.6769	5.1579	81.2057	129.0016
MO3	0.11924	15.0837	4.5398	177.9698	18.8056
M3	0.12077	3.7139	4.5398	125.3072	67.6475
SO3	0.12206	8.051	4.5398	122.1818	36.112
MK3	0.12229	30.0144	4.5398	144.138	9.021
SK3	0.12511	3.8654	4.5398	50.7738	71.7952
MN4	0.15951	13.8405	4.196	344.7606	16.5284
M4	0.16102	54.0026	4.196	66.7994	4.2479
SN4	0.16233	2.8181	4.196	65.0105	83.2027
MS4	0.16384	18.5691	4.196	171.7864	12.6621
MK4	0.16407	29.3885	4.196	234.7991	9.4763
S4	0.16667	2.776	4.196	264.1427	86.8121
SK4	0.16689	8.1114	4.196	67.8428	35.1905
2MK5	0.2028	30.911	6.11	324.3025	11.5156
2SK5	0.20845	1.6562	6.11	310.2002	225.7873
2MN6	0.24002	4.4685	4.2358	167.1614	50.4825
M6	0.24153	14.9651	4.2358	306.8879	15.1157
2MS6	0.24436	17.479	4.2358	53.5213	13.2647
2MK6	0.24458	16.2466	4.2358	344.1302	16.9032
2SM6	0.24718	5.9431	4.2358	106.273	39.9859
MSK6	0.24741	6.0997	4.2358	125.4356	46.1452
3MK7	0.28331	14.3315	2.6309	34.5333	10.4469
M8	0.32205	2.7069	2.1728	343.6907	41.8721

Table 14: Race Rocks North-South Tidal Components

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<u>Publications:</u>

Niet, T., G. McLean and W. Merida, "Fuel Cell Operation Using Oxygen Enhanced Oxidant Flow," Report prepared for Questor Industries, Burnaby, BC, February, 2001.

McLean, G., T. Niet, S. Prince-Richard, N. Djilali, "An Assessment of Alkaline Fuel Cell Technology," Report prepared for Questor Industries, Burnaby, BC, April 2000.

Niet, T. and G. McLean, "Race Rocks Sustainable Energy System Development," Presented at the 11th Canadian Hydrogen Conference, Victoria, BC, June 17-20, 2001.

McLean, G., T. Niet, S. Prince-Richard, N. Djilali, "An Assessment of Alkaline Fuel Cell Technology," Accepted for publication in the International Journal of Hydrogen Energy.

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