Performance-Objective Design for a Renewable Energy Transportation Circuit of Christchurch, New Zealand

Susan Krumdieck, Andy Hamm, Andre Dantas and Simon Minges

***Abstract*—A systems engineering based methodology for exploring technical sustainability in the social and environmental context was used to investigate a specific transportation load in the city of Christchurch. The process includes defining sustainability performance parameters in engineering terms, defining service objectives in socio-economic terms, and then generating concept designs using standard engineering modeling.**

The approach reflects a balance between form and function, and we refer to the resulting concepts as energy architecture. In this study, the performance-objective methodology was used to develop the energy architecture for a wind and solar powered public transportation service that provides a 35km circuit of schools, shopping malls, and industrial parks. The service objective for the design was set by an existing bus service.

A number of concepts were explored for the renewable energy supply of an electric light rail trolley circuit on a dedicated (not grid connected) electric supply network. Each concept represents a different degree of capital investment and system complexity, and achieves a certain level of the desired transportation service on any given day. Real-time simulated performance modeled with historical local weather data was used to compare the performance of each of the possible architectures to the objective. A service factor was calculated to evaluate the level of transport service performance compared to the objective. The results demonstrate that no amount of investment in wind and solar energy *capacity* can provide the same service as the fossil fuel system. When pumped-hydro storage of wind and solar energy was added to the system, the service factor could be increased to 100%. The modeling exercise points out that a relatively modest investment in wind generation can produce a useful service. However, the schedule would need to be flexible to match the wind energy availability. A system like this could work if a communication system could be implemented to provide real-time schedule information.

S. Krumdieck, Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand, Phone: (+64) (3) 364 2987 ext 7249, email: susan.krumdieck@canterbury.ac.nz

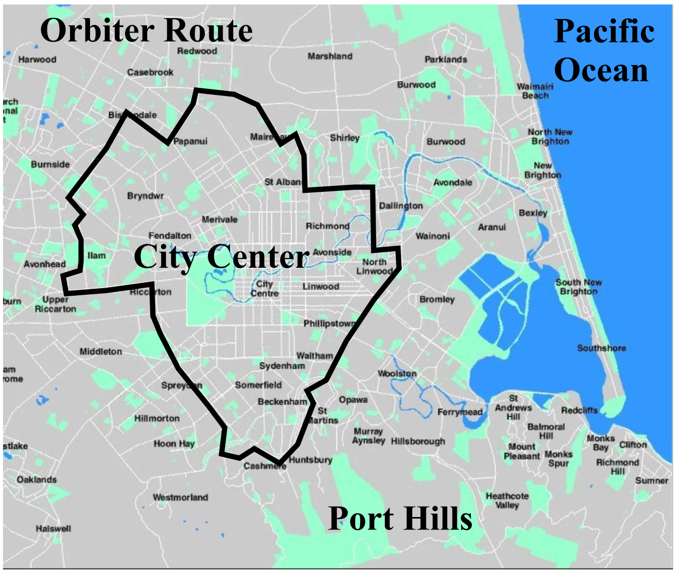

Fig. 1. Map of Orbiter Bus Route

I. Introduction

New Zealand is a remote island nation without major oil resources and an agriculture and tourism-based economy. Christchurch has an established program to explore sustainability, and the city leaders have interest in renewable energy for transportation in urban areas. Even though the public perception is that renewable energy will power the transport systems of the future, limited analysis exists to describe renewable transport systems. This project aims to examine the level of investment required, the nature of the performance, and the type of service provided by such a system. An electric light rail passenger system has been designed with the same route and schedule as the existing Orbiter service shown in Figure 1. The renewable energy is converted to electricity and supplied through a dedicated network (not grid connected) from the modeled renewable generating plants, through a power conditioning and control center, then to the rail line. A schematic overview of the system is shown in Figure 2. Several combinations of renewable energy and storage technologies were modeled to provide the transportation energy to meet the same service load as the present bus system. A real-time reservation and schedule information service has been proposed to optimize the utilization potential, maximizing service while minimizing investment. The resulting idea of a public transport system is different than the current fossil-fuelled arrangement. However, in the absence of fossil fuel for either public or private transportation, several of the renewable energy transport architectures would be both technically feasible and useful.

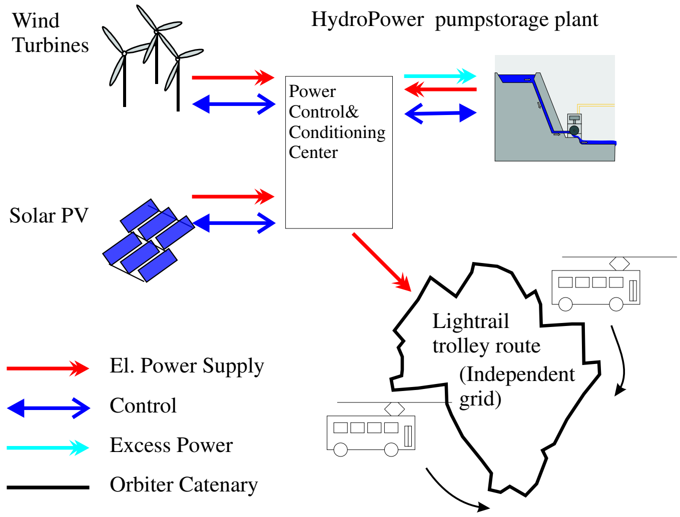

Fig. 2. Functionality of the New Renewable Energy Lightrail System

II. Performance-Objective Design Parameters

A. The Orbiter Service Performance

With a population of $350,000$, Christchurch is the largest city in New Zealand's South Island. The City covers a land area of $450km^2$ and is bounded by the Waimakariri River to the north, the Pacific Ocean to the east, the Canterbury Plain to the west, and the Port Hills to the south. The Port Hills extend for $16km$ along the south and rise to approximately 500 meters. The area of the city served by the *Orbiter* is characterized by flat outwash plains. The trolleys are modelled as light-weight passenger conveyance for city-only driving conditions, with average speed of $35km/hr$ and $25kW$ electric motor and water-cooled gel batteries as backup. The trolley line uses overhead power cables and traction rails, and the system maximum power consumption is $430kW$ (18 buses) during peak load. Trolleys travel in both directions continuously, with pickup frequencies of 10-min during business hours, 15-min in off-peak, and 30-min late night and weekends. The service is currently most vital to high school and university students, and those without the ability or means to use personal automobiles. The schedule reflects high ridership around school and shopping hours. The service costs $2NZ ($1.30US) for adults and $1NZ for students.

B. Renewable Energy Objective

The objective was to simulate the performance of a transport system which consumes only wind or solar generated energy. The 15-minute wind and solar data used for the study was resourced from the weather station in the Department of Geography, University of Canterbury. The solar radiation is total horizontal radiation (beam and diffuse). The wind resource has not been well studied, but is in the range of class 4-5 on the hills. The national electric grid system is supplied primarily by hydroelectricity (57%) and natural gas (30%), with geothermal generation (7%) and coal and others making up the remaining 6%. The grid network was built several decades ago, and the power supply to Christchurch cannot be increased for the purposes of providing transportation without major network upgrades. The national generating capability has been near capacity in three of the last four years, requiring national campaigns to reduce electricity consumption during the winter months. The country's largest gas field is set to go into decline by 2005. Thus, the constraining factors for the model system are that wind and solar energy can be developed, but the transport system must be served by an independent electrical network. The wind turbines are modeled by commercial three-blade variable speed machines, with specifications matching the *DE-Wind D6* model. The solar PV system was modeled on the *UniSolar* specifications, with nominal conversion and conditioning efficiency of 8%. In the last concept architecture developed, a pump-storage water system was designed using a Francis turbine with maximum pump energy efficiency of 80% and generation efficiency of 85% with decreasing per-

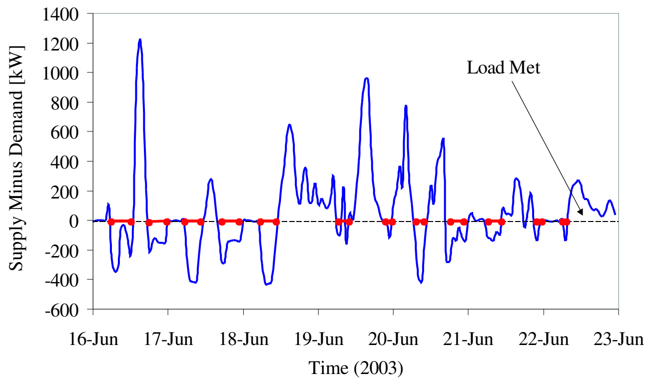

Fig. 3. Set Schedule Load Supplied by a Wind Turbine

formance for part load operation.

III. Energy Architecture

A. Concept of the Performance-Objective Design

Engineers usually approach design projects in a different way than architects. Engineers define the customer's requirements in terms of engineering parameters, then go through the concept generation and design optimization process to produce a product or system that will meet the requirements. Architects are interested more in aesthetic aspects and they work to balance the utility of the structure, site integration, occupant aspirations and expectations, against budget and structural constraints. Houses, buildings, landscapes and other architectures are not thought of as *optimal* as is the case for engineering design. Architecture creates the structures in which people go about their daily lives, without dictating the choices or nature of activities people can pursue. An engineered product, such as a DVD player, must be used as intended to provide the service for which it was designed. For many years, engineers have worked to develop low cost solar and wind technology because people want cheap and unlimited energy. While engineers work to provide what people want, most architects know to listen to what people want, and then gently show them what they can actually afford, and how it will fit their desires. After years of research, we have reached the conclusion that a sustainable energy *system* must be designed by engineers who think like architects.

The *Orbiter* bus service is successful in terms of ridership due to high quality vehicles, route plan, and most importantly, frequent service availability. Evening and weekend buses typically run below 5% occupancy, with only one or two passengers. At the first level of investigation we modeled a simple renewable energy system, then calculated, hour by hour, how many of the trolleys we could run compared to the current schedule. In order to compare performance between concepts we use a service factor S_a which is the total trolleys that were run over the year compared to the schedule.

$$S_a = \frac{\sum buses \quad run}{\sum buses \quad demanded} \tag{1}$$

IV. Results

A. Concept 1: One Wind Turbine

The first architecture explored was the lowest investment concept – a single wind turbine with no energy storage. A wind turbine with $1MW$ rated power, placed in a wind power site on the Port Hills with an utilization factor of 0.4 would produce an annual *average* power generation of $435kW$, which is a good match with the *maximum* transport load of $430kW$. Of course, while the total energy generated exceeds the requirements for the trolley system, the power is available only on the same schedule as the wind. This case of one wind turbine produced an annual service factor of 61%. To point up the meaning of the service factor Figure 3 shows when the demand was met and by how much the wind power generation exceeded the electric trolley load or how far it fell below it. Of course, in the 11:00pm to 5:00am timeframe, there is no trolley load, so the load is met regardless of the wind generation.

B. Concept 2: Multiple Wind Turbines

Our group wanted to investigate the relationship between wind generation *capacity* and a scheduled service load. Increasing the number of $1MW$ wind turbines did increase the service factor. Two turbines improved the service factor from 61% to 69%. Three turbines increased the service factor to 73%, and four turbines gave a factor of 75%. However, even increasing the number of $1MW$ wind turbines to ten provides a service factor of just 80%.

C. Concept 3: Solar PV

The solar resource in Christchurch is not ideal, with the coastal weather patterns producing a climate somewhat similar to Portland, Oregon. The South Island in mid winter has an average daily insolation of $1.25kWh/m^2$. Given a daily transport demand of $4,440kWh$ and 8% PV system efficiency, a total of $35,000m^2$ of solar PV would be indicated. Using the actual solar incidence data, hour by hour assessment gave a service factor of 56% for this concept.

The service factor reaches its maximum value at 62% for a collector area equal or greater than $65,000m^2$.

D. Concept 4: One Wind Turbine plus Solar PV

In the fourth concept, we investigated the idea that the wind and the sun might compliment each other over the course of the year. The $1MW$ wind turbine output power was combined with the power from $20,000m^2$ solar PV panels. For this concept fewer hours had no service provided. However, the service factor was still 80% over the year. Figure 4 shows the wind energy, solar energy, and trolley service provided compared to the service schedule for a winter day in 2002. In the time period from 11:00am until 4:00pm, all 18 trolleys were running according to schedule. However, there were approximately 7 hours where trolley service was severely reduced or curtailed.

E. Concept 5: Wind Turbine plus Pumped-Hydro Storage

The wind energy available often exceeds the transport load by as much as a factor of two. As seen in Figure 4 for June 19, 2003, the nature of the variable wind resource means that there are a significant number of periods with no or strictly reduced service. The pumped-hydro storage plan involves a $500kW$ electric generation plant using a Francis turbine. A water storage facility is placed on a nearby hill with a storage capacity of $1 \cdot 10^6 m^3$ and a head of $100m$. The model uses the turbine to pump water from a small reservoir on the river up to the storage facility whenever the wind power exceeds the load by the minimum pump power of $150kW$. Unlike battery storage, the pump cannot come on-line until sufficient power is available to operate it at the minimum part load operation

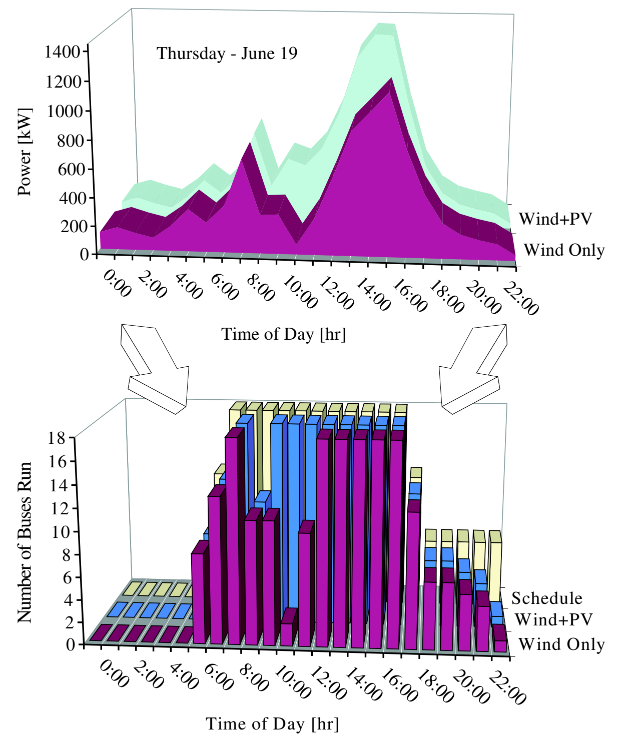

Fig. 4. Wind and Solar Energy Resource and the Resulting Possible Transport Load for one Winter Day

specification. Therefore the utilization factor may be enhanced by increasing the number of (pump-) turbines. The functionality and the total service factor are increased when adding complexity to the system by using three smaller $200kW$ Francis turbines on separate penstocks. The smaller penstocks, however, have higher friction head loss and lower pumping efficiency. We can operate the first pump to store water when the wind power exceeds trolley demand by only 20%. We can also run just one turbine at higher flow volume, and thus higher generation efficiency when the wind power is 20% below the demand. The service factor for the $500kW$ pumped-hydro storage design is 97%, while it increases to 99.1% for the system with three $200kW$ pump/generators on three separate penstocks.

V. Discussion

Our research group aimed to explore the idea of a truly sustainable, renewable energy transportation service. We also wanted the concepts we generated to be relevant. We chose to perform engineering design and simulations for a stand-alone electric trolley service in our city. The trolley ser-

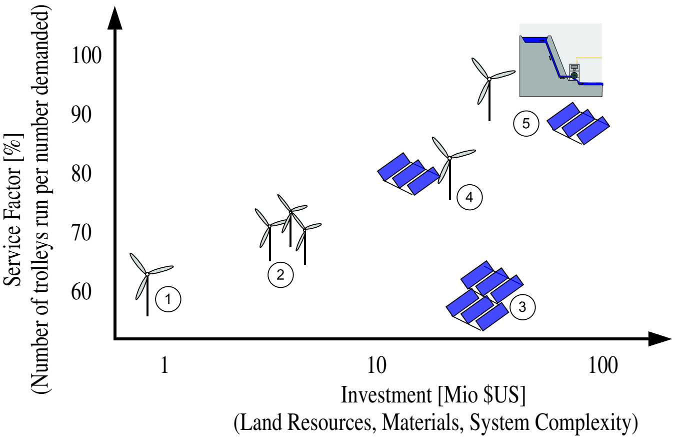

Fig. 5. Investment for an Energy System Compared to the Achievable Service Factors

vice was based on an existing popular bus route and used known vehicle and power systems technology. We didn't know which type of renewable energy, or which combination would provide the same service that fossil fuel now provides. Thus, we investigated possible *Energy Architectures* by simulating the performance of different conceptual power configurations and comparing by calculating an annual service factor. We used existing commercial wind and solar PV product specifications, and historical wind and solar data to run hour-by-hour simulations of each concept. Cost was not the first consideration in developing the concepts as we primarily wanted to investigate technical feasibility and performance. However, using rough estimates of capital investment costs we conclude that the cost of providing exactly the same service currently provided by fossil fuels would likely exceed the economic value of the transportation service to the consumers.

Figure 5 depicts the results of the design conceptualization and simulation study, showing the relative investment in power production plant compared to the annual service factor. The lowest investment system would be a single wind turbine. The single wind turbine would cost several orders of magnitude less than the concept which would replicate the fossil fueled bus schedule. The single wind turbine concept had no storage except onboard the trolleys. Of course, the fossil fuel system uses 100% stored energy. From an engineering perspective, the only solution to meet the schedule requirements would be concept 5 with significant hydro storage. However, we reason that the costs of replicating the service afforded by fossil fuel with renewable energy will be higher than the value of the service to riders. From an architectural perspective, we need to examine the service schedule and work out some compromise between customer desires and technical and economic feasibility.

We propose that a renewable energy architecture must have a degree of flexibility in the delivery schedule and availability of service in order for the cost to be viable. Is this acceptable to the users? Is it technically possible? We would suggest that the more successful modern public transport services are actually using this model now to deal with schedule variability caused by increasing congestion. At many bus centers, like the central city bus exchange in Christchurch, the real-time arrival and departure times are displayed for riders waiting in the common area. There is evidence that riders would rather just look at a board to see when the next bus will come than to try to work out a schedule, and wonder if the bus is on time. It is technically possible to produce the power, control, and information system to let passengers at each stop know what trolleys are available, when they will arrive, and a forecast for near-term availability. A renewable trolley system like this may not seem attractive as part of the current automobile-dominated market. We propose that in an environment of restricted fossil fuel availability, the overall energy architecture would be designed for pedestrian and bicycle dominated personal travel. In this context, many people might find the possibility of a ride appealing, even if they had to inquire as to availability before deciding to go to the trolley stop to get a ride. We further propose that in an environment of very scarce fossil fuel for urban transportation, delivery of food and goods and removal of waste will be priorities. In this context, the exact timing of deliveries may not be as important as the capability to conduct trade and maintain economic activity.

We draw an important conclusion from this project about the nature of any engineering planning for sustainability. The role of energy in the current fossil-fuel transportation situation is fundamentally different from that of a sustainable society which relies on renewable energy. Technology and information systems in a renewable energy transportation network would provide an active link between services desired and services available. These capabilities would allow the sustainable society to maintain daily productivity and activity while coping with energy variability and constraints. However, the system would have to be designed, built, and operated for sustainability in the first place. We have demonstrated that renewable energy cannot substitute for fossil fuel, and thus we conclude that the current energy architecture, based on 100% stored energy, cannot be adjusted or developed or improved to operate in a sustainable way. Our group is working to discover sustainable system designs, and to develop the modeling and analysis tools to assist in the process of energy architecture development for the new renewable energy systems.

Dr Susan Krumdieck has worked in energy engineering and renewable technology development since the 1980's. With Professor B. Wood, she developed a theory modeling the energy/environment/society as a feedback control system. That work has led to new and intriguing ideas in technology, modeling, problem solving and the role of engineering in the development of humanity toward a sustainable destination.