MODELING SEAWATER DESALINATION USING WASTE INCINERATION ENERGY - FUNDAMENTAL MODEL

Ken Udono and Renate Sitte
School of Information Technology
Faculty of Engineering and Information Technology
Griffith University, Gold Coast Campus
PMB 50 Gold Coast Mail Centre
Queensland 9726, AUSTRALIA
Email: k.udono@griffith.edu.au
Email: r.sitte@griffith.edu.au

KEYWORDS
Waste, Energy, Modeling, Dynamic System, Seawater Desalination, Incineration

ABSTRACT

This paper models the potential use of waste-to-energy conversion of municipal solid waste to power seawater desalination, using a dynamic system approach with control theory as basic methodology. Australia has been hit by one of the worst droughts causing water shortage in many places, including the city of Gold Coast. As so many cities, this city is also faced with the handling of waste generated by its inhabitants. Currently most of the waste generated from the city goes into landfills despite that waste can be a source of cheap fuel to obtain power. The Gold Coast has been the fastest growing city in Australia for quite sometime and a long-term solution for both these issues is needed. In this paper, incinerating waste to obtain electricity to power desalination of seawater is investigated. The fundamental model is implemented with a modular hierarchical structure in Matlab/Simulink^{TM} and the result of the simulation is presented.

INTRODUCTION

This paper models the potential use of Municipal Solid Waste (MSW) incineration to power seawater desalination in order to overcome water shortage and waste landfill issues surrounding Gold Coast city in Australia. Australia has been hit by one of the worst drought ever resulting from climate changes such as El Niño, global warming, etc. The latest drought between 2001 and 2003 was the worst in the recorded history of the Gold Coast city. A year after the drought, the city of Gold Coast is still under water restriction and the city council is forced to consider several solutions to alleviate the repeated shortage of fresh water. Despite of good rainfalls breaking the drought, the main supplier of water i.e. the Hinze dam is less than 50% of its capacity. A fast growing population of the city also adds additional strain to the city's infrastructure in the long term. The Gold Coast city is the sixth largest city in Australia, which has a population of 425,418 (GCCC 2003). The yearly population growth is estimated at about 13000 and predicted to reach 1.2 million by year 2056 (GCCC 2003). An average daily water usage was of 156 million litres during 2003 with water restriction in place, however on a hot summer day, it can be as high as 300 million litres (GCCW 2003). By 2056, the daily water demand is estimated to increase up to 465 million litres a day, which is over 2.5 times more than the current demand of 185 million litre (GCCC 2003). Therefore a long term solution to the water shortage is mandatory and so far has not been satisfactorily found.

This paper investigates the introduction of desalination to produce fresh water from seawater, while powering the desalination plant by Waste-To-Energy (WTE) conversion of MSW. The model presented in the paper is the fundamental model that simulates how drought and desalinated water affect the water availability and how much of electricity can be potentially obtained from the incineration of the MSW. This study is motivated on waste incineration successfully being practiced in several parts of the world (Austria, Japan, Germany), for obtaining energy for different purposes. According to a report made by the city council (GCCC 1997; GCCC 2002), 437,447 tonnes of solid waste was collected during 2000-2001. 87 % of waste collected have been buried in landfill and only 13% was recovered to be recycled, reused and avoided landfill. This has been despite of almost 70% of the waste generated being combustible and potentially a source of cheap fuel for obtaining energy. Seawater desalination is well proven and widely used method for fresh water production in regions where fresh water is scarce. Saudi Arabia is the largest producer of desalinated water and has 27 desalination plants (SAIS 2003). In Saudi Arabia, the desalinated water is distributed using 2,300 miles of pipelines and fills 70% of drinking water demand in the country. With completion of additional plants, the country is able to produce 3028 million litres of fresh water per day from seawater desalination. Water desalination is an expensive production process, but it ensures continuation of fresh water supply in dry weather conditions.

There are a number of WTE conversion techniques for generating energy from waste, in different stages, ranging from already-in-use to research and

Proceedings 18th European Simulation Multiconference
Graham Horton (c) SCS Europe, 2004
ISBN 3-936150-35-4 (book) / ISBN 3-936150-36-2 (CD)

experimental level. Common techniques are thermal conversion including pyrolysis, gasification, and incineration and other types of processes such as landfill gas and ethanol production. Typically in an incineration method, the heat from combustion of MSW is used to raise steam in a boiler. It is then passed through a turbine generator to produce electricity (Baird 1993). There are several seawater techniques currently in use. Some of the major ones are distillation such as Multiple Effect Distillation (MED) and Multistage Flash Distillation (MSF) and membrane methods such as Reverse Osmosis (RO). In RO method, seawater is forced through the semipermeable membrane by mechanical pressure. It is more energy efficient than the distillation method, which uses thermal energy to evaporate the seawater. This is why RO is gaining popularity in recent years, however in oil rich countries like Saudi Arabia, where energy is not an issue, MSF is still the most often practiced method.

The model presented in this paper is an adaptation and extension to the economic model that utilised a dynamic system approach with control theory presented by R. Sitte (Sitte 1998; Sitte 2001; Sitte 2002). This approach has been successfully applied into modelling green energy export as well as the El Niño effect on Australian economy. This methodology allows focusing on a higher level of resolution, without the loss of relevant sub-models, whenever required. This approach gives us the prospect of integrating all three, the water desalination, and the El Niño and green energy effect models. Our model uses simulation to examine how the desalination assists in the city's water supply, while reducing the landfill. The model itself is implemented in Matlab/Simulink^{TM} as a dynamic model simulating the sequence of economic cycle as it is affected by climatic fluctuations. The overall goal is to investigate whether this can be successfully achieved in an Australian city, such as the Gold Coast City while incorporating future population growth, and deficiency of rainfall during drought conditions. The model can be adapted to simulate other cities, by simply changing the local parameters.

FUNDAMENTAL MODEL

This model follows a dynamic system approach with control theory as basic discipline, as opposed to the statistical approach that is traditionally used in economic modelling (Sitte 1998). The benefit is that the high level of resolution can be better maintained and the cause and effect dynamics are more visible than in a statistical model. The long-term behaviour of the system can be observed without being side tracked by minute detail. The aim of this model is to obtain a faster result with accuracy within 5%-10% error rate.

The fundamental model has two major components: Water dynamics and Waste dynamics. The top level of the fundamental system implemented is shown in Figure 1. In the water dynamics section, the flows between blocks represent the amount of water. The waste dynamics section models the power generation from WTE conversion and the power required for the desalination of seawater. The fresh water resulting from desalination in the waste dynamics section is added to the available water in the water dynamics section. This is the only coupling between the two components.

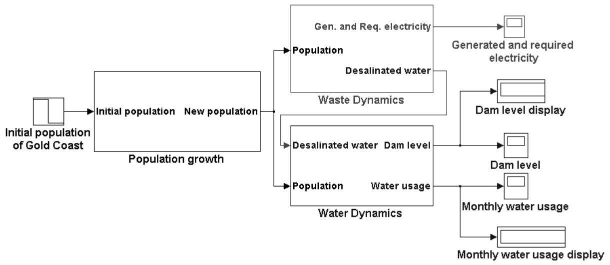

Figure 1: Top Level Featuring Water and Waste Section

The simulation is run for a monthly step size and the population is used to initiate the system. There are various types of data used in this model including water, energy, population, and amongst others. The data related Gold Coast City was taken from Gold Coast City Council (GCCC 2003) and the Australian Bureau of Statistic (ABS 2003). Local weather data such as average rainfall were collected from the Bureau of Meteorology (BOM 2003). The desalination process and incineration related data, which are mostly the result of years of operation experience, were taken from the literature. The following sections provide a brief description of each component.

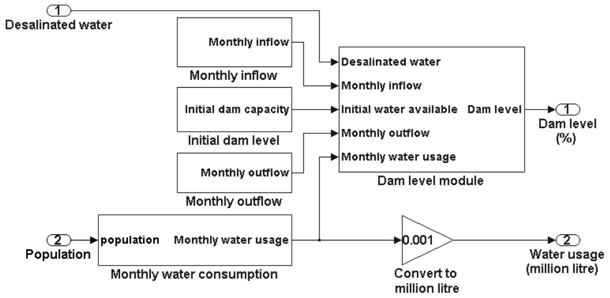

Figure 2: Water Dynamics Model

Water dynamics model

The water dynamics model (Figure 2) involves rainfall-runoff model surrounding city's major source of water, the Hinze dam, to determine the availability of water for the city. However the main focus of this research is on effects of the desalination powered by incineration, but not on building a superior rainfall-runoff model (water balance model). In this fundamental model, the black box modeling approach was chosen for the water balance model using rainfall data, dam level, catchment size etc, because of its simplicity. As only a limited amount of data is currently available, the conceptual models or physically based distributed model, which should be used only when available data is able to support it, cannot be used in this case (Ragab 1999). An inflow of the dam was approximated as a function of monthly rainfall onto a certain percentage of catchment areas of the dam (in this case 66%). An evaporation is removed and regarded as part of the outflow. To model the rainfall, data of monthly average rainfalls were taken from the Bureau of Meteorology (BOM 2003) and approximated using a best fit cubic polynomial, to be used as a typical monthly rainfall in the model.

$$f(x) = 0.04989x^3 - 0.6083x^2 - 0.4653x + 23.71 \qquad (1)$$

Equation (1) above is the polynomial approximation used in the model. The comparison of approximated and actual average rainfall is shown in Figure 3.

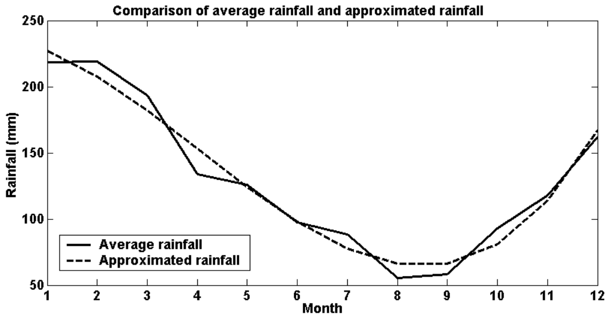

Figure 3: An Approximated and Average Rainfall

Waste dynamics model

The waste dynamics model (Figure 4) analyses and determines the amount of power generated from incineration and the energy required for the desalination plant. The WTE conversion method investigated in this model is a mass burning method of MSW. A physical composition heating value estimation model by K. Amz and A. Ghrarah (Amz and Ghrarah 1991), was chosen to estimate the heating value of waste (Equation (2)). This model uses a weighted (in %) function of heating coefficients of the incinerable components of waste: food, paper and plastic. The relative accuracy of this model was demonstrated by Abu-Qudais and Abu-Qdais (Abu-Qudais and Abu-Qdais 2000).

$$E\ (kj/kg) = (23(F + 3.6(PA)) + 160(PL)) * 2.324 \qquad (2)$$

Where F, PA and PL are the proportion (%) in weight of food, paper and plastic respectively in the waste incinerated. This composition detail for the Gold Coast is unknown due to lack of recorded data. Instead, the waste composition from its neighbouring Brisbane city was chosen to be used because the waste composition the two cities would be similar (GCCC 1997). The waste compositions of Brisbane city as well as other cities are shown in Table 1 for comparison. Using Brisbane data, the heating value was estimated to be 9134.16kj/kg in our model.

Table 1: Waste Composition from Various Cities

Waste type	Brisbane	Melbourne	Wollongong	Jordan	Ontario
Newspaper	5.20	7.20	12.50	11.45	35.80
Other Paper	13.50	16.70			
Plastic	7.70	7.70	12.80	16.15	7.50
Rubber	1.00	N/A	N/A	N/A	
Glass	10.50	6.90	3.50	2.06	7.80
Aluminium	1.00	0.60	N/A	N/A	N/A
Steel	3.00	3.30	5.70	2.06	14.00
Other Metal	2.10	0.10	0.30		
Food	28.00	31.20	52.10	62.64	16.00
Wood and Garden	21.00	20.70		N/A	11.90
Other Organic	N/A	N/A	10.70	N/A	N/A
Rags	2.00	2.20	N/A	N/A	N/A
Inert	N/A	3.40	N/A	N/A	N/A
Other	5.00	N/A	2.40	5.64	7.00
Reference	GCCC 1997	GCCC 1997	GCCC 1997	Abu-Qudais and Abu-Qdais 2000	Morris 1996

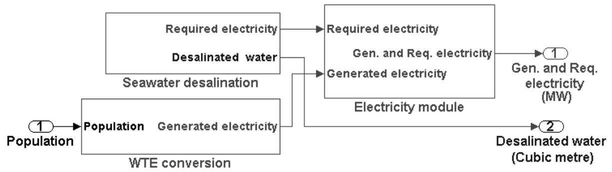

Figure 4: Waste Dynamics Model

The electricity generation from incinerating MSW typically has an efficiency of 10%-15% lower than fossil combustion, which has a 30%-40% efficiency. To estimate the potential electricity generated from incineration of MSW, an average heating value required for producing 1kw of 20089kj from various literature sources was used in this model (Baird 1993; Kathirvale et al. 2003; Morris 1996; Otomoa et al. 1997). The amount of waste generated from the city is estimated using data from the council report in 2002 (GCCC 2002), which is 1.1 tonnes per person per year. At this stage we use the assumption that the entire combustible waste included in the heating value estimation (77% of total waste generated) is incinerated for power generation in regardless of processing capacity of the incineration plant. We do this to examine how waste can power desalination and find the potential of desalination powered by waste incineration.

We also calculate the estimated electricity required for desalinating seawater in the waste dynamics model. Theoretically 0.86kWh of energy is required for conversion of $1m^3$ of seawater to freshwater (DESWARE 2003). However, the actual power consumption figure can be much higher, up to 20 times more depending on method used. As for our fundamental model, no particular desalination method was chosen in this estimation, but an average power consumption of common desalination methods ($10.2kwh/\ m^3$) was used to find the electricity required for desalinating seawater (DESWARE 2003). This is because further investigation is required to find the best suitable desalination method for our case using power from incinerating MSW. There are at least two possible options for implementing desalination powered by waste incineration. Such options are for example locating desalination plant and incineration plant side by side to use heat directly from incineration plant for distillation desalination process or alternatively locating them remotely to use the electricity generated from the incineration plant for a non-thermal desalination method. At this time our immediate interest is to investigate how much of desalination process can be powered from incinerating the MSW in general term.

SIMULATION EXPERIMENTS AND RESULTS

This section explains the calibration of the model conducted prior to examining the effect of each element on water availability. Several experimental simulations and their results are then discussed by investigating the effects of each chosen parameter for a period of 10 years.

Model Calibration

The purpose of the calibration is to obtain stable conditions represented by a flat (or horizontal wiggle) curve of the dam level (%) over a medium time span (in this case for 10 years). This is done by fine-tuning parameters and some of the approximated values in the water dynamics component. The calibration was done using the average rainfall with and without population growth. The initial population was set to 425,418 (year 2001 figure). The calibrations were repeated four times for different initial dam levels: 25%, 50 %, 75% and 100% for a span of 120 months (10 years). Figure 5 shows the dam level output from the calibration using an average rainfall without population growth.

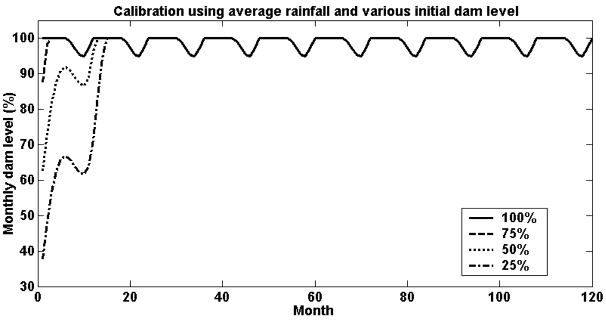

Figure 5: Calibration Results Using Average Rainfall

With this calibration setting, it maintained a relatively flat horizontal wiggle after reaching full capacity. The wiggle is caused due to variation in the seasonal rainfall on the Gold Coast. Typically winter weather conditions are much drier, causing a definite drop of dam level by about 7% during winter. With an initial level of 100%, it never drops down below 100% until the winter month of July. When the initial dam level was decreased to 75%, it took several months to restore its full capacity. If the initial level was further dropped to 50% and then 25%, the number of months taken to reach full capacity increased to 12 months and 14 months respectively.

Same calibrations were also repeated with projected population growth. Overall, this calibration provided almost identical result to the first calibration without population growth. This indicated that effect of population growth on overall water availability in this simulation duration (10 years) is fairly low, however the effect can become greater for longer term. The only obvious difference between these two simulations was higher amplitude of the wave, which is gradually becoming greater, during wintertime. The higher consumption of water from increased population results this increase of amplitude. Overall these calibrations gave satisfactory result of a slightly oscillating but generally stable dam capacity level as expected.

We verified the short-term behaviour of the water dynamics model, using recorded data of the Hinze dam level and the rainfall during latest drought between February 2001 and October 2003. Figure 6 shows a comparison of our simulated dam level and the actual dam level recorded.

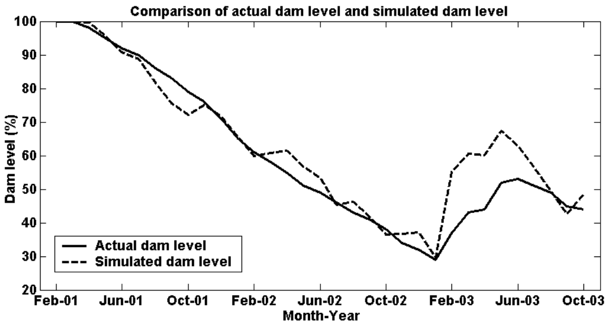

Figure 6: Dam Level Result Using Latest Drought Data

As it can be seen, our model tends to overestimate the dam level, particularly in second half of the graph. This is because due to the long drought condition during 2001-2002, the catchment area had dried out and the rainfall during early 2003 was ineffective. The rainfall was absorbed into the ground before it reached the dam instead of flowing into the dam. However our black box model approximates inflow into dam directly using rainfall without reflecting geographic characteristic or weather conditions of the catchment. This results overestimation of inflow in the case of rainfall after a long period of dry weather condition. Despite of this, the overall error percentage was found to be about 10% although highest error percentage being 50%. At this time, this error rate is acceptable because a vast amount of data is still missing and other modeling methods are also being considered.

Drought effects on water availability

Following the calibration, in order to examine the effects of each chosen parameter on dam level for a period of 10 years, we performed a set of systematic simulations. The first set of experiment was to investigate the effect of drought on the dam level and the recovery of the dam level from various lengths of drought. To replicate drier weather during drought, the average rainfall was reduced by 50%. This is justified because in the drought year of 2002, the rainfall was about 50% of its normal average. The drought was set to start at beginning of the third year of the simulation with three different lengths of drought: 1 year, 2 years and 3 years. Figure 7 shows the result of these drought simulations.

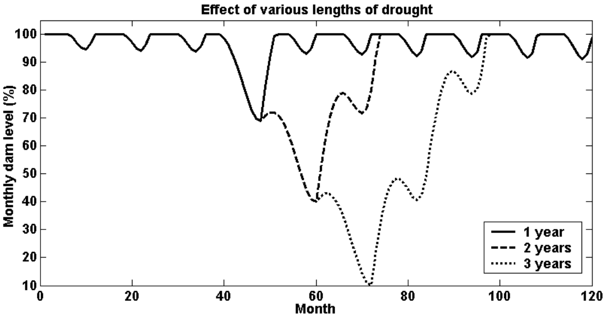

Figure 7: Drought Effects on Dam Level

In all cases, the dam was able to recover from drought within the simulation period. In the case of 1 year drought, it took 4 months to reach full capacity after the end of the drought. For the case of 2 years drought, 14 months were needed to reach full capacity. In the case of 3 years drought, 25 months of recovery were required. The lowest dam levels reached in each case were 68.98%, 40.08% and 10.06% at the last month of drought year respectively. From this simulation, it can be seen that with a drought of 3 years or more there is already a danger of running out of fresh water. Considering that we actually have now less than average rainfall after two years of severe drought, these simulations appear realistic.

Desalination effects on water availability

The purpose of the next two simulations is to examine the influence of a desalination facility on the availability of water. For convenience we measure this availability again on the dam level, although transporting the water from sea level up to the dam might not be very realistic, but these are issues beyond the purpose of our research. Three different capacity sizes of desalination plants, 10,000m^3/d, 20,000m^3/d and 40,000m^3/d were simulated in this experiment. Figure 8 shows the comparison of the dam level using rainfall data between February 2001 and October 2003 with three different desalination plants as well as without any desalination plant. In the case of no desalination as previously shown in Figure 6, it reached lowest dam level of 29.56%, but with introduction of desalination, it improved to 33.6%, 37.6% and 45.4% using 10,000 m^3/d, 20,000 m^3/d and 40,000m^3/d of desalinated water respectively. An average improvement of the dam level from desalination was found to be 2.73% per 10,000m^3/d throughout the simulation period.

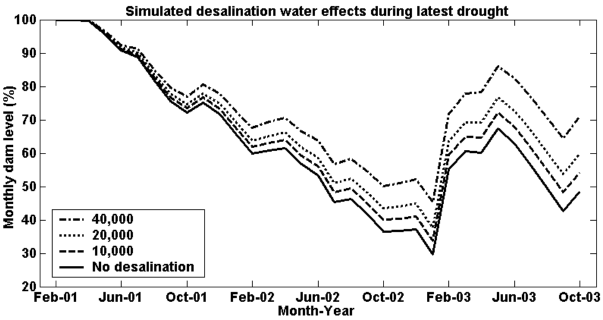

Figure 8: Effects of Desalination During Latest Drought

Figure 9 shows results of the dam level simulation during 3 years drought with same desalination capacity setting. This simulation was conducted to examine how desalinated water improves water availability during 3 years drought, which was previously shown in Figure 7. During the 3 years drought without desalination, it reached the lowest dam level of 10.06%. With inclusion of desalinated water, it was improved to 16.20%, 22.34% and 34.62% respectively. An average dam level improvement per 10,000m^3/d during the drought period was 2.82%.

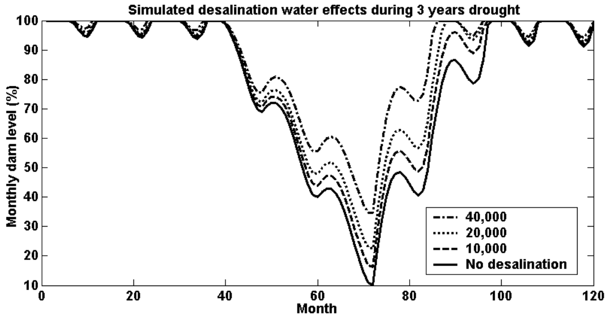

Figure 9: Effects of Desalination on Drought of 3 Years

Electricity generation and requirements

Figure 10 shows the comparison of electricity generated from incinerating MSW and electricity required for desalinating 20,000m^3/d of seawater from waste dynamics model. The result is from an early stage of our model development for initial comparison. It showed that it is possible to generate twice as much as electricity required for desalination process from incineration initially. At the end of the simulation, it simulated three times more electricity than electricity required for desalination due to increased MSW generated from population growth. However this may not be realistic, because while there might be sufficient waste the incineration facility may not have capability of processing all of MSW from the city. Moreover, the amount of energy required for desalination can be potentially reduced or possibly increased when the most suitable desalination method is determined at later stage of the research.

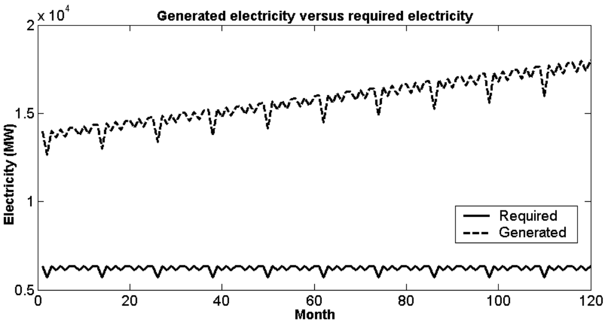

Figure 10: Generated Versus Required Electricity

CONCLUSION

This paper presented our fundamental model for modelling seawater desalination powered by waste incineration using a dynamic system approach, with underlying control theory. The fundamental model was built in Matlab/Simulink^{TM}. This version of our model was implemented following investigation of desalination and incineration technologies described in the literature and the collection of Gold Coast city data including population, weather, water and waste. The water dynamics model was calibrated to current conditions and several experiments were conducted using a 10 years period. The water dynamics model incorporated population growth and subsequent water demand increase. Our model was found to overestimate the dam level of the Hinze dam due to the approximation method of inflow (rainfall/runoff) under the current absence of an accurate estimate of the catchment area. However, in the verification process using data between 2001 and 2003, the average error was found to be about 10%. The effects of additional water from desalination on the dam level during a drought were also observed using recorded data as well as long drought conditions. The initial results from the waste dynamics model revealed that more than twice of electricity required to desalinate 20,000m^3/d of water could be obtained from waste incineration. Future work for the advanced model includes integration of El Niño effect and the economical impact, as well as alternative renewable energy.

REFERENCES

Australian Bureau of Statistic (ABS). 2003. http://www.abs.gov.au/.

Abu-Qudais M. and H. A.Abu-Qdais. 2000. “Energy content of municipal solid waste in Jordan and its potential utilization”. *Energy conversion and Management*, Vol. 41, 983-991.

Amz K. and A. Ghrarah. 1991. “New approach for estimating energy content of municipal solid waste”. *Journal of environmental engineering*, Vol. 117, 376-380.

Baird S. 1993. “Energy from Waste”. *Energy Fact Sheets,* The Energy Eduators of Ontario, http://www.iclei.org/EFACTS/ENRGYWST.HTM.

Bureau of Meteorology (BOM). 2003. http://www.bom.gov.au/.

DESWARE. 2003. “Energy requirements of desalination processes”. http://www.desware.net/desware/desa4.asp.

Gold Coast City Council (GCCC). 1997. “State of the Environment – City of Gold Coast Benchmark ‘97”. http://www.goldcoast.qld.gov.au/t_std2.asp?PID=2267.

Gold Coast City Council (GCCC). 2002 Solid Waste advisory Committee. *2002 Vision on Waste: A solid waste management strategic plan for Gold Coast City*. Gold Coast City Council (GCCC). http://www.goldcoast.qld.gov.au/.

Gold Coast City Water (GCCW). 2003. http://www.goldcoastwater.com.au/.

Kathirvale S.; M. N. Muhd Yunus; K. Sopian; and A. Halim Samsuddin. 2003. “Energy potential from municipal solid waste in Malaysia”. *Renewable Energy*, Vol. 29, 559-567.

Morris J. 1996. “Recycling versus incineration: an energy conservation analysis”. *Journal of Hazardous Materials*, Vol. 47, 277-293.

Otomoa S.; U. Mori; A. Terazono; T. Aso; and R. Sameshima. 1997. “Estimation of energy recovery and reduction of Co$_2$ emissions in municipal solid waste power generation”. *Resources, conservation and Recycling*, Vol. 20, 95-117.

Ragab R.; K. Blyth; M. France; I. Littlewood; C. Loumagne; C. Michel; M. Monfort; C. Perrin and A. Weisses. 1991. “Survey of modelling approaches suitable for AIMWATER”. *European research project “AIMWATER”*, September 1999, http://dataserv.cetp.ipsl.fr/AIMWATER/reports/modelsurvey_report.pdf.

Saudi Arabian Information Source (SAIS). 2003. http://www.saudinf.com/main/a541.htm.

Sitte R. 1998. “Modeling The Propagation of El Niño Climatic Oscillations on Australian Economy – Part I: The basic model”. In *Proceedings of the IFAC/SICE Workshop on Control in Natural Disasters (*Tokyo, Japan, Sep. 21-22). Elesevier, 35–38.

Sitte R. 2001. "Modelling Green-Energy Export in Australian Economy - Part II Advanced model”. In *Proceedings of the IFAC Workshop on Modelling and Control in Environmental Issues (*Yokohama, Japan, Aug. 22-23). Elesevier.

Sitte R. 2002. "Zooming-In Modelling Method For Managing Complexity”. *International Journal of Modelling and Simulation*, Vol. 21, No. 4, 104-109.

AUTHOR BIOGRAPHIES

KEN UDONO has received his Bachelor of Information Technology with Honours from Griffith University in 2001. He is currently PhD student in the Faculty of Engineering and Information Technology, Griffith University, Australia under supervision of Dr. Renate Sitte.

RENATE SITTE obtained her PhD (1995) and MPhil (1993) from Griffith University in Microelectronic Engineering. She received her Systems Engineering degree (Ingeniero de Sistemas) in 1985 from the Universidad de Los Andes in Venezuela. She is a Senior Lecturer in the Faculty of Engineering and Information Technology, Griffith University, Australia, where she has been faculty staff since 1986. Her field of research is in modeling and simulation, one major ongoing project is Virtual Reality Prototyping Micro-electro-mechanical systems (MEMS).