Simplifications of Simulation on Energy Balances and Estimations of a Hybrid Renewable Energy System for Use in Cold Climate Regions*

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A simplified double grade meteorological data model for the simulation of the annual performance of a domestic-size renewable energy system is proposed. With the model, only two representative days (clearest and cloudiest) during each season of the year are necessary to estimate annual energy balances, carbon emissions and the running costs. The model was chosen in preference to other simplified models based on the error distributions from the results of the continuous simulations in a test period. Detailed numerical simulation studies show that the carbon emissions from the renewable energy system are about 16% of a comparable conventional system. The thermal energy produced by a solar collector during the winter season, however, is insufficient to meet all the loads so that frequent heat pump operations and the auxiliary boiler are necessary in cold climate regions.

Key Words: Renewable Energy, Carbon Emissions, Hybrid Solar Panel, Energy Balance

1. Introduction

There is now an ongoing interest in new sources of energy that are both affordable and environmentally friendly. Fossil fuels which provide the bulk of the world's energy needs are environmentally unfriendly as clearly seen in the effects on global warming. Moreover, fossil fuels are non-renewable and there are growing concerns that the world will soon be faced with a serious energy deficit because of the depletion of the conventional energy resources. On the other hand, renewable energy sources like wind, solar energy, geothermal sources and biomass energy have the potential of deceleration towards the global warming syndrome because of their low carbon emissions and of their virtual inexhaustibility.

A number of researchers have considered various types and configurations of possible and affordable renewable energy systems. Sims⁽¹⁾ has given a theoretical consideration on the reduction of carbon dioxide emissions and the role that the global renewable energy industry might play in this regard. He compared the costs of

renewable energy systems with the fossil fuel-derived energy sources and considered how placing a value on carbon emissions might help reduce the effects on climate change. Nakata, et al.⁽²⁾ used optimization modelling to study efficient ways of renewable energy systems integration to provide both electricity and heat in rural areas of Japan. They specifically considered four kinds of renewable energy sources: PV, wind power, biomass generation and geothermal heat pump. Their integrated renewable energy system reduced the annual costs of the entire system by 31% and carbon emissions by about 50%. Other studies like Hutter⁽³⁾, and Lund and Freeston⁽⁴⁾ have also been reported in the literature.

In the present work, we propose and consider a hybrid renewable energy system for domestic use in the northern cold region of Japan, with Kitami city as a case study. The solar energy collected with a photovoltaic/thermal collector and geothermal energy drawn from the ground with a heat pump are used as the primary renewable energy sources in the present system. The system is tailored for a typical residential family of four persons.

In order to objectively evaluate the cost merit and feasibility of any renewable energy system, it is imperative to evolve a method for estimating the annual performances and energy balances of the system. It is not usual to always implement continuous annual simulations using the actual and true meteorological data but the usual practice

* Received 5th January, 2006 (No. 05-4279)

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has been to devise some simplified model (or representative days) with which seasonal or annual performance of the system can be predicted. In this work, the accuracies of several simplified meteorological data models are also investigated by comparison with the results of detailed real-time continuous simulations using actually measured data during the period under investigation. The best model is proposed and then used for the annual estimations of system and components energy balances.

Nomenclature

T : temperature [$^{\circ}\text{C}$]

E : annual energy balance [kWh]

H : energy quantity [W]

I : instantaneous solar intensity [W/m^2]

A : area [m^2]

K : incidence angle modifier

m : mass [kg]

c_p : specific heat [$\text{J}/\text{kg}\cdot\text{K}$]

n : number of days

Greek Symbols

Δ : change in quantity

η : efficiency

β : efficiency coefficient

θ : incidence angle

χ : ratio

Subscripts

cell, pv : PV/solar cell

ref : reference condition

panel : PV/thermal collector

e : electrical

th : thermal

s : clearest day

c : cloudiest day

$\tau\alpha$: transmittance-absorptance

GHP : geothermal heat pump

con : electrical consumptions

2. Renewable Energy System

Figure 1 shows the schematic of the domestic-size renewable energy system under consideration. The system provides both electric and thermal energy using a hybrid solar panel mounted on the roof of the house. The solar panel consists of photovoltaic (PV) cells laminated on a thin foil of aluminium thermal absorber. The azimuth angle of the system is zero (due south), with the total surface area of the solar panels at about 26 m^2 (40 modules) and inclined at 30° to the horizontal. The total surface area and number of modules of the hybrid solar panel was estimated with respect to the total area of the south-facing roof (about 31 m^2) of the model house that was used for this research. It is usual to design the solar panels array to almost cover the entire south-facing roof for maximum energy collection. The dimension of the commercial hy-

Fig. 1 Schematic of a domestic-size renewable energy system

brid solar panel module is $0.79\text{ m} \times 0.823\text{ m}$. The hybrid solar panel has a single glass cover, excluding the glass that covers and supports the PV cells as part of an ethylene vinyl acetate (EVA) encapsulant assembly. During operation, heated propylene glycol is circulated through a heat exchanger at the storage tank and is then led through a 70 W pump to three fan convectors at each room to provide room heating during cold seasons. Each of the fans is driven by a 30 W electric motor. Propylene glycol is also used as the heat transfer medium through the solar panel in order to avoid freezing conditions during winter. Rooms temperatures are set for air-conditioning at 25°C between 6:00AM – 10:00PM and 15°C between 10:00PM and 6:00AM. Hot water from the storage tank is drawn directly to supply the load at the kitchen, bathroom, laundry and showers. During such draw-offs, the same quantity of water is replenished from the city water supply. Whenever the temperature of water at the tank is insufficient for load supplies, geothermal heat is supplied through a ground-source heat pump in series with the storage tank to top up the water temperature. This top-up heat from the heat pump may still be insufficient especially during the cold seasons and at such periods, additional thermal energy is supplied from an auxiliary kerosene boiler placed in series with the water tank. The heat pump is operated with city electricity which also operates a refrigerator, a vacuum cleaner and other home appliances. The electrical energy produced by the hybrid solar panel is sold to an electric company through an inverter with 0.85 conversion efficiency. This sold electricity actually offsets the cost incurred in using the city electricity to run equipment such as the collector and room heater circulation pumps.

3. Meteorological Data Models

The renewable energy system simulations were implemented using several simplified meteorological data models as described below, and the results were compared with those from detailed, minute-by-minute real-time sim-

ulations for the month of May, 2002 which we used as the reference base for the purpose of estimating the errors of the various simplified models.

3.1 Actual data simulations (reference)

Detailed, minute-by-minute real-time simulations for the month of May, 2002 were implemented using the actually measured daily temperature and insolation (beam and global radiation data) profiles measured at the Kitami Institute of Technology (KIT) for the system simulation model during the respective days. Because the data for two days (days 24 and 28) were lost due to the measuring instruments malfunctioning, the detailed simulations were actually implemented for 29 days. The initial storage tank temperature for day 1 was initialized to 40°C but for the rest of the days, the final tank temperature for any day serves as the initial tank temperature for the next day. The month of May was selected as the reference month because the thermal energy balances during the clearest day in May were similar to those of a clear day in summer, while those of the cloudiest day in May were similar to a day in winter in very cold regions such as Kitami. The energy balances during the month of May were thus regarded as miniature energy balances for the year.

3.2 Average day model (single grade)

This is the simplest meteorological data model and is based on the average day of the month. Mean monthly values of the beam and global radiations and the ambient temperature were used for the system simulations to estimate the energy balances for the average day. The monthly energy balances were then obtained by multiplying the results of the day by the total number of days in the period.

3.3 Representative days model (double grade)

During the period, a representative day which had the highest total horizontal global radiation was selected and designated as the clearest day. Similarly, another day which had the lowest total horizontal global radiation was also selected and designated as the cloudiest day. The clear and cloudy days' ratios for the period were then computed according to Eqs. (1) and (2) below:

$$E_s \cdot \chi_s + E_c \cdot \chi_c = \frac{\Sigma E}{n} \quad (1)$$

$$\chi_s + \chi_c = 1 \quad (2)$$

where ΣE is the sum total of the measured global horizontal radiation within the period, χ_s and χ_c are respectively, the clear and cloudy days ratios, E_s and E_c are the total global horizontal radiation during the representative clearest and cloudiest days respectively, and n is the total number of days within the period. The actual clear and cloudy days' ratios in this test month (May, 2002) are shown in Table 1.

3.4 Ambient temperature models

3.4.1 Double grade1

Here, a day was classified as belonging to a clear day group if its total horizontal global radiation falls within the range of $E_{\max}/2 \sim E_{\max}$,

Table 1 Clear and cloudy day's ratios for May, 2002

Group	Ratio	Number of Days
Clear Day	0.5938	17.22
Cloudy Day	0.4062	11.78

Table 2 Four grades classifications (30° panel inclination)

Group	Horizontal Global Radiation (MJ/m ² .day)	Number of days
1	0~8	4 days
2	8~16	5 days
3	16~24	9 days
4	24~	11 days

where $E_{\max}$ is the maximum total horizontal global radiation during the period. Similarly, a day was classified under a cloudy day group if its total horizontal global radiation falls within the range of $0 \sim E_{\max}/2$. The mean temperature profile of the clear day group was then used during the system simulations of the representative clearest day while the mean temperature profile of the cloudy day group was also used during the simulation of the representative cloudiest day.

3.4.2 Double grade2 The actually measured true temperature profile during the two representative days (clearest and cloudiest) were respectively used during the system simulations.

3.4.3 Double grade3 The mean temperature profile during the whole period under consideration (May, 2002) was used for the simulations of the two representative days.

In each of the double grade models, the energy balances during the representative clearest day were multiplied by the total number of days in the clear day group (17.22 days) while the energy balances during the cloudiest day were also multiplied by the number of days in the cloudy day group (11.78 days). Their sums provided an estimate of the energy balances during the period.

3.5 Four grades model

Under this model, the period was divided into four groups with respect to the highest measured horizontal global radiation during the month of May, 2002 as shown in Table 2. For every group, the mean insolation and the mean ambient temperature profiles were used to make system simulations and the total monthly energy balances were computed as the sum total of the group energy bal-

ances.

4. Component Models

The following component models were used to predict the overall system performance of the renewable energy system.

4.1 Hybrid solar panel

4.1.1 Electrical efficiency The maximum power point efficiency, η_0 of an actual commercial module made in Japan is 0.115. The dependence of the cell efficiency, η_e on the cell temperature, T_{cell} was predicted according to⁽⁵⁾:

$$\eta_e = \eta_0 [1 - \beta_{\text{ref}}(T_{\text{cell}} - T_{\text{ref}})] \quad (3)$$

T_{ref} and β_{ref} is the maximum power point efficiency temperature coefficient which is also a function of temperature:

$$\beta_{\text{ref}} = \frac{1}{T_0 - T_{\text{ref}}} \quad (4)$$

T_0 is the cell temperature at which the cell efficiency drops to zero. Generally, T_0 is taken as 270°C. The average surface temperature of the PV was evaluated through an energy balance.

4.1.2 Thermal efficiency The thermal characteristic of the commercial module measured at KIT and used in the simulations is:

$$\eta_{\text{th}} = 0.65 - 7.55 \frac{\Delta\theta}{I} \quad (5)$$

where η_{th} is the thermal efficiency, I is the instantaneous solar intensity and $\Delta\theta$ is the temperature difference between the solar panel inlet and the outlet. This efficiency is normally indicated for zero angles of incidence of available radiation. In order to account for the variation of the efficiency with the incidence angles (due to the variation of the transmittance of the incidence radiation), an incidence angle modifier coefficient was used to correct for incidence angles other than zero. For flat-plate collectors, Souka and Safwat⁽⁶⁾ have suggested the following general expression for the variation of the transmittance and absorptance with angles of incidence:

$$K_{\tau\alpha} = 1 + b_0 \left(\frac{1}{\cos\theta} - 1 \right) \quad (6)$$

where θ is the incident angle and b_0 is generally a negative number.

4.2 Geothermal heat pump

The geothermal heat pump was assumed to be operated at a constant coefficient of performance (COP) of 3 and to supply a constant power of 3 kW whenever it is operational. The capacity of the geothermal heat pump was estimated based on the actual ratings of conventional room heaters in the northern cold region of Japan such as in Kitami city. Typical household heaters are normally rated between 6 kW and 8 kW and it was estimated that a 3 kW geothermal heat pump with a COP of 3 would be sufficient

for room heating and also supplement the hot water supply during cold seasons, except during the peak hot water demand described in section 4.4. On/Off control strategy was assumed for the operation of the heat pump.

4.3 Heat losses from the house and tubings

A heat loss coefficient, Q value of 1 W/m²·K has been established for 'high insulated house' in the cold northern part of Japan. This ' Q value' is commonly used in the building industry. The total heat loss from the house is defined simply with the floor area as follows:

$$\Delta H_{\text{house}} = Q \cdot A_{\text{floor}}(T_{\text{room}} - T_{\text{air}}) \quad (7)$$

For the house heat loss modelling, ventilation was not taken into account and solar infiltration was neglected in this study.

Heat losses from the tubings were assumed to be 3% of the total heat flow through the tubing. The main tubings under consideration were: supply/return to the solar panel from the storage tank; supply/return to the room heaters from the storage tank; hot water load supply from the storage tank.

4.4 Thermal storage tank

The fully mixed temperature model was used for a single storage tank which volume is 0.5 m³. The energy balance at any minute of the storage tank is then given as:

$$m c_p \frac{dT_{\text{tank}}}{dt} = (H_{\text{panel}} + H_{\text{GHP}} - H_{\text{losses}} - H_{\text{load}} - H_{\text{heater}}) \quad (8)$$

where m is the total mass of water inside the storage tank, c_p is the specific heat capacity of water and H denotes the total energy available to/from each device associated with the storage tank. A large tank capacity of 500 L was used in order to ensure adequate thermal storage (high thermal capacitance) and availability of thermal energy as at when required. The daily hot water load and the electricity consumption profiles for a typical residential family of four are shown in Fig. 2. These profiles were arranged from measurements at an actual residential house in Kitami city. In order to meet the hot water demand profile shown in Fig. 2, effective thermal storage is essential over

Fig. 2 Daily hot water and electricity consumption profiles

a relatively long period. Furthermore, the large tank capacity per collector area improves the thermal efficiency of the hybrid solar panel because lower temperature water from the tank is routed to the panel inlet through a heat exchanger. Integration of Eq. (8) was done with the fourth-order Runge-Kutta algorithm for integrating Ordinary Differential Equations (ODE).

A 10 kW auxiliary kerosene boiler was configured in series with the storage tank to augment the hot water supply temperature during very cold seasons. The capacity of this boiler was estimated based on the peak demand hot water load pattern of 10 L/min as shown in Fig. 2. During the winter season, a large temperature drop was envisaged, even with the operations of the geothermal heat pump. It was estimated that a 10 kW boiler would be sufficient to raise 10 L/min of the hot water supply through 12°C to account for the sudden temperature drops during peak demand period.

5. Simulation Results

5.1 Simplified meteorological data model results

Table 3 shows the results of the various simplified meteorological data models as compared to the reference results of minute by minute simulations using actually measured air temperature and insolation profiles for the fully continuous period. Relative errors of energy gains and consumptions at components are also shown in Fig. 3. As expected, the Average Day Model (Single Grade) gives large errors (about 40% for the boiler). The best model with the most reasonable error distribution is the Double Grade1 model which used two different mean air temperature profiles, each for the clearest and cloudiest days. Be-

cause the error distribution across the various system components for this model was better than the rest of the models, it was the model of choice for estimation of the annual system performance and energy balances.

5.2 System performance and annual estimations

Employing the Double Grade1 meteorological model proposed above, full time simulations were carried out for each of the representative days (clearest and cloudiest) for the four seasons of the year. Thus, a total of eight, 24-hours, and minute by minute detailed simulations were done in order to predict the performance of the renewable energy system during the different seasons of the year. Annual energy balances were then estimated from the seasonal representative days by multiplying the representative day's results by their respective ratios as shown in Table 4.

Fig. 3 Error distributions in various meteorological models

Table 3 Simplified meteorological data models and associated errors

Model	Thermal Energy Balances†						Electric Energy Balances†			
	Supply			Consumptions			Production		Consumptions	
	Solar Panel	Heat Pump	Boiler	Heater	Hot Water	Tank Losses	PV Panel	Sale	Heat Pump	Electric Load
Actual Data Simulations (Reference)	330.7	304.5	21.6	250.3	254.4	33.1	180.9	153.8	101.5	369.3
Single Grade	254.0	243.6	12.9	163.1	262.2	30.7	183.0	155.6	81.2	318.4
%error	23.2	20.0	40.1	34.8	3.0	7.3	1.2	1.2	20.0	13.8
Double Grade1	323.1	282.6	20.9	254.1	255.0	34.2	176.7	150.2	94.2	360.0
%error	2.3	7.2	2.9	1.5	0.2	3.5	2.3	2.3	7.2	2.5
Double Grade2	359.2	397.9	23.4	296.6	252.8	33.9	177.1	150.5	132.6	419.2
%error	8.6	30.7	8.8	18.5	0.66	2.6	2.1	2.1	30.7	13.5
Double Grade3	327.8	258.0	19.8	184.2	256.0	33.2	175.9	149.5	86.0	335.7
%error	0.88	15.3	8.1	26.4	0.62	0.3	2.8	2.8	15.3	9.1
Four Grade	306.7	291.4	20.8	224.1	255.1	33.0	181.3	154.1	97.1	358.5
%error	7.2	4.3	3.3	10.5	0.25	0.18	0.23	0.23	4.3	2.9

† Energy balances in kWh

Table 4 Seasonal distribution of clear and cloudy days during 2002 for Kitami (43°49'N, 143°55'E)

Season	Spring	Summer	Autumn	Winter
Distribution	February-April	May-July	August-October	November-January
Clearest Day	April 21	June 23	August 14	January 22
Cloudiest Day	April 30	July 16	August 27	November 16
Clear Day Ratio	$\chi_s=0.503$ $n_s=44.28$	$\chi_s=0.477$ $n_s=42.93$	$\chi_s=0.416$ $n_s=34.11$	$\chi_s=0.545$ $n_s=48.51$
Cloudy Day Ratio	$\chi_c=0.497$ $n_c=43.72$	$\chi_c=0.523$ $n_c=47.07$	$\chi_c=0.416$ $n_c=47.89$	$\chi_c=0.455$ $n_c=40.49$

n_s =number of clear days; n_c =number of cloudy days

Fig. 4 Panel outlet and tank temperatures — the summer clearest day

Fig. 5 Storage tank energy balance — the summer clearest day

5.2.1 Storage tank and panel outlet temperatures

Figure 4 shows the thermal collector outlet and storage tank temperature profiles during the clearest day in summer. Figure 5 shows the time-dependent profile of the thermal energy balance during the summer clearest day. During the summer cloudiest day (profiles not shown), the available insolation was not sufficient to operate the solar panel for collection of useful energy. As a result, almost all required thermal energy must be supplied with

Fig. 6 Panel outlet and tank temperatures — the winter clearest day

the geothermal heat pump and the auxiliary boiler. During the clearest day in summer (Figs. 4 and 5) the storage tank temperature is maintained above 35°C during the early morning periods by the operation of the geothermal heat pump and if necessary, the auxiliary boiler. This is to enable load supplies to the kitchen, bath, etc. and the room heating, all of which draw their heat from the storage tank. The same operations are carried out late in the evening when the solar panel ceases its operation. In the morning, when the pump is turned on, the storage tank is steadily charged with thermal energy from the panel until the turn-off criterion of the collector pump is satisfied at which time the switch is turned off. Also, when the panel outlet temperature exceeds the maximum allowable operational temperature of the system (80°C) or the panel exit temperature equals the temperature inside the storage tank, the panel operation is stopped and the brine (propylene glycol) is drained out from the system to avoid depletion. The panel average temperature surges rapidly due to lack of fluid flow. During this period, supply to the storage tank is stopped to forestall boiling and excessive pressures. The system performances during the clearest days in the autumn and spring seasons (not shown in figures) are similar to the system performance during the clearest day in summer.

Figure 6 shows the thermal collector outlet and storage tank temperature profiles during the clearest day in winter and Fig. 7 shows the time-dependent profile of the thermal energy balance during the winter clearest day. During the clearest day in winter (Figs. 6 and 7), the operation of the solar panel is insufficient to meet the load due to low solar radiation and very low ambient temperatures. Thus, during the winter, the load must be serviced by frequent heat pump and boiler operations.

5.2.2 Annual energy balances and carbon emissions

Figure 8 shows the annual energy balances of the renewable energy system as compared to an equiva-

lent conventional system, where E_{pv} denotes the annual amount in kWh, of the electricity produced by the hybrid solar panel, E_{con} refers to the consumption of electricity by electrical appliances and the geothermal heat pump, and E_{th} denotes the thermal input of various devices into the storage tank. Also shown in Fig. 8 is a comparison of the carbon emissions between the renewable and non-renewable energy systems. For the renewable energy system, the geothermal heat pump provided more than two-thirds of the total annual thermal loads and this highlights one of the advantages of the use of renewable energy sources. In Fig. 8, it was assumed that in the conventional system, all the thermal needs will be provided through the use of a conventional oil-fired boiler and room heaters.

The amount of carbon emissions from electricity strongly depends on the composition of the energy sources. The energy sources in Hokkaido Electric Power Company consists of coal-31%, petroleum-24%, and non-fossil fuel sources, accounting for about 45% of the total energy sources. The amount of carbon emissions from only fossil fuels was counted in the computations. It was estimated that the amount of carbon emissions from coal

was about 1.2 times greater than those from petroleum at the same energy output. The emissions in the renewable energy system are only about 16% of the emissions given off by the non-renewable energy system. This is due to the fact that though the rate of emissions due to electricity utilization was higher in the renewable energy system, the utilization of the fuel oil in the renewable system was extremely small when compared to the conventional system.

6. Discussions: Cost Considerations

It is difficult to accurately estimate the initial cost and running cost merits and demerits of the proposed renewable energy system as compared to a conventional system because of fluctuating cost change factors. The price of a geothermal heat pump and the cost of excavation have a trend of drastic reductions. At present, a part of the costs for the construction of renewable energy systems such as PV and thermal collector and the geothermal heat pump is funded by the government and/or municipalities in Japan. As popularizations of these renewable energy systems progresses in the future, it is expected that such subsidies will be reduced.

On the other hand, the running cost has two main change factors, the electricity billing rate and the actual price of fuel oil (kerosene). The local electricity billing rate depends on the price menu which is determined by regional electric power companies. The price of kerosene surged rapidly in 2005, and it is envisaged that the trend of rising prices would continue into the foreseeable future.

Even with the use of a lower price of fuel oil (average in 2002) and a higher rate of electricity (normal contract menu of Hokkaido Electric Power Company), the annual running cost of the renewable energy system reduced to about 40% of that of the conventional system. The reduction of the running cost was mainly due to the lower consumption of fuel oil in the renewable energy system. The PV panel produced more than 38% of the total annual electric load which can be sold to an electric company through

Fig. 7 Storage tank energy balance — the winter clearest day

Fig. 8 Comparison of annual energy balances and carbon emissions

an inverter. Even though the renewable energy system has the disadvantage of high initial costs at present, the period for redeeming the initial cost might be considerably short because of the expected decrease of the initial cost and relative decrease of the running costs in the future.

7. Conclusions

A domestic-size renewable energy system for use in the cold regions around the mid-latitude using a hybrid solar panel and a geothermal heat pump as the primary renewable energy sources was investigated. Based on error analysis for several simplified meteorological data models, a very simplified system where only two representative days were necessary for each seasonal energy balance estimations was proposed. Through numerical simulations, it has emerged that the renewable energy system is capable of meeting all year-round thermal loads and about 38% of the electric loads. The system is environmentally friendly with carbon emissions at about 16% of that from a comparable non-renewable energy system.

A drawback of the system is the insufficiency of the available energy during winter to meet hot water and heating loads. During this period, additional energy from frequent heat pump operations and the auxiliary boiler were used to service the energy needs of the house. However, it is certainly possible to improve the thermal gain during

winter by employing better performance components.

Acknowledgement

The authors are deeply indebted to Sekisui Chemical Co., Japan for offering commercial hybrid solar panel modules.

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