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Original Paper

Estimation of Renewable Energy Potentials Using Geographic and Climatic Databases
—A Case Study of the Tochigi Prefecture of Japan—

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Abstract

Real-time weather data were used in the simulation to promote renewable energy utilisation in the smart grid approach. The case study was conducted for the 11 cities in the Tochigi prefecture to show the suitability of renewable energy and to determine the regions that might use it. Solar power had the highest capability of producing electricity, followed by biomass, hydropower, and wind power. The ratio of each renewable energy generation depends on the characteristics of each city's geographical and climatic conditions. The amount of surplus electricity for one year was not considered in the yearly and monthly estimations. In the hourly estimation, 3,363 MWh/year of surplus electricity was available for use in city shortfalls using smart-grid approaches. The maximum surplus electricity was found to be 4,235 MWh/year through a daily estimation; in contrast, 9,075 MWh/year was observed as the surplus in hourly estimations for Nasu city of the Tochigi prefecture. We have found that surplus electricity was higher at Nasu due to the geographic and climatic conditions available for wind power generation. A similar approach to renewable energy potential can be considered for rural areas in Japan for additional sources of energy besides fossil fuel and nuclear plants.

Keywords

biomass, hydropower, solar power, wind power, GIS

Introduction

Renewable energy is becoming more important; solar, wind, hydropower and biomass sources of energy have become substitute options for fulfilling energy demand in rural sectors. In this rural sector, renewable energy estimation policy is important for identifying substitute or additional sources of energy to decrease dependence on fossil fuel and nuclear sources. Geographical distribution can help policy planners increase renewable utilisation in rural areas. Researchers have contributed to the development of estimation methods of renewable energy that consider geographical location (Gemelli et al. 2011) (Voivontas et al. 2001) (Ramachandra and Shruthi 2007). Regional analyses of renewable energy have contributed significantly in different parts of the world to solar, wind, hydropower and biomass energy development. A solar energy planning system consisting of a methodology and a decision support system was prepared for planners and energy advisers. The study was primarily intended to predict and realise the potential of solar energy on an urban scale, and the system supported decisions concerning key solar technologies such as solar water heating, PV and passive solar gain. The methodology takes into account baseline energy consumption and projected energy saving benefits (Suri et al. 2007) (Vries et al. 2007). A GIS methodology was developed to map solar resources on the basis of satellite data by considering radiation at top of the atmosphere, albedo, downward radiation at the surface and to match these criteria with demand modelling on the basis of habitat (population density, energy demand intensity) (Rylatt et al. 2001). Local measurement data were converted to the employed GIS grid. The quantitative effects of different nature conservation cri-

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teria on wind energy potential were analysed using GIS (Krewitt and Nitsch 2003). Wind energy potential feasibility is demonstrated by quantifying the potential while taking into account detailed site-specific information about aspects of natural conservation. Wind energy potential amounts to only 25% of the theoretical potential. A GIS system was initiated to locate wind farms in the UK (Serwan and Parry 2001). In terms of area, the most suitable areas represent the smallest group, as we might expect, occupying only 3.79% of the total study area while the least suitable sites cover some 73.34% of the area. The suitability map using weighted layers showed a very similar pattern. The most suitable areas in this map occupy 8.32% of the total study area, while the least suitable sites cover 70.26% of the area. On the other hand, small hydropower holds great possibility for generation in rural mountainous areas. Small hydropower does not affect the environment greatly when compared with ordinary hydropower plants. GIS was also used for the mapping of site locations of small hydropower (Yi et al. 2010), and many site-specific analyses were performed (Dursun and Gokcol 2011). Again, renewable energy in China shows great promise; biomass is found to be one of the most promising renewable energy resources, showing great potential for development. Almost 20% of the primary energy consumed in China is biomass energy (Changa et al. 2003). The potential of renewable energy sources to meet the growing energy demand in Turkey has also been assessed (Evrendilek and Ertekin 2003). The pursuit and implementation of sustainability-based energy policies could provide approximately 90% and 35% of Turkey’s total energy supply and projected consumption in 2010, respectively. Utilisation of renewable energy technologies for electricity generation would necessitate approximately 23.2 Mha (29.8%) of Turkey’s land resources.

The smart grid approach has been proven an efficient method for understanding demand and supply utilisation in the renewable energy sector. In addition, the estimation method of renewable energy potential on time series in rural areas is one of the most important factors in the progress of smart grid technology. The smart grid is expected to be the next power network for renewable energy (Ministry of Economy Trade and Industry (Japan) 2010a) (Mizuho Information & Research Institute (Japan) 2010). This grid approach is able to control electricity flow for both sides of supply and demand by stabilising voltage and frequency with regard to geographical locations. Power transmission technologies for the prevention of voltage that decreases and inverses load through the fluctuations of renewable energy and systems for the management of supply and demand in different localities have been studied (Energy Forum (Japan) 2010) (Santo 2010) (Lovins 2002). Based on these developments, renewable energy potential in a rural area of Japan was estimated by Regional New Energy Vision (NEDO (Japan) 2008a). However, the conditions for the estimation of energy potential were different, for example, between Utsunomiya New Energy Vision (Utsunomiya City government (Japan) 2002) and Nikko New Energy Vision (Nikko City government (Japan) 2009). Controversy emerged about the estimation methods proposed by the different contributors. A certain importance was thus placed on the need to figure out the renewable energy potential in rural areas. In this regard, we proposed a new estimation method for renewable energy utilisation that makes use of geographical detail based on data concerning geographic and climatic conditions. Uniformed data including biomass energy utilization from academic journals, governmental reports was used to identify reliable result of renewable energy potential and its tendency. Furthermore, we identify the shortcomings of the previous study performed by Regional New Energy Vision (Wakeyama and Ehara 2009). Although Wakeyama’s research has grasped the abundance of recyclable energy, such as wind power, hydropower, and solar power based on unific data, it is not in investigating biomass. Moreover, there is no research to show the evaluation of the utilizable amount of the renewable energy which changes every moment in a rural community. Then, a constantly varying climatic condition and geographical conditions for judging a suitable area for installing facilities of renewable energy were focused in this research to estimate changing of renewable energy potential. And difference of each renewable energy potential on time series were discussed to manage the demand and supply of electricity by smart grid technology in future. Alongside the overall goal of providing accurate estimation methods, the immediate objectives of this study were to develop a methodology to estimate the renewable energy potentials in rural areas and to undertake a case study to show the renewable energy potential in the Tochigi prefecture of Japan.

Materials and Methods

METPV-3 (NEDO 2006) and AMeDAS (Meteorological Agency (Japan) 2010) were used as a climatic database in this research. METPV-3 was applied to estimate the value of solar radiation, and AMeDAS was applied to estimate the value of velocity of wind and rainfall intensity.

Solar power generation

Electric power generation by solar panel (E_S) is related to the surface area of the solar panel and to solar radiation change accumulated over time and can be expressed as:

$$E_S = \int \left\{ H_S(t) \cdot K_{1S}(t) \cdot K_{2S} \cdot \eta_S \cdot A_S \right\} dt \tag{1}$$

where H_s is the solar radiation in the unit area, K_{1S} is the temperature correction coefficient, K_{2S} is the total correction coefficient,

Table 1 Solar power generation: specification and conditions for calculating energy potential

Variable		Unit	Specific
Electric power generation	E_{S}	kWh	
Surface area of solar panel	A_{S}	m^2	house: 24 m^2, 3 kW, office: 40 m^2, 5 kW, school: 67 m^2, 10 kW$^{1)}$
Conversion efficiency	η_{S}	—	0.15$^{3)}$
Solar radiation	H_{S}	$\mathrm{kWh/m}^2$	8,760 hours of global solar radiation in METPV-3$^{2)}$
Temp. correction coefficient	$K_{1\mathrm{S}}$	—	0.9: Dec. to Feb., 0.85: Mar. to Nov., 0.8: Jun to Aug.
Total correction coefficient	$K_{2\mathrm{S}}$	—	0.8: shadow, power conditioner, mechanical efficiency, etc.$^{1)}$
Available area of installation		%	80%
Geographical condition	Roof of housing, office, and school		
Climatic condition	More than 0.1 $\mathrm{kWh/m}^2$: average of global solar radiation in one year		

1) Utsunomiya City government (Japan) (2002)
2) NEDO (Japan) (2006a)
3) Kyocera (Japan) (2010)

η_{S} is the conversion efficiency and A_{S} is the surface area of the solar panel (NEDO (Japan) 1998). The parameters for the estimation of energy potential from solar energy are listed in Table 1. In the Tochigi prefecture, the solar panel installation area was selected based on solar radiation (H_{s}), with the guideline that H_{s} should be more than 0.1 $\mathrm{kW/m^2/day}$ (NEDO (Japan) 2006a). Most of the roof areas, including those of houses, schools and offices, had the opportunity to install solar panels. We have observed that 80% of the roof areas received the abovementioned level of solar radiation (Kyocera (Japan) 2010) (Tochigi Prefecture government (Japan) 2005) (Tochigi Prefecture government (Japan) 2010).

Wind power generation

Wind power depends on the wind receiving area, air density and kinetic energy. Kinetic energy can be estimated from the mass and velocity of air. The wind energy potential can be expressed as:

$$P_{\mathrm{WT}} = \frac{1}{2}\cdot \rho\cdot A_{\mathrm{W}} \cdot V^3 \cdot e_w \cdot 10^{-3} \tag{2}$$

where P_{WT} is the total power received from the wind turbines, ρ is the air density, A_{W} is the wind receiving area, V is the velocity of air, and e_{W} is the conversion efficiency (NEDO (Japan) 2008b). In this equation, 10^{-3} means to change the unit from k to kW. Therefore, the total wind energy potential (E_{W}) can be expressed as

$$\begin{aligned} E_{\mathrm{W}} &= \int P_{\mathrm{WT}}\,dt \\ &= \int \left\{ \frac{1}{2}\cdot \rho\cdot A_{\mathrm{W}} \cdot V^3(t) \cdot e_w \cdot n \cdot 10^{-3} \right\} dt \end{aligned} \tag{3}$$

where V is the function of time t, and n is the number of wind turbines. The parameters for the estimation of energy potential from wind are listed in Table 2. The specific conditions based on geography and climate for each of the parameters have been defined in detail. Wind turbines (1,000-kW-rated output) were installed in the selected geographical locations based on slope, height, and

Table 2 Wind power generation: specification and conditions for calculating energy potential

Variable		Unit	Specific
Electric power generation by wind turbine	E_{W}	kWh	
Wind power	P_{W}	kW	
Velocity of wind	V	m/s	8,760 hours of AMeDAS$^{4)}$ in 2009
Wind receiving area	A_{W}	m^2	D: Diameter of rotor, $A_{\mathrm{W}}=\pi(D/2)^2$, D=60 m: Large-size$^{1)}$ $10D\times3D$: Distance of wind turbine
Air density	ρ	$\mathrm{kg/m}^3$	1,225 $\mathrm{kg/m}^3$: Average in level ground of Japan, 1 atm, 15°C
Conversion efficiency	e_{W}	—	0.36: 0.4–0.5: Wind turbine, 0.8–0.95: Gear box, 0.8–0.95: Generator$^{5)}$ 1,000 kW: Rated output, 4 m/s, 25 m/s: Cut-in and Cut-out velocity
Number of wind turbine	n	—	
Available area of installation		%	10% of area with satisfactory geographical and climatic conditions $^{2)}$
Geographical condition	Below 20°: Maximum angle of inclination, below 1,000 m high, outside area of natural park or building lot, inside area of 300 m from public road$^{3)}$		
Climatic condition	More than 5.0 m/s: average velocity of wind in one year		

1) NEDO (Japan) (2008a)
2) Utsunomiya City government (Japan) (2002)
3) Wakeyama and Ehara (2009)
4) Meteorological Agency (Japan) (2010)
5) Ushiyama (2005)

surroundings. The land slope for the turbines should usually not exceed more than 20°, and installations should not be placed at more than a 1,000-m height from ground level. Wind turbines must be installed outside the areas of natural parks and buildings. In addition, turbines should not be installed more than 300 m away from public roads (Wakeyama and Ehara 2009). Wind turbines were set to capture stable winds by considering the recommended cut-in velocity, the recommended cut-out velocity of the wind, and the recommended distance between the wind turbines. In our study, the cut-in velocity, the cut-out velocity of the wind, and the distance between wind turbines were 4 m/s, 25 m/s, and $10D \times 3D$, respectively, where D is the diameter of the rotor (NEDO (Japan) 2008a). With the considerations of climatic and geographical conditions discussed above, the installation of wind turbines was limited. For example, only 10% of the area of Utsunomiya city satisfied the geographical and climatic conditions for the installation of the wind turbines (Ustunomiya-City 2002). The potential areas for the installation of wind turbines were analysed based on a grid, with each sector of the grid equal to 500 m (NEDO (Japan) 2006b) (Ministry of Land, Infrastructure, Transport and Tourism (Japan) 2007a) (Ministry of Land, Infrastructure, Transport and Tourism (Japan) 2007b). The grid included information about natural parks and roads (GSI 2010). ArcGIS 9.1® was used to analyse the grid information to locate potential areas for the installation of wind turbines. The AMeDAS (Meteorological Agency (Japan) 2010) database, containing 8,760 hours of data, was used to estimate wind power generation.

Hydropower generation

Theoretical hydropower (P_H) was obtained from the potential energy of water (NEDO (Japan) 2003). The formula for small hydropower P_H can be expressed as:

$$P_H = g \cdot Q_H \cdot H_e \tag{4}$$

where g is the gravitational acceleration, Q_H is the amount of water discharge, and H_e is the effective head. The energy potential (E_W) of small hydropower can be expressed as:

$$E_w = \int \left(P_H \cdot \eta \cdot K_W \cdot t \right) dt \tag{5}$$

where η is the conversion efficiency in small hydropower generation, K_W is the available ratio, and Q_H changes over time t as in the following equation:

$$Q_H(t) = \frac{1}{3.6} \cdot f \cdot r(t) \cdot A_W \tag{6}$$

where f is the discharge coefficient, 0.7 (Ministry of Construction River Bureau (Japan) 1997) , r is the rainfall intensity, and A_W is the size of the catchment area. The parameters for estimation of energy potential from hydropower are listed in Table 3. Polygon data in the catchment area was calculated by use of driver data of digital national land information (Ministry of Land, Infrastructure, Transport and Tourism (Japan) 2007a), water system of GIS data (Ministry of Land, Infrastructure, Transport and Tourism (Japan) 2007b), and vertical control point of basic map information (Ministry of Land, Infrastructure, Transport and Tourism (Japan) 2010) based on arithmetic function of ArcGIS. Then, each size of a catchment area, A_w was estimated using the polygon data in the catchment area. The specific conditions based on the geographical locations for each of the parameters have been defined in detail. The hydropower units were installed in the

Table 3 Small hydropower generation: specification and conditions for calculating energy potential

Variable		Unit	Specific
Electric power generation by small hydropower	E_H	kWh	
Theoretical hydropower	P_H	kW	9.8 m/s^2: Gravitational acceleration
Conversion efficiency	η	—	0.68$^{4)}$: 0.8: turbine efficiency, 0.85: generator efficiency
Amount of flowing water	Q_H	m^3/s	Product of precipitation and discharge coefficient using rational method (Assumption)
Effective head	H_e	m	70% of the level difference between upper stream and confluence of rivers$^{2)}$
Size of a catchment area	A_W	km^2	
Discharge coefficient	f	—	0.7$^{3)}$
Rainfall intensity	r	mm/h	Average value for each month of AMeDAS$^{1)}$ in 2009
Available ratio	K_W	%	10% of theoretical hydropower (Assumption)
Geographical condition	Below 20°: Maximum angle of inclination, outside area of natural park, or building lot, inside area of 1,000 m from public road, more than 0.01 m^3/s: amount of flowing water		
Climatic condition	—		

1) Meteorological Agency (Japan) (2010)
2) Ministry of Land, Infrastructure, Transport and Tourism (Japan) (2007a)
3) Ministry of Construction River Bureau (Japan) (1997)
4) Kobayashi (2006)

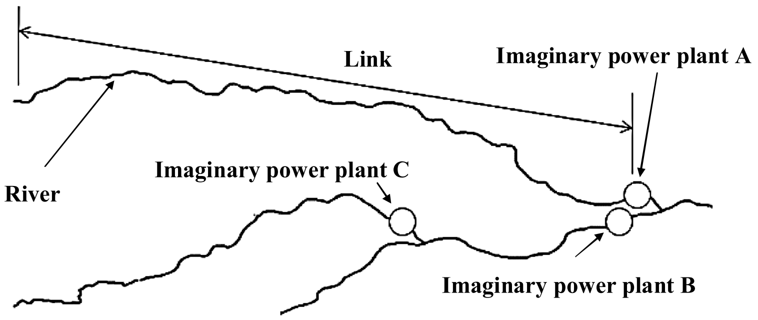

Fig. 1 Imaginary small hydropower power plant on a link unit of the river for calculation

selected geographical locations based on the slope, surroundings, distance from public roads and discharge rate of water (Table 3). An imaginary power plant was set just ahead of a junction of rivers to calculate the energy potential of each link unit (Fig. 1). These link points were selected from the Tochigi prefecture map (Ministry of Land, Infrastructure, Transport and Tourism (Japan) 2007a) using the spatial search function of ArcGIS. In most cases, a 70% height between the upper point of river and the junction or between the two junctions was considered an effective head (H_e) for hydropower estimation. Hydropower, Q_H, was estimated from the monthly average precipitation collected from AMeDAS (Tochigi Prefecture government (Japan) 2010) and from river, location (Ministry of Land, Infrastructure, Transport and Tourism (Japan) 2007b), altitude and watershed data. The databases were analysed in the Arcview environment using a field arithmetic function to display the spatial distribution for the discharge of water and the energy potential for each of the junction points. Available ratio, K_w with degree of variability was not able to be determined because of lack of relevant information. So, 10% of available are of information in wind power generation was referred to determine a value of K_w.

Biomass: energy potential

Electric power generation from biomass (E_B) can be determined from the surface area of the field (S_B) used for biomass production (M_B). The energy potential can be expressed as:

$$E_B(B) = e_B \cdot P_B(B) \cdot S_B(B) \cdot M_B(B) \tag{7}$$

where B is the variety of biomass, e_B is the conversion efficiency of biomass, and P_B is the calorific value of biomass. The parameters for the estimation of energy potential from biomass are listed in Table 4. The utilisation of abandoned fields (for energy crop production) and rice fields (for residue, i.e., chaff and straw) was used to estimate biomass energy potential. We calculated the total surface area of abandoned fields and rice fields using the rural agricultural households card (Ministry of Agriculture, Forestry and Fisheries (Japan) 2008). Rural agricultural household's card which is most detailed data of settlement unit was used to estimate the area of paddy field, and unpractical and unused field to determine prospect area of biomass production for biomass generation. The "fukuhibiki" variety of feed rice was selected because of its high yield. All parts of the rice (unpolished rice, straw, and chaff) were used as energy crops for biomass generation in this research (Saga et al. 2007). The ratio of dry weight in the unpolished rice, straw and chaff was 1:1.2:0.22. The ratio of available weight for straw and chaff was 0.75:0.37 in the rice field to be used for biomass energy (NEDO (Japan) 2006c).

Evaluation method for renewable energy utilisation

Electricity load L[kWh] can be estimated from the supply of and demand for power. The load change over time $L(t)$ can be expressed as (Tamura et al. 2010):

Table 4 Biomass generation: specification and conditions for calculating energy potential

Variable		Unit	Specific
Electric power generation by biomass	$E_B(B)$	kWh/year	B: Variety of biomass, "Fukuhibiki" (8,250 kg/ha of average yield)
Surface area of field	$S_B(B)$	ha	Abandoned field, rice field 1)
Amount of biomass production	$M_B(B)$	kg/ha	8,250: unpolished rice (0.15: moisture content) 12,021: rice straw (0.3: moisture content) 2,204: rice chaff (0.3: moisture content)
Conversion efficiency	e_B		0.3 2)
Calorific value of biomass	$P_B(B)$	MJ/kg	14.63: unpolished rice, 11.41: rice straw and rice chaff
Geographical condition	Abandoned field for energy crop production, General rice field for residue utilisation		
Climatic condition	—		

1) Ministry of Agriculture, Forestry and Fisheries (Japan) (2008)
2) Ito and Nakata (2007)

$$L(t) = D(t) - E(t) \tag{8}$$

where D is the demand of electric power generation in kWh, E is the electric power generation by renewable energy in kWh and t is the time expressed in months, days and hours. In this research, month units consisted of t=1, 2, 3, ..., 12, day units consisted of t=1, 2, 3, ... 365 and hour units consisted of t=1, 2, 3, ..., 8,760. The renewable energy in this calculation was used to generate electricity. Sometimes surplus electricity was generated in excess of demand. The amount of surplus electricity (S_{E}) was integrated for one year and can be expressed as:

$$S_{\mathrm{E}} = \int \left\{ -L(t) \,\middle|\, _{L(t) \leq 0} \right\} dt \,. \tag{9}$$

The degree of self-sufficiency of renewable energy can be calculated from total electric power generation (E), surplus electricity generation (S_{E}) and demand (D) over time. The degree of self-sufficiency in energy, S_{R} [%], can be expressed as:

$$S_{\mathrm{R}} = \frac{\int E(t)\,dt - S_{\mathrm{E}}}{\int D(t)\,dt} \times 100 \,. \tag{10}$$

However, surplus energy generated in rural areas cannot contribute to S_{R}. When electricity loads occur, a substitute power plant can help to fulfil any shortage of electricity in rural areas. The maximum electricity load (M_{L}) occurring in one year's time in kWh can be expressed as:

$$M_{\mathrm{L}} = max\ L(t) = max\left\{ D(t) - E(t) \right\} . \tag{11}$$

In this research, hour units were used for the minimum separation time for calculating solar power and wind power. Month units were used for small hydropower generation because of the time lag between rainfall and flowing water. Year units were used for biomass generation. Averaging for monthly data or yearly data and integration of hourly data were used to compare the different type of renewable energy (Table 6).

Study Area

A study was undertaken in the Tochigi prefecture, and 11 cities were selected for data collection and analysis (Fig 2). The cities were Utsunomiya, Shioya, Sano, Kanuma, Oyama, Moka, Ohtawara, Nasu, Nasukarasuayama, Nasushiobara, and Nikko. These cities were selected based on sufficient geographic and climatic data for their discussion within an account of renewable energy utilisation in rural areas. The analysis of demand included the civil sector, which includes households, offices, schools and hospitals. The electricity demand of the civil sector, which consumes approximately 30% of the final energy use in Japan (Ministry of Economy, Trade and Industry (Japan) 2010b) was focused on evaluating renewable energy utilisation. The electricity demand curve for 24 hours in the 11 cities was fitted to electricity consumption during 12 months in Japan as a whole (Tochigi Prefecture government (Japan) 2010) (Ministry of Economy, Trade and Industry (Japan) 2008). We assumed that electricity demand was proportional to the number of households.

Results and Discussion

Renewable Energy Utilisation

The regions with the highest potential for solar energy were located in the central and southwest part of the Tochigi prefecture, including Utsunomiya, Sano and Oyama (Fig 3). The other potential regions were identified in Nikko, Kanuma, Nasushiobara and Ohtawara. Again, Shioya, Nasu and Nasukarasuyama also had the opportunity to install solar panels in limited areas.

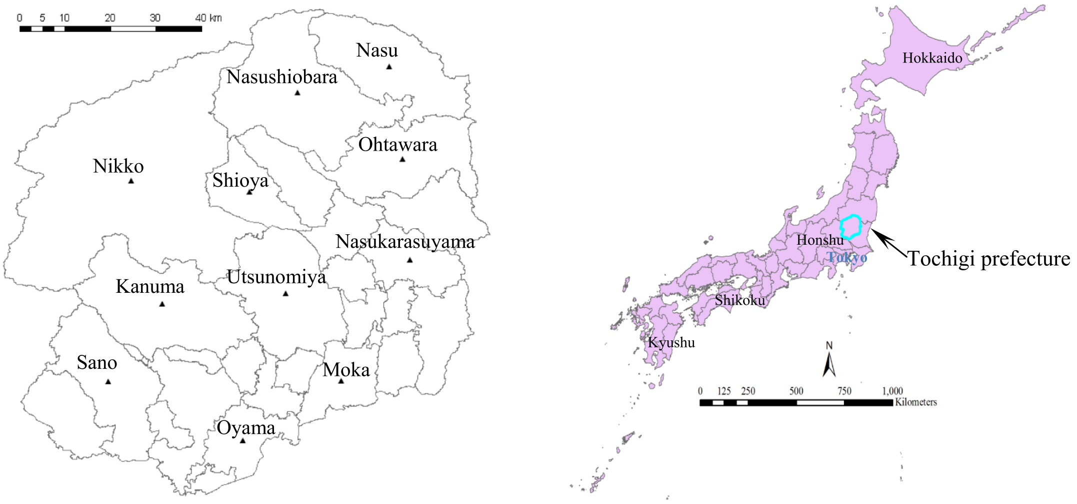

Fig. 2 Estimates of renewable energy potential for (a) Tochigi prefecture and the 11 cities (b) Tochigi prefecture and main islands of Japan

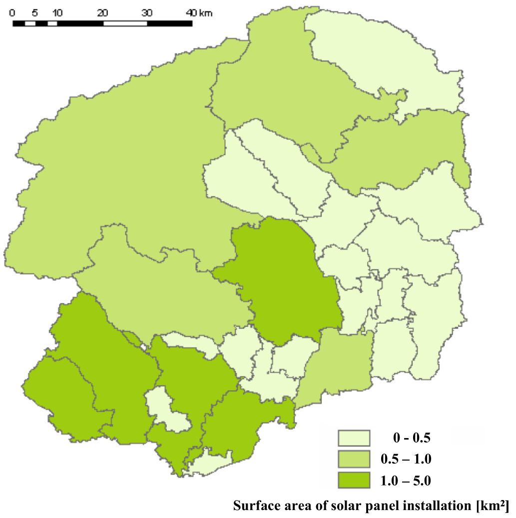

Fig. 3 Distribution map of the surface area of solar panel installation in Tochigi prefecture

The geographic and climatic conditions for the installation of wind turbines were analysed for the Tochigi prefecture (Fig. 4a and b). The potential areas for the installation of wind turbines were identified (Fig. 4c). The most suitable wind power installation regions were in the northern part of the Tochigi prefecture, including Nasu and Nasushiobara (Fig. 4d). The other suitable areas were in the northeastern part of the Tochigi prefecture including Nikko and Shioya (Fig. 4d). Hydropower power generation was analysed in terms of geographical conditions in order to determine the most suitable location for the installation of hydropower units (Fig. 5a). The maximum number of hydropower units could be installed in Nikko, Kanuma and Utsunomiya followed by Nasushiobara, Nasu, and Sano (Fig. 5b). However, suitable locations were limited due to the presence of natural parks and their gradients. Abandoned areas in the Tochigi prefecture were identified for biomass production. The largest amount of biomass production using abandoned fields was located mainly in Nasu-

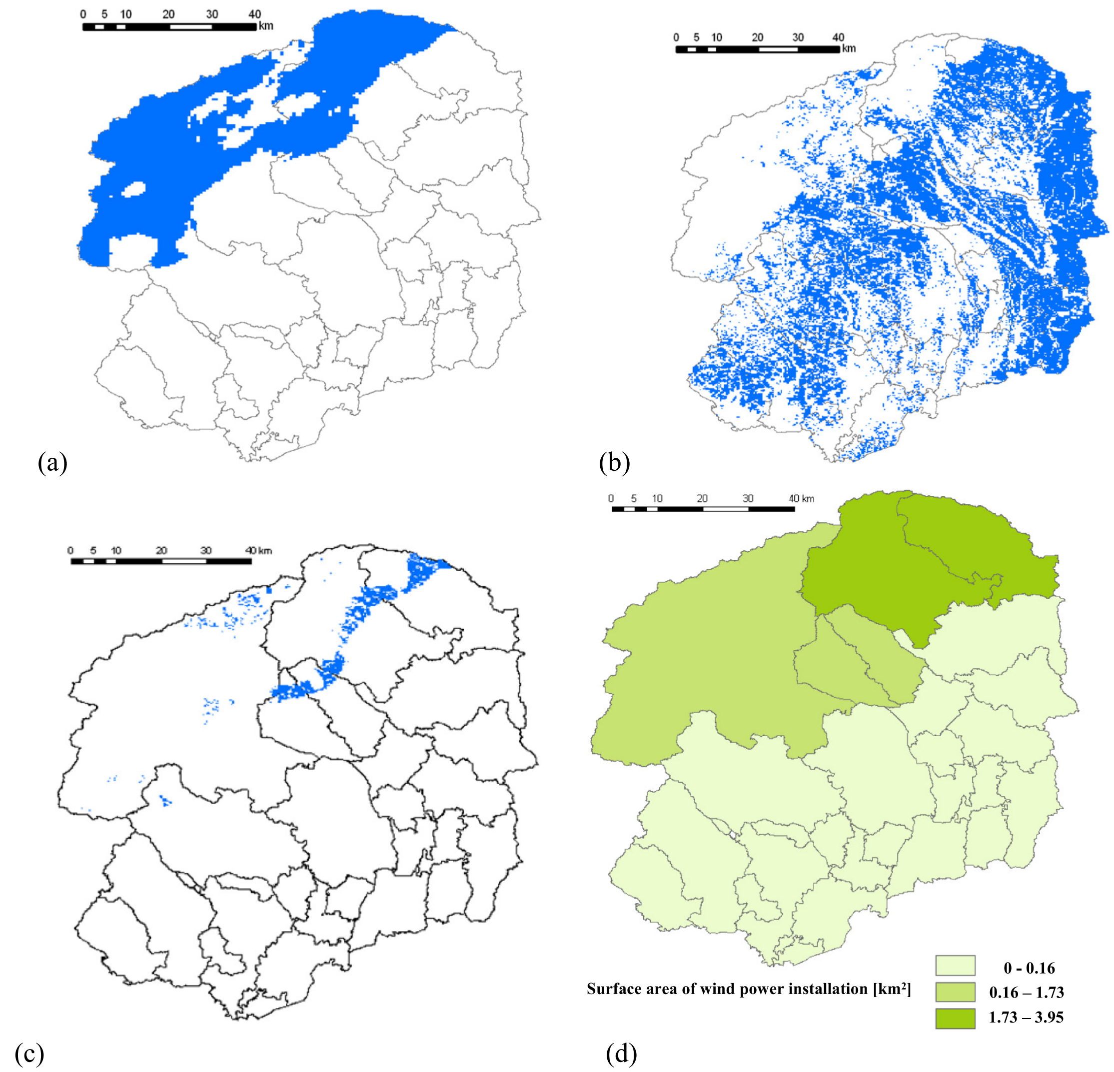

Fig. 4 Distribution map of the surface area for wind power installation in Tochigi prefecture; (a): with satisfactory climatic conditions, (b): with satisfactory geographical conditions, (c): with satisfactory geographical and climatic condition, (d): surface area of wind power installation expressed as city units

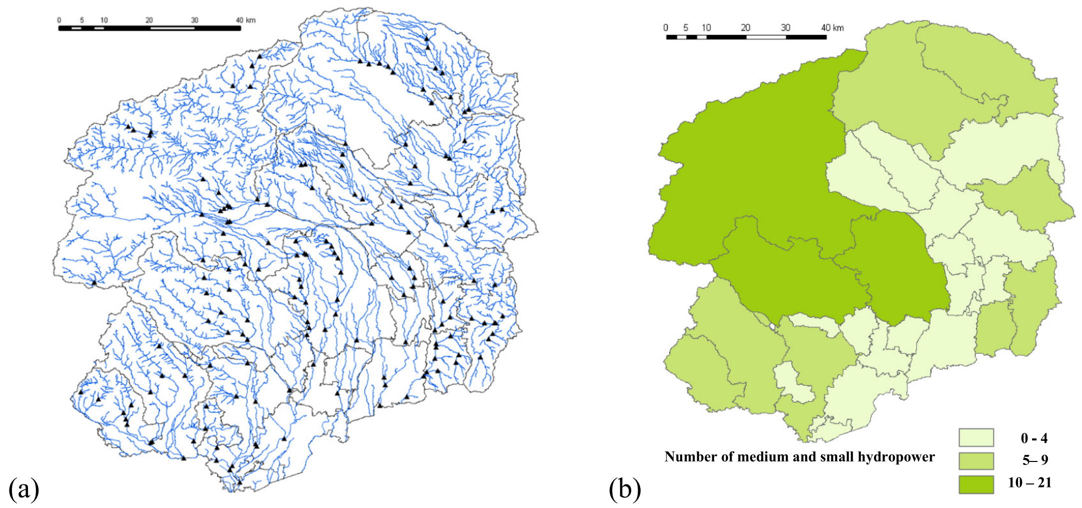

Fig. 5 Distribution map for small hydropower plants in Tochigi prefecture; (a): imaginary power plant, (b): number of small hydropower plants expressed for each city

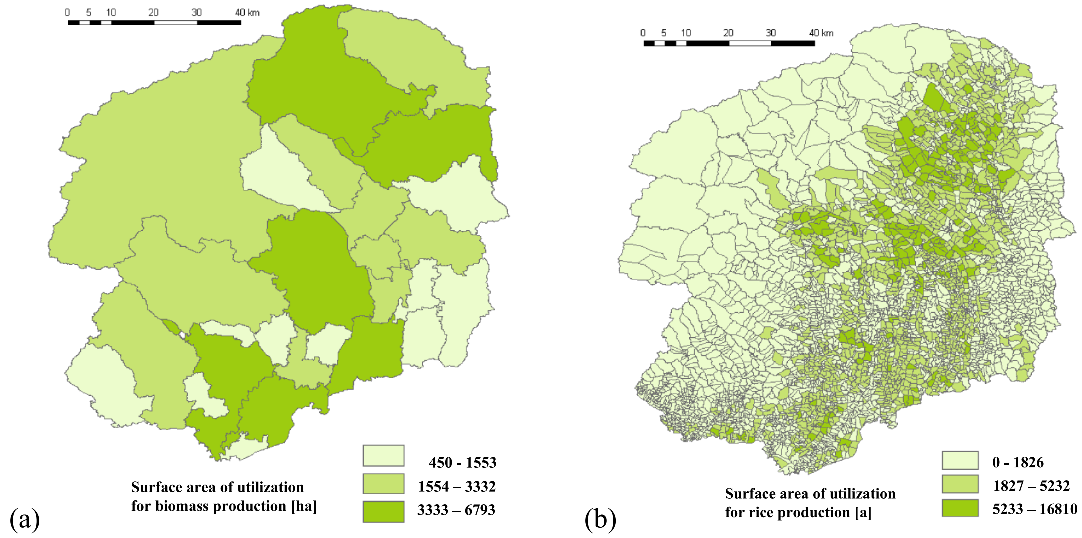

Fig. 6 Distribution map for biomass production of energy in Tochigi prefecture; (a): surface area of utilisation for biomass production, (b): surface area of utilisation for rice production expressed for each agricultural settlement

shiobara, Ohtawara, Utsunomiya and Moka (Fig. 6a). The other potential regions were Nikko, Nasu, Kanuma and Sano. However, belt-shaped areas in the northeast and south were found to be the most suitable for producing fukuhibiki-variety rice for biomass. After addressing these concerns, GIS analysis was performed to determine the agricultural settlement map (Fig. 6b).

Renewable Energy Potentials

The energy potential and specification of renewable energy installations for 11 cities were estimated and listed in Table 5. In the case of solar power generation, Utsunomiya, Sano, Oyama, and Nasushiobara had energy potentials of 581,276 MWh/year, 134,244 MWh/year, 160,967 MWh/year, and 110,956 MWh/year, respectively. Many buildings in those cities could be used to contribute to the generation of solar power. In the calculation of wind power generation, Shioya, Kanuma, Nasu, Nasushiobara, and Nikko were selected from among the 11 cities of the Tochigi prefecture for the installation of wind turbines. Their potentials were estimated at 739 MWh/year, 52 MWh/year, 11,563 MWh/year, 3,765 MWh/year, and 9,682 MWh/year, respectively. The potential electricity generation of wind power for these cities was less than that of solar power. In our estimation, 30 wind turbines could be installed to produce 3,765 MWh/year at Nasushiobara, and 16 wind turbines could be installed to produce 9,682 MWh/year at Nikko. Therefore, little correlation between number of wind turbines and the total amount of wind power generated was observed. Because capable area of constructing wind turbine was not always the suitable area of obtaining sufficient wind power. In the case of windpower, a maximum of 11,563 MWh/year could be generated at Nasu. We observed that electricity generation

Table 5 Energy potential and specification of renewable energy installation at 11 cities of Tochigi prefecture

	Solar power generation	Wind power generation	Small hydropower generation	Biomass generation
Name of city	Electricity (/year) (Number of houses:offices:schools)	Electricity (/year) (Surface area: Number of wind turbines)	Electricity (/year) (Number of dams)	Electricity (/year) (Rice field:Abandoned field)
Utsunomiya	581,276 MWh (196,732:21,800:109)		1,809 MWh (17)	65,047 MWh (6,481 ha:311 ha)
Shioya	10,937 MWh (3,841:531:7)	739 MWh (1.14 km^2, 11)	1,968 MWh (3)	14,496 MWh (1,507 ha:46 ha)
Sano	134,240 MWh (43,888:7,023:46)		2,210 MWh (9)	18,731 MWh (1,698 ha:153 ha)
Kanuma	98,790 MWh (33,837:5,090:43)	52 MWh (0.16 km^2, 1)	6,662 MWh (13)	26,368 MWh (2,267 ha:262 ha)
Oyama	160,967 MWh (57,225:7,003:43)		514 MWh (1)	36,475 MWh (3,622 ha:179 ha)
Moka	79,198 MWh (26,906:3,573:31)		1,616 MWh (4)	38,842 MWh (4,174 ha:72 ha)
Ohtawara	75,543 MWh (26,617:3,496:39)		1,844 MWh (3)	60,382 MWh (6,416 ha:138 ha)
Nasu	22,946 MWh (8,016:1,630:19)	11,563 MWh (3.95 km^2, 37)	2,847 MWh (6)	24,892 MWh (2,270 ha:198 ha)
Nasu-karasuyama	31,362 MWh (9,680:1,606:12)		13,695 MWh (2)	19,623 MWh (1,554 ha:245 ha)
Nasu-shiobara	110,956 MWh (40,917:5,500:39)	3,765 MWh (3.19 km^2, 30)	15,432 MWh (8)	42,255 MWh (4,406 ha:129 ha)
Nikko	97,173 MWh (33,790:4,837:48)	9,682 MWh (1.73 km^2, 16)	11,305 MWh (21)	28,110 MWh (2,629 ha:199 ha)
Total	1,403,388 MWh	25,801 MWh	59,902 MWh	375, 221 MWh

from small hydropower was less than that of solar power. In the city of Utsunomiya, 17 hydropower plants could be installed and a total of 1,809 MWh/year could be generated. In contrast, only two hydropower plants, capable of producing 13,695 MWh/year, could be installed in the city of Nasukarasuyama. The geographical conditions, especially the factor of gradient, affected the total amount of small hydropower generation. Suitable area of small hydropower generation was concentrated in junction of river in north part of Tochigi prefecture. However, suitable area of small hydropower generation showed decrease because of geographical condition of maximum angle of inclination below 20° and the natural park area. In the case of biomass, unpractical and unused paddy fields were used for estimation of biomass production of high yield feed rice "Fukuhibiki". Total biomass production of fukuhibiki was considered for electric power generation. Furthermore, all rice chaff and rice straw produced in general paddy field were used for the power generation too. Utsunomiya and Ohtawara were found to be the high biomass-energy-potential regions for the Tochigi prefecture. This estimation was performed based on the fukuhibiki variety of rice as biomass and found a potential of 65,047 MWh/year for Utsunomiya and 60,382 MWh/year for Ohtawara. The total biomass energy potential was estimated at over 60 GWh for these two cities.

The total amount of renewable energy potential was estimated for 11 cities in the Tochigi prefecture. And solar power had the highest potential for electricity production, followed by biomass, hydropower and wind power. We observed that 1,403,388 MWh/year (75.3%) could be produced from solar power, 25,801 MWh/year (1.4%) from wind power, 59,902 kWh/year (3.2%) from small hydropower and 375,221 MWh/year (20.1%) from biomass.

A coefficient of equation in our methodology for estimating renewable energy potential was referred from academic journals, and governmental reports based on the present technologies for renewable energy utilization. The coefficient in this research was applied as fundamental value to calculate renewable energy potential considering geographic and climatic data in Japan. Energy profit ratio is important indication for discussing introducing facility of renewable energy. Cost of construction and management considering with a life time are required for calculation for indirect energy and direct energy of input energy. However, there are insufficient data of indirect energy and direct energy in current situation. So, energy profit ratio should be examined in next research.

Electricity generation in time series

The difference of electricity estimation was twice that of the minimum and maximum rating of total electricity estimated for a year. We observed a small difference in trends of electricity change when solar power is used. However, there was a large difference in the trend of electricity change in May 2003 (Fig. 7) in the city of Utsunomiya. Total electricity generation by solar power was higher than other renewable energy utilisation. Solar power generation was expected to be introduced area-wide. More electricity could be generated using more wind turbines in the winter season. Wind velocities were higher in the winter compared with spring, summer and fall. The observations of the ratios of wind power change in a day and in a month were found to be very high compared to those of solar power generation. We have noticed that this fluctuation occurred in a time series for wind power and showed discontinuity (Fig. 8). The power and frequency of wind characteristics must be investigated for the imple-

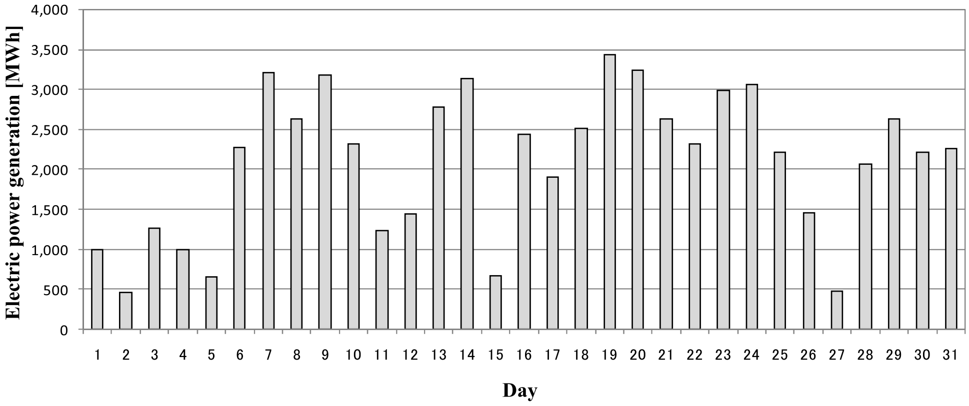

Fig. 7 Electricity generated by solar panels in Utsunomiya for 31 days in May 2003 (NEDO (Japan) 2006a)

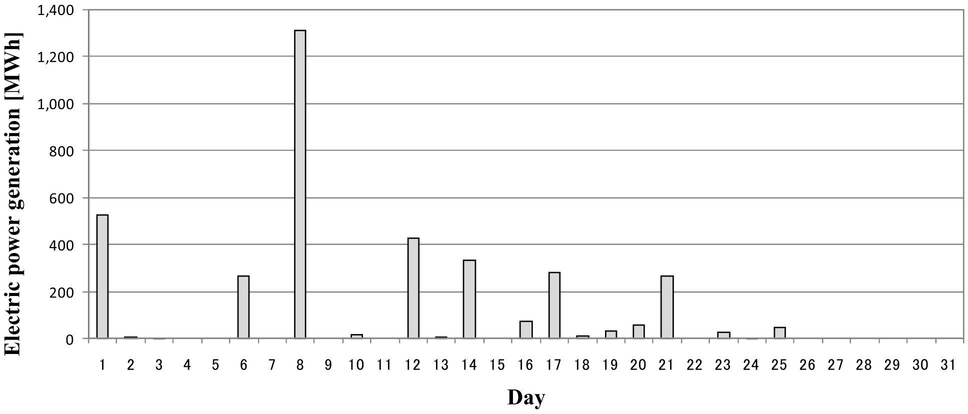

Fig. 8 Total electricity generated by wind power in Nasu for 28 days in February 2009 (Meteorological Agency (Japan) 2010)

mentation of wind turbines. As with solar power, a high-durability system to meet the difficulties of wind power fluctuation must be discussed before wind power is widely introduced. The maximum value of electric power generation for small hydropower for 12 months was reported for August in the 11 cities. The amount of hydropower generation in August was indicated to be approximately 10 times that of December. Electric power generation by small hydropower was proportional to the average monthly precipitation. The difference in precipitation between August and September was very large, and the 11 cities had different trends within the precipitation record. Power generation could be affected by precipitation upstream. In these cases, the amount of precipitation and the total amount of water downstream must be measured to estimate the total amount of electricity that can be generated from small hydropower units. Finally, solar power generation showed a great deal of potential as a renewable energy source in Tochigi prefecture compared with other forms of renewable energy. The ratio of each kind of renewable energy generation differed according to the characteristics of each city's geographical and climatic conditions. Estimating the change of energy potential for 4 types of renewable energy based on time series was focused in this research. On the other hand, the relative frequency of wind power could be applied, if more detailed data of energy potential of wind power are requested.

Renewable energy potential in time series

Electricity consumption was integrated for one year in Tochigi prefecture (Tochigi Prefecture government (Japan) 2010). An electricity consumption curve (Ministry of Economy, Trade and Industry (Japan) 2008) was used to calculate the degree of energy self-sufficiency (S_R), surplus electricity (S_E), and maximum electricity load (M_L) for the yearly, monthly, daily, and hourly estimation of the integrated year listed in Table 6. We found a maximum S_R of 56% at Nasu and a minimum S_R of 24% at Utsunomiya. Since the S_R was found to be low for all the cities in the Tochigi prefecture, our preliminary assumption that smart grid applications should be introduced for the adoption of renewable energy was not sufficient. The amount of surplus electricity of the one integrated year (S_E) was not considered for the yearly and monthly estimations (Table 6). In the hourly estimation, 3,363 MWh/year of S_E could be used to make up shortfalls in the cities using smart grid methods. The maximum S_E was found to be 4,235 MWh/year using daily estimation, and 9,075 MWh/year was observed in hourly estimations at Nasu. S_E was higher at Nasu due to the geographical and climatic conditions there that facilitate wind power generation. In addition, biomass energy

Table 6 Rate of energy sufficiency, surplus electricity, and maximum electricity load per year, per month, per day, and per hour of the integrated one year in 11 cities

Estimation unit	yearly	monthly	daily	hourly
Name of city (Demand)	S_R: Self-sufficient degree in energy, S_E: Surplus electricity, M_L: Maximum electricity load			
Utsunomiya (2,668,839 MWh)	S_R: 24% S_E: 0 MWh M_L: 2,016,744 MWh	S_R: 24% S_E: 0 MWh M_L: 213,800 MWh	S_R: 24% S_E: 0 MWh M_L: 8,542 MWh	S_R: 24% S_E: 6,279 MWh M_L: 459 MWh
Shioya (52,106 MWh)	S_R: 54% S_E: 0 MWh M_L: 23,967 MWh	S_R: 54% S_E: 0 MWh M_L: 2,995 MWh	S_R: 54% S_E: 0 MWh M_L: 123 MWh	S_R: 52% S_E: 1,093 MWh M_L: 7MWh
Sano (595,378 MWh)	S_R:26% S_E: 0 MWh M_L: 439,274 MWh	S_R:26% S_E: 0 MWh M_L: 47,023 MWh	S_R:26% S_E: 0 MWh M_L: 1,856 MWh	S_R:26% S_E: 2,581 MWh M_L: 99 MWh
Kanuma (459,028 MWh)	S_R:29% S_E: 0 MWh M_L: 326,469 MWh	S_R:29% S_E: 0 MWh M_L: 35,438 MWh	S_R:29% S_E: 0 MWh M_L: 1,379 MWh	S_R:28% S_E: 2,109 MWh M_L: 76 MWh
Oyama (776,306 MWh)	S_R:26% S_E: 0 MWh M_L: 577,258 MWh	S_R:26% S_E: 0 MWh M_L: 61,305 MWh	S_R:26% S_E: 0 MWh M_L: 2,386 MWh	S_R:25% S_E: 2,196 MWh M_L: 130 MWh
Moka (365,003 MWh)	S_R:33% S_E: 0 MWh M_L: 244,823 MWh	S_R:33% S_E: 0 MWh M_L: 269,655 MWh	S_R:33% S_E: 0 MWh M_L: 1,064 MWh	S_R:32% S_E: 2,118 MWh M_L: 59 MWh
Ohtawara (361,082 MWh)	S_R:38% S_E: 0 MWh M_L: 222,768 MWh	S_R:38% S_E: 0 MWh M_L: 24, 9445 MWh	S_R:38% S_E: 0 MWh 988 MWh	S_R:38% S_E: 2,785 MWh 56 MWh
Nasu (108,744 MWh)	S_R:56% S_E: 0 MWh M_L: 47,276 MWh	S_R:56% S_E: 0 MWh M_L: 5,034 MWh	S_R:53% S_E: 4,235 MWh M_L: 269 MWh	S_R:49% S_E: 9,075 MWh M_L: 16 MWh
Nasu-karasuyama (131,318 MWh)	S_R:49% S_E: 0 MWh M_L: 66,396 MWh	S_R:49% S_E: 0 MWh M_L: 8,911 MWh	S_R:49% S_E: 0 MWh M_L: 352 MWh	S_R:47% S_E: 2,956 MWh M_L: 20 MWh
Nasu-shiobara (555,074 MWh)	S_R:31% S_E: 0 MWh M_L: 382,104 MWh	S_R:31% S_E: 0 MWh M_L: 42,338 MWh	S_R:3 1% S_E: 0 MWh M_L: 1,620 MWh	S_R:31% S_E: 2,665 MWh M_L: 92 MWh
Nikko (458,390 MWh)	S_R:32% S_E: 0 MWh M_L: 312,065 MWh	S_R:32% S_E: 0 MWh M_L: 34,473 MWh	S_R:32% S_E: 0 MWh M_L: 1,363 MWh	S_R:31% S_E: 2,992 MWh M_L: 75 MWh
Total (2,668,839 MWh)				S_E: 36,849 MWh
Synthesised total of 11 cities	S_R:29% S_E: 0 MWh M_L:4, 659,143 MWh	S_R:29% S_E: 0 MWh M_L: 503,095 MWh	S_R:29% S_E: 0 MWh M_L: 18,223 MWh	S_R:29% S_E: 3,363 MWh M_L: 1,076 MWh

potential contributed to the estimation of total renewable energy potentials in the Tochigi prefecture.

Conclusions

The renewable energy potentials from solar power, wind power, small hydropower, and biomass were estimated for rural areas based on geographic and climatic conditions. Real-time weather data were used in the simulation to calculate renewable energy utilisation. METPV-3 (NEDO 2006) and AMeDAS (Meteorological Agency (Japan) 2010) were used in the simulation to calculate renewable energy utilization as a climatic database in this research. More detailed of weather data could be applied to analyze the real-time potential of renewable energy considering with unstable factors of weather condition. Furthermore, this study was conducted for the 11 cities in the Tochigi prefecture to illustrate the potential of renewable energy. Themethodology for estimating renewable energy potential was developed for rural areas using GIS. Based on the case study, the following conclusions can be drawn:

1) Solar power had the highest potential for electricity production, followed by biomass, hydropower and wind power. We observed that 1,403,388 MWh/year (75.3%) could be produced from solar power, 25,801 MWh/year (1.4%) from wind power, 59,902 kWh/year (3.2%) from small hydropower and 375,221 MWh/year (20.1%) from biomass. The ratio of each kind of renewable energy generation changed according to the characteristics of each city's geographical and climatic conditions.

2) Renewable energy was not sufficient to fulfil electricity demand for domestic purposes, which cover the needs of the households, offices, schools and hospitals of each area. The amount of surplus electricity of the integrated one year was not considered for yearly and monthly estimations. In hourly estimation, 3,363 MWh/year of surplus electricity could be used to make up shortfalls. The maximum surplus electricity was found to be 4,235 MWh/year using daily estimation, and 9,075 MWh/year was observed in hourly estimations in the city of Nasu. We found that surplus electricity was higher at Nasu due to specific geographical and climatic conditions that facilitate wind power generation there.

3) Renewable energy could be used as an additional source of energy to that of fossil fuel in rural areas. However, to achieve the same benefits in domestic use, energy conversion efficiency in renewable energy plants needs to be improved, and energy-saving measures should be considered.

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