Wind-Solar Hybrid System Analysis for Westville, Indiana, USA

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Abstract: Wind energy and solar energy are two of the most reliable energy sources on earth while also being environmentally safe and sufficient. The search for more reliable sources has brought the two energy sources together in areas that alone they would be insufficient. For a solar-wind hybrid system, the economic efficiency is strictly dependent on both resources combined to be efficient no matter the time or the location. The strength of one source can overcome the weakness of the other which makes this design so useful around most areas of the world.

Keywords: Power grid, f-chart method, solar energy, wind energy, water heater.

1. INTRODUCTION

Solar panels and wind turbines systems capture the sun's and wind's energy to supplement the existing heating system for a home. The heating system heat water that is then used to heat the home and supply hot water to the home. There is a complementary effect of the energy resource between wind energy and solar energy. These resources can be integrated into solar-wind hybrid optimum combination. The strength of one source could over come the weakness of the other during a certain period. This is apparent by realizing the fact that in Westville, according to data of NASA Surface meteorology and Solar energy, more solar radiation and less wind are available during the summer months, and similarly, more wind and less solar radiation are available during the winter months. There are many methods used to design a hybrid solar-wind system and to calculate the reliability of its power generating capacity. The method used in this report is the f-chart method for the solar energy and the wind power. Duffie and Beckman [1] authoredsolar engineering of thermal processes. Gorla and Salako [2] analyzed the feasibilty of wind-solar hybrid system for Cleveland, Ohio, USA. Sateikis *et al*. [3] analyzed the feasibility of heating a single-family home by using solar and wind energy. Yang *et al.* [4] analyzed a hybrid photovoltaic/wind system for Hong Kong. Celik [5] optimized a photovoltaic/wind system. Yang and Aydin [6] analyzed the wind energy/hydrogen storage hybrid power station. Elhadidyand Shaahid [7] looked at the feasibility of a hybridsolar and wind system for Dhahran, Saudi Arabia. Gorla [8] presented a finite element analysis for a solar collector system. Kimura *et al.* [9] presented a demonstrative study of wind/solar hybrid system. The objective of the present study is to identify the potential of satisfying about 50% of heating needs of single family houses in Westville (for space and water heating) in the hybrid system by using solar and wind energy.

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2. HEATING PROCESS

A hybrid of 4m × 1m (13.12 ft. x 3.28 ft.) solar collector area and a 1 m(3.28 ft.) diameter wind turbine is proposed for the space heating of a one-storied house and heating of 150 liters(40 gallons) hot water tank in Westville. The solar tubes are mounted directly on the roof of the one-story house and the wind turbines mounted 10m above grade. The main storage tank and the water heater are installed in the basement.

2.1. Wind Power

The available power from the wind can be expressed as the average wind flow power passing through the wind turbine blades area. Air density decreases with temperature and altitude and the major factor in power generation is wind velocity. The Betz limit says that the maximum percentage of power we can harvest from the wind is 59.26%. The energy generated by a wind turbine depends on how many hours the wind blows or the "wind speed frequency distribution" at the actual location. The electric energy generated (auxiliary) in Figure **1** is fed to heat the water heater tank.

$$Power: P = \rho A v^3 \left(\frac{W}{m^2}\right)$$

Actual Available Power: $P_a = \frac{1}{2}\xi\rho A v^3$

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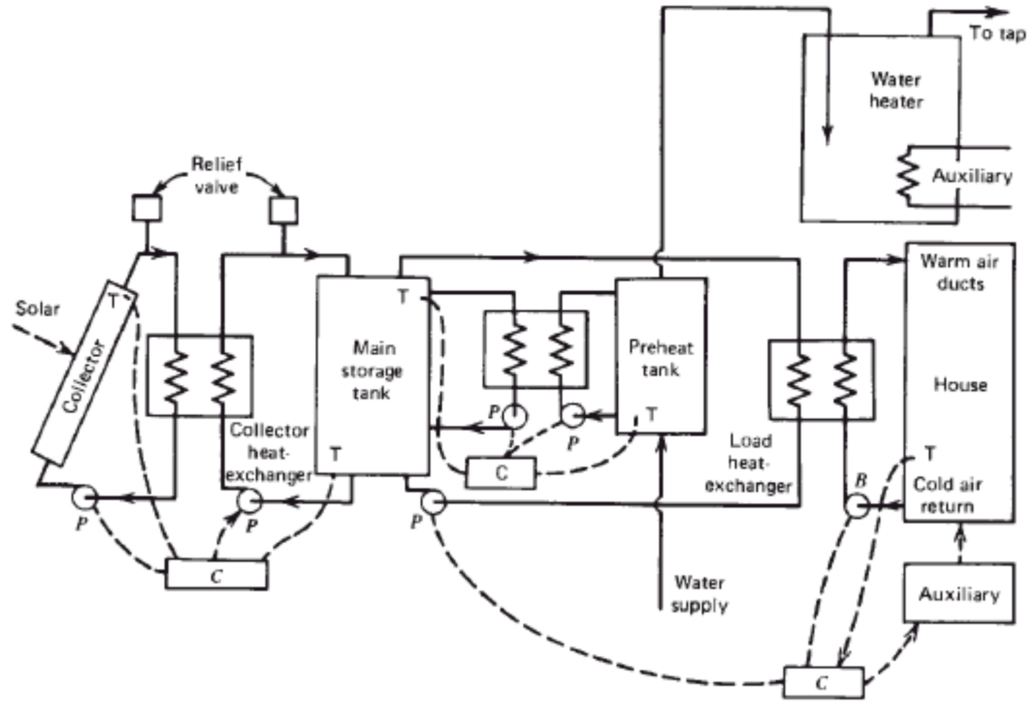

Figure 1: Schematic of solar heating system, P-pump, C-controller, B-blower.

where ξ = efficiency of the wind turbine (in general less than 0.4, or 40%).

2.2. Solar Heating System

This report used a standard heating system using liquid heat transfer fluids as shown in Figure **1**. This system normally uses an antifreeze solution in the collector loop and water as the storage medium. Collectors may be drained when energy is not being collected; in which case water is used directly in the collectors and a collector heat exchanger is not needed. During this time, an auxiliary heater is used to supply energy for the heating load when it cannot be met from the solar collector. The solar energy is collected by the solar collector, then the solar energy is transferred *via* a heat exchanger to a domestic hot water preheat tank, which supplies solar-heated water to a conventional water heater where the water is further heated to the desired temperature if necessary. A tempering valve may be provided to maintain the tap water below a maximum temperature. These changes in the system configuration do not have major effects on the performance of the system.

2.2.1. The f-Chart Method

The f-chart method is used for designing the solar thermal processes, which provides a means for estimating the fraction of a total heating load that will be supplied by solar energy for a given solar heating system. The primary design variable is the collector area. Secondary variables are collector type, storage capacity, fluid flow rates, and load and collector heat exchanger sizes. The method is a correlation of the results of many hundreds of thermal performance simulations of solar heating systems. The conditions of the simulations are varied over appropriate ranges of parameters of practical system designs. The resulting correlations give f, the fraction of the monthly heating load for hot water supplied by solar energy as a function of two dimensionless parameters X and Y. Where X is related to the ratio of collector losses to heating loads, and Y is related to the ratio of absorbed solar radiation to heating loads.

$$X = \frac{A_c F_R' U_L \left(T_{ref} - \bar{T}_a\right) \Delta t}{L} \quad (1)$$

$$Y = \frac{A_c F_R' \left(\overline{\tau\alpha}\right) \bar{H}_T N}{L} \quad (2)$$

Fraction of the monthly total load supplied by the water heating system is:

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \quad (3)$$

The two dimensionless groups are used to determine the monthly fraction (f_i) of the load supplied by solar energy. The energy contribution for the month is the product of f_i and the monthly heating and hot water load (L_i). The fraction of the annual heating load supplied by solar energy F is the sum of the monthly solar energy contributions divided by the annual load.

$$F = \frac{\sum f_i L_i}{\sum L_i} \tag{4}$$

The f-chart method was developed for a storage capacity of 75 liters of stored water per square meter of collector area. The performance of systems can be determined by multiplying the dimensionless group (X) by a storage size correction factor $\left(\frac{X_c}{X}\right)$.

$$\frac{X_c}{X} = \left(\frac{Actual \quad storage \quad capacity}{Standard \quad storage \quad capacity}\right)^{-0.25} \tag{5}$$

A measure of the size of the heat exchanger needed for a specific building is provided by the dimensionless parameter $\left(\frac{\varepsilon_L C_{\min}}{(UA)_h}\right)$. The f-chart method for liquid systems was developed with $\left(\frac{\varepsilon_L C_{\min}}{(UA)_h}\right)$=2. The performance of systems with other values can be estimated by multiplying the dimensionless group (Y) by a load heat exchanger correction factor $\left(\frac{Y_c}{Y}\right)$,

$$\frac{Yc}{Y} = 0.39 + 0.65\exp\left[-0.139 * \frac{(UA)}{\varepsilon_L C_{\min}}\right] \tag{6}$$

The f-chart for liquid heating systems can be used to estimate the performance of solar water heating systems by defining an additional correction factor on X. The mean water temperature T_m and the minimum acceptable hot water temperature T_w; both affect the performance of solar water heating systems by affecting the average system operating temperature level and the collector energy losses. The performance of systems can be determined by multiplying the dimensionless group (X) by a water heating correction factor $\left(\frac{X_c}{X}\right)$.

$$\frac{X_c}{X} = \frac{11.6 + 1.18T_w + 3.86T_m - 2.32\bar{T}_a}{100 - \bar{T}_a} \tag{7}$$

The water heating correction factor assumes a well-insulated solar preheat tank, and losses from an auxiliary tank were not included in the f-chart correlations. It is recommended that tank loss calculations assume that the entire tank is at the water set temperature T_w. The method indicated here can be used for systems with or without the tempering valve. Other assumptions are: 1) Liquid storage tanks are assumed to be fully mixed both for main storage tanks for liquid systems and preheat tanks for all water heating. 2) All days were considered symmetrical about solar noon. 3) Very well insulated storage tanks with no leaks in the system. 4) Systems are well built. 5) Flow distribution to collectors is uniform. 6) Flow rates are as assumed. 7) System configurations are close to those for which the correlations were developed. 8) Control strategies used are nearly those assumed in the f-chart development. The f-chart method is more accurate for annual fractions instead of monthly fractions, therefore should be used to estimate annual performance only. Systems with a problem in the design or construction of the system are generally within ±15%.

2.3. Solar-Wind Hybrid

The Hottel-Whillier-Bliss equation is used to calculate the total rate of useful energy gain from the solar collector.

$$Q_u = A_c F_R \left[H_a - U_c\left(T_i - T_a\right)\right]\left(\frac{\frac{kWh}{m^2}}{day}\right),$$

The average quantity of thermal energy obtained from the wind power.

$$q_w = 0.32 P \Delta t \left(\frac{\frac{kWh}{m^2}}{day}\right)$$

For this system, the electric power generated from the wind is used for heating the hot water tank. The gross average coefficient of wind energy conversion into heat is accepted as 0.32.

3. RESULTS AND DISCUSSION

To design and optimize solar heating systems, for residential houses in Westville, Indiana at latitude of 41.5°, longitude -81.5° and elevation 582m, the f-chart was utilized in the design of the liquid-based solar heating system to determine the annual load fraction in conjunction with a 1 m diameter wind turbine.

Table 1: Single Hybrid Useful Energy Balance

Months	Single Hybrid (1) Solar Collector and (1) Wind Turbine										
	Available		Useable Heat Energy								
	(kWh/m²/day)		(kWh/m²/day)					30% Hybrid Contribution			
	Solar	Wind	Solar	Wind	Hybrid	Utility	Load	Solar	Wind	Hybrid	Utility
January	2.11	1.79	12.81	13.77	26.58	188.39	214.97	6%	6%	12%	88%
February	2.94	1.72	19.28	13.18	32.46	160.68	193.14	10%	7%	17%	83%
March	3.77	2.22	26.26	17.08	43.34	119.89	163.23	16%	10%	27%	73%
April	4.36	2.00	31.59	15.40	46.99	69.73	116.72	27%	13%	40%	60%
May	4.80	1.52	35.64	11.67	47.31	41.21	88.52	40%	13%	53%	47%
June	5.10	1.02	38.66	7.86	46.52	17.96	64.48	60%	12%	72%	28%
July	5.06	0.78	38.66	5.98	44.64	16.48	61.12	63%	10%	73%	27%
August	4.84	0.70	36.94	5.39	42.33	17.02	59.35	62%	9%	71%	29%
September	4.42	0.81	33.23	6.22	39.45	17.79	57.24	58%	11%	69%	31%
October	3.72	1.35	27.15	10.40	37.55	43.51	81.06	33%	13%	46%	54%
November	2.23	1.57	14.85	12.06	26.91	151.76	178.67	8%	7%	15%	85%
December	1.60	1.69	9.26	13.00	22.26	211.76	234.02	4%	6%	10%	90%

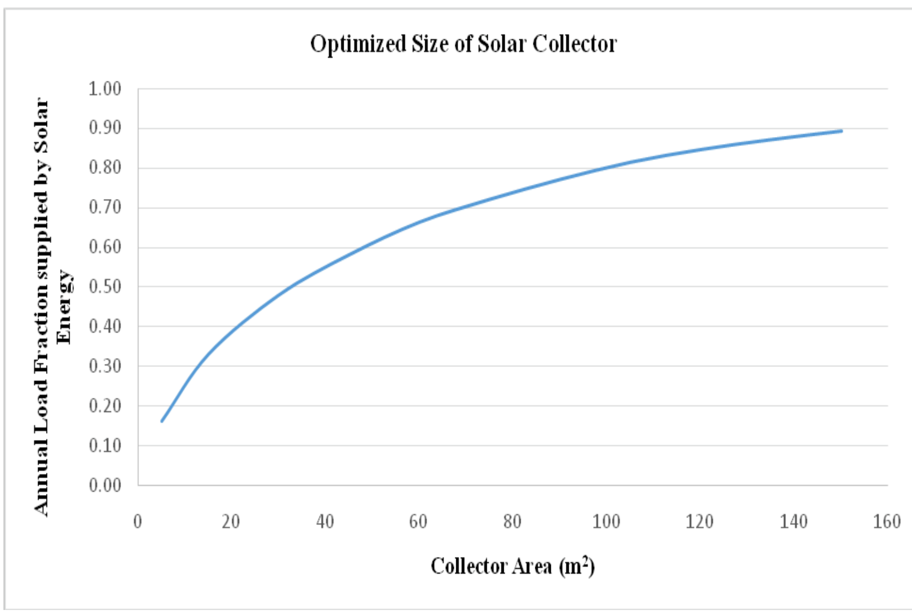

Figure 2: Optimal Solar Collector Size.

3.1. Results for Solar Power System Operating Alone

The Solar Collector chosen was a vacuum tube solar collector. The choice of this type of solar collector was because there were very little losses through the collector it self making the system very efficient. According to the f-chart method, to supply half the load for the home, the solar collector area would need to be at least 30 m^2 as projected in Figure **2**.

3.2. Results for Wind Power System Operating Alone

The wind turbine chosen was a small vertical wind turbine. The vertical wind turbines are not efficient. The average efficiency of a vertical wind turbine is 10%. According to calculations, the wind turbine provides energy in the winter months when the solar contribution is not as strong. Therefore, to account for the increased load in the winter months and lower availability of

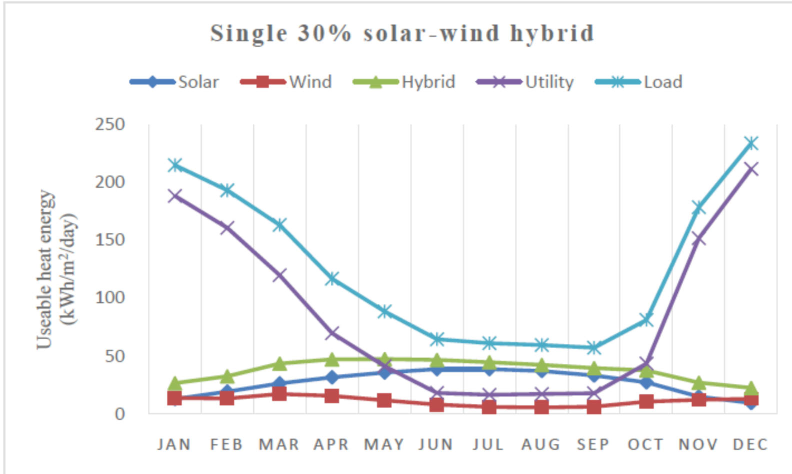

Figure 3: Monthly 30% Solar-Wind Hybrid, Utility and Load Useful Energy.

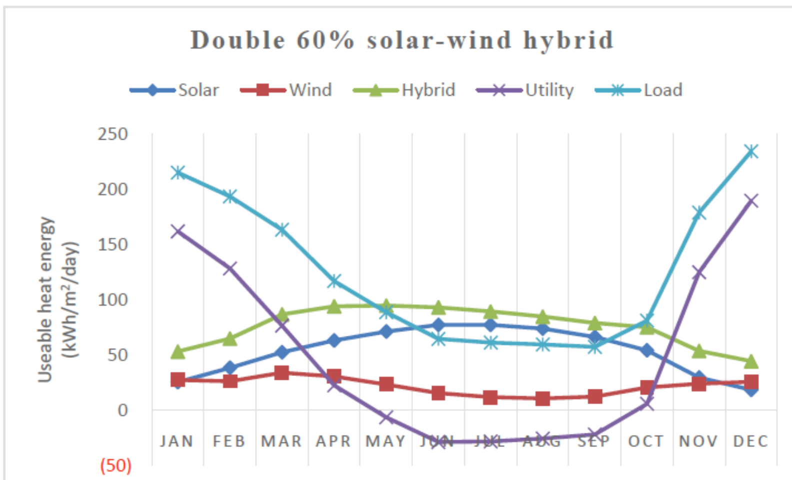

Figure 4: Monthly 60% Solar-Wind Hybrid, Utility and Load Useful Energy.

useful solar energy, multiple wind turbines would be needed to reach at least 50% of the load in all months.

3.3. Results for Hybrid Solar-Wind Power System

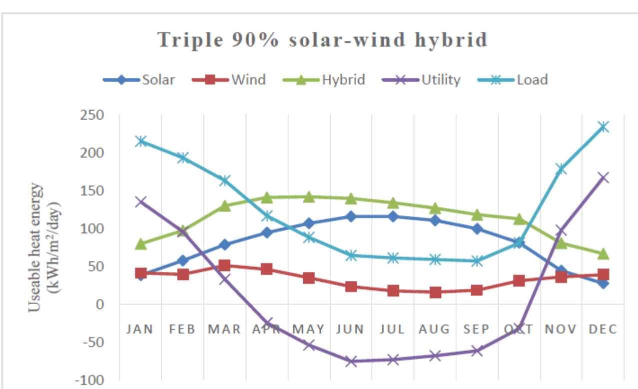

Figure 5: Monthly 90% Solar-Wind Hybrid, Utility and Load Useful Energy.

3.4. Results for Cost Analysis

The initial costs of the water heating system involve the costs of the solar collector, water tank, the heat exchanger, pumps, and other miscellaneous costs of parts for the installation of the system as well as any installation costs. Each year, maintenance costs and insurance costs apply to the system. In Indiana, homeowners can file to have the solar system be exempt from their property tax assessment so no increase in taxes would apply to the system. Federal taxes allow for a tax credit of 30% of the system cost, including installation, if 50% of the energy needed comes from the sun.

The initial costs of the system, without any labor to install it, are just under $3800. The cost of one solar collector is just under $1200 with tax. To provide 50% of the annual load, two of these would be needed. The

Table 2: Double Hybrid Useful Energy Balance

Months	Single Hybrid: (2) Solar Collectors and (2) Wind Turbines										
	Available		Useable Heat Energy								
	($kWh/m^2/day$)		($kWh/m^2/day$)					60% Hybrid Contribution			
	Solar	Wind	Solar	Wind	Hybrid	Utility	Load	Solar	Wind	Hybrid	Utility
January	2.11	1.79	25.62	27.54	53.16	161.77	214.93	12%	13%	25%	75%
February	2.94	1.72	38.56	26.36	64.92	128.22	193.14	20%	14%	34%	66%
March	3.77	2.22	52.52	34.16	86.68	76.55	163.23	32%	21%	53%	47%
April	4.36	2.00	63.18	30.80	93.98	22.74	116.72	54%	26%	81%	19%
May	4.80	1.52	71.28	23.34	94.62	(6.10)	88.52	81%	26%	107%	-7%
June	5.10	1.02	77.32	15.72	93.04	(28.56)	64.48	120%	24%	144%	-44%
July	5.06	0.78	77.32	11.96	89.28	(28.16)	61.12	127%	20%	146%	-46%
August	4.84	0.70	73.88	10.78	84.66	(25.31)	59.35	124%	18%	143%	-43%
September	4.42	0.81	66.46	12.44	78.90	(21.66)	57.24	116%	22%	138%	-38%
October	3.72	1.35	54.30	20.80	75.10	5.96	81.06	67%	26%	93%	7%
November	2.23	1.57	29.70	24.12	53.82	124.85	178.67	17%	13%	30%	70%
December	1.60	1.69	18.52	26.00	44.52	189.50	234.02	8%	11%	19%	81%

Table 3: Triple Hybrid Useful Energy Balance

Months	Triple Hybrid: (3) Solar Collectors and (3) Wind Turbines										
	Available		Useable Heat Energy								
	($kWh/m^2/day$)		($kWh/m^2/day$)					% Contributed			
	Solar	Wind	Solar	Wind	Hybrid	Utility	Load	Solar	Wind	Hybrid	Utility
January	2.11	1.79	38.43	41.31	79.74	135.19	214.93	18%	19%	37%	63%
February	2.94	1.72	57.84	39.54	97.38	95.76	193.14	30%	20%	50%	50%
March	3.77	2.22	78.78	51.24	130.02	33.21	163.23	48%	31%	80%	20%
April	4.36	2.00	94.77	46.20	140.97	(24.25)	116.72	81%	40%	121%	-21%
May	4.80	1.52	106.92	35.01	141.93	(53.41)	88.52	121%	40%	160%	-60%
June	5.10	1.02	115.98	23.58	139.56	(75.08)	64.48	180%	37%	216%	-116%
July	5.06	0.78	115.98	17.94	133.92	(72.80)	61.12	190%	29%	219%	-119%
August	4.84	0.70	110.82	16.17	126.99	(67.64)	59.35	187%	27%	214%	-114%
September	4.42	0.81	99.69	18.66	118.35	(61.11)	57.24	174%	33%	207%	-107%
October	3.72	1.35	81.45	31.20	112.65	(31.59)	81.06	100%	38%	139%	-39%
November	2.23	1.57	44.55	36.18	80.73	97.94	178.67	25%	20%	45%	55%
December	1.60	1.69	27.78	39.00	66.78	167.24	234.02	12%	17%	29%	71%

main storage tank was approximately $630 and the preheat tank was around $100. Another $1300 was estimated for parts such as the blower, controller, piping, wiring, brackets, and other miscellaneous items needed to connect the solar collector system to the house and secure it in place. A 100W 12V/24V AC 1.2m wheel diameter 3Pcs Fiberglass Blades Wind Turbine Generator cost about $350. Another $3000 was estimated for installation costs. A cost analysis is shown in Table **4**. Because of the nature of the evacuated tube solar collectors chosen, maintenance costs should be minimal, likely not occurring until after the first 10 years of service according to the manufacturer.

Table 4: Cost Analysis of Three Hybrid Systems

Years	Fuel Costs w/o Hybrid	Fuel Savings	Maint / Power Costs	Solar / Wind Parts	Solar / Wind Labor	Federal Tax Savings	Total Savings
0	-	-	-	(6,830.00)	(3,000.00)	2,949.00	(6,881.00)
1	808.00	727.20	-	-	-	-	(6,153.80)
2	808.00	727.20	-	-	-	-	(5,426.60)
3	808.00	727.20	-	-	-	-	(4,699.40)
4	808.00	727.20	-	-	-	-	(3,972.20)
5	808.00	727.20	-	-	-	-	(3,245.00)
6	808.00	727.20	-	-	-	-	(2,517.80)
7	808.00	727.20	-	-	-	-	(1,790.60)
8	808.00	727.20	-	-	-	-	(1,063.40)
9	808.00	727.20	-	-	-	-	(336.20)
10	808.00	727.20	-	-	-	-	391.00

The breakeven time for the savings from the tax credits and energy savings is 9 years using three systems of the hybrid at 90% energy contribution, 12 years using two systems of the hybrid at 60% energy contribution, and 26 years using one system of the hybrid at 30% energy contribution. This does not account for any rate increases on the cost for the utilities without the solar.

CONCLUSIONS

This paper analyzes and confirms that wind and solar energy can satisfy 50% of the energy demands to heat individual houses in Westville, Indiana if double or triple wind-solar hybrids are implemented. It also confirms that houses in Westville, Indiana qualify for the Federal tax credit of 30% of the system cost, including installation, since 50% of the energy needed comes from the sun. The analysis used conservative average weather data of NASA Surface meteorology as the typical weather year to analyze the complementary characteristics of solar radiation and wind power in developing the solar-wind hybrid energy. The analysis has shown that the generated energy of the triple hybrid system can satisfy up to 90% of the energy requirements for the hot water and the premise heating during the year. It is recommended that the excess power generated by the wind-solar hybrid during the non-winter months (April through September) be fed into the national power grid as part of the savings analysis.

NOMENCLATURE

A Area wind passing through perpendicular to the wind(m_2)

A_c Collector area

F Monthly heating load fraction supplied by solar energy, correlation between X and Y

F_R Collector heat-removal factor

H_a Solar radiation absorbed by the collector absorber

H_t Total (beam and diffuse) incident radiation on the tilted collector surface

K_a Asymmetry coefficient

N Number of days in the month

P Average wind flow power

P_a Actual wind flow power

S Service water heating correction factor

Q_u Rate of energy collection by the flat-plate collector

Q_w Average quantity of thermal energy obtained from the wind power-plant (kWh/m^2/day)

T_a Monthly average ambient temperature (°C)

T_i Collector fluid inlet temperature (°C)

T_m Temperature of cold water supply (°C)

T_o Outdoor temperature (°C)

T_w Minimum acceptable hot water temperature (°C)

U_c Collector overall heat-loss coefficient

v Wind velocity (m/s)

X Ratio of the reference total energy loss to the total heating load during the period Δt

Y Ratio of the total absorbed solar energy to the total heating load during the period Δt

α Plate solar absorptivity

Δt Time span (second or hour)

ρ Density of air (kg/m^3)

τ Plate solar transmissivity

θ Collectors tilt angle

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