Feed-In Tariff Scheme for Promoting Wind Energy Generation

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***Abstract*--This paper proposes feed-in tariff scheme as investment incentive to promote wind energy generation under a regulated environment. The tariff design problem is to determine proper price premium that would be added to electricity purchasing rate when electricity generation is from wind energy. The problem was formulated as a mixed-integer nonlinear programming and solved for optimum capacity and price premium of each wind turbine model. The premium schemes are proposed to be fixed or time-varying, depending on generation capacity of a wind turbine. The impacts of implementing the premium schemes on generation capacity of different wind turbines, cost of subsidy, and generation profit are addressed.**

***Index Terms*—feed-in tariff, renewable energy policy, wind energy.**

NOMENCLATURE

a_{it}	premium (price adder) for wind turbine model i in year t (US$/kWh)
b_{it}	generation benefit from wind turbine model i in year t (US$/kWh)
C_{it}	average cost of generation of wind turbine model i in year t (US$/kWh)
C_A	annual cost of wind power generation (US$/y)
C_E	average cost of wind energy generation (US$/kWh)
CF	capacity factor of wind power generation
F_t	subsidy fund for wind power in year t (US$/y)
G_i	generation capacity of wind turbine model i (kW)
G^{max}	maximum generation capacity of wind power (kW)
G^{min}	minimum generation capacity of wind power (kW)
N	number of wind turbine models under consideration
n_i	number of generators of wind turbine model i
R_t	generation capacity target of wind power in year t (kW)
S_t	subsidy period for the wind park installed at the beginning of year t (years)
T	number of study periods (years)
ρ_t	electricity purchasing rate in year t (US$/kWh)

I. INTRODUCTION

Wind power generation has been rapidly prospering in electric supply industry around the world during the last two decade because of the clean and environmental friendly perspective. However, wind power investment is highly capital intensive and wind energy generation relies on the intermittent and unpredictable nature of the wind. The investment is thus difficult on both technical and economic points of view, such as installation site, energy yield and average generation cost. As a result, the investment decision of wind power generation must be made very carefully to mitigate financial risk.

To promote electricity generation from renewable resources, a number of countries (especially Germany, Denmark, and the United States) have attempted to implement various supporting mechanisms and policies to provide incentive or subsidy for renewable energy generation. The success and effectiveness of those mechanisms and policies were presented in [1]-[10]. In Thailand, the utilization of renewable sources for electricity generation has emerged recently. The Royal Thai government enforced a Renewable Portfolio Standard (RPS) policy into the electricity roadmap of the country, known as the Power Development Plan (PDP) program in 2004 [11]. According to the RPS policy, electric utilities must install or purchase contract for renewable generation capacity at least 5 percent of new generation capacity. Unfortunately, it has been found that the renewable capacity was significantly below the target level, especially the penetration of wind and photovoltaic power generation. A simple explanation is that the generation costs of wind and solar energy in Thailand are much higher than that of fossil-fuelled power plants. In case of wind energy generation, most areas in Thailand have moderate to low mean wind speed (4-6 m/s) [12]. The high wind speed areas can rarely be found along the coastlines and on the top of mountains. As a consequence, the investment of wind energy generation could hardly be cost-effective compared with conventional power generation.

As aforementioned, the Ministry of Energy has initiated a feed-in tariff scheme, called price adder, to promote electricity generation from renewable resources [13]. The feed-in tariff offers fixed premiums on regular electricity purchasing rate for small power producers, given that their renewable capacity is up to 10 MW. Initially, the duration of support was 7 years and the fixed premium for wind power was 0.0625 US$/kWh. In 2008, the duration of support was extended to 10 years [14]. The fixed premium was increased to 0.0875 US$/kWh.

The objective of this work is to investigate the feed-in tariff scheme for wind energy generation by means of determining proper premium and duration of support. Furthermore, the

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proper premiums for different generation capacities are also of interest. In section II, the generation cost of wind energy generation in Thailand is assessed. Determination of proper feed-in tariff is discussed and the tariff design problem is then formulated in Section III. In section IV, numerical simulations of various feed-in tariff schemes are illustrated and the results are discussed. Finally, this work is concluded in section V.

II. GENERATION COST OF WIND POWER

In this work, six wind turbine models with different generation capacities were selected for installation in Thailand. They are 100-kW, 250-kW, 500-kW, 750-kW, 1000-kW, and 2000-kW wind turbine models. The mean wind speed is assumed to be between 4-6 m/s resulting in capacity factors of 8-24%. The discount rate is assumed to be 9 percent per annum. The cost of wind energy generation comprises capital cost and operating & maintenance (O&M) costs. The annual O&M costs are assumed to be 2.0 percent of the capital cost.

The annual energy generation of a wind turbine was assumed to be calculated from its generation capacity and capacity factor. So, the average cost of wind energy generation can be computed as follows:

$$C_E = \frac{C_A}{8760 \cdot CF \cdot G} \tag{1}$$

The average cost of wind energy generation in Thailand is shown in Fig. 1. The average costs are between 0.05 and 0.35 US$/kWh. It can be seen that the average cost would be higher when either the generation capacity of wind turbine or the capacity factor is lower. When breakeven in cost is concerned, the premiums (price adders) must be varied with generation capacity and capacity factor (location). As shown in Fig. 2, the fixed premiums at breakeven are up to 0.30 US$/kWh.

III. THE DESIGN PROBLEM OF FEED-IN TARIFF

A. Implication of Feed-In Tariff on Investment Decision

To investigate the implication of feed-in tariff on investment decision of wind power generation in Thailand, a preliminary study assumes 12% capacity factor and compares two different schemes. The fixed premiums for scheme 1 and 2 are 0.0625 and 0.0875 US$/kWh, respectively. The duration of support was varied from 7 to 10 years. The Internal Rates of Return (IRRs) of both schemes are compared in Fig. 3. It can be concluded that the IRR is directly proportional to generation capacity as a result of economies of scale in wind power generation. It is noticed that the IRRs of the 100-kW and 250-kW wind turbines are negative. Obviously, the investment in both capacities is not attractive although the feed-in tariff has been implemented. Given that the discount rate is 9 percent per annum, the investment in either 750-kW or 1000-kW wind turbine is still marginal. Under these two schemes, the investment is financially attractive for only the 2000-kW wind turbine.

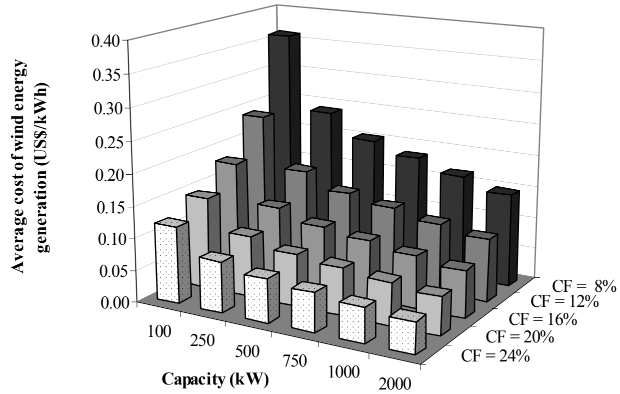

Fig. 1. Average cost of wind energy generation in Thailand.

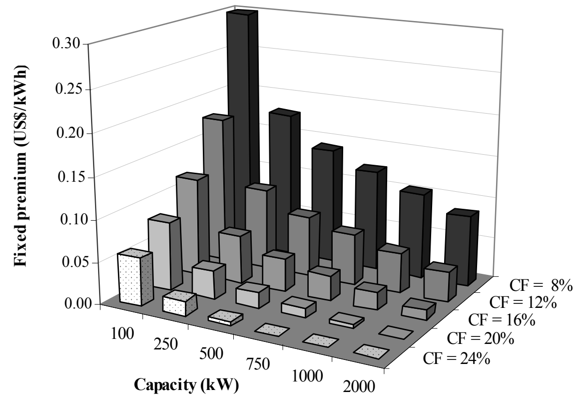

Fig. 2. Fixed premium at breakeven for wind energy generation in Thailand.

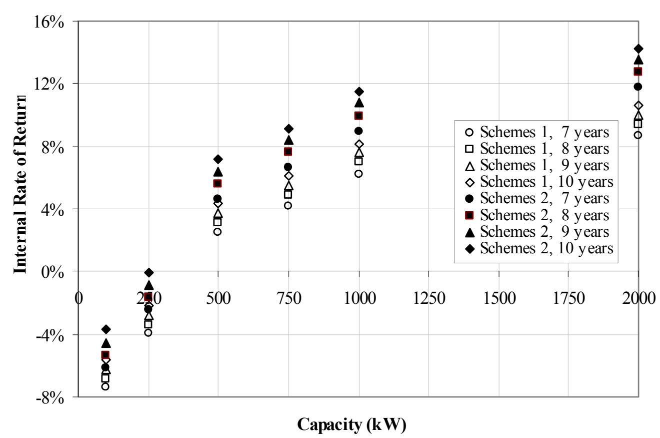

Fig. 3. Comparison of internal rate of returns of wind power generation in Thailand under two feed-in tariff schemes.

On one hand, the fixed premium was varied from 0.0625 to 0.1125 US$/kWh to provide more financial incentive for small wind turbines. The IRRs are compared in Figs. 4 and 5 when the durations of support are 7 and 10 years, respectively. As expected, the IRR would be higher when either the fixed premium is higher or the duration of support is longer. However, the IRRs of both the 100-kW and 250-kW wind turbines are mostly negative in the given range of fixed premiums.

On the other hand, the IRR was varied from 6 to 10 percent per annum and the fixed premiums were then calculated. The fixed premiums are compared in Figs. 6 and 7 when the durations of support are 7 and 10 years, respectively. It is obvious that the higher of the IRR resulting in the higher of the fixed premium. For any given IRR, the fixed premium could be lower when the duration of support is longer. It should be pointed out that the 100-kW wind turbine requires much higher premiums that other wind turbines. This implies that the investment of small wind turbines could hardly be financially attractive, especially in the low wind speed area.

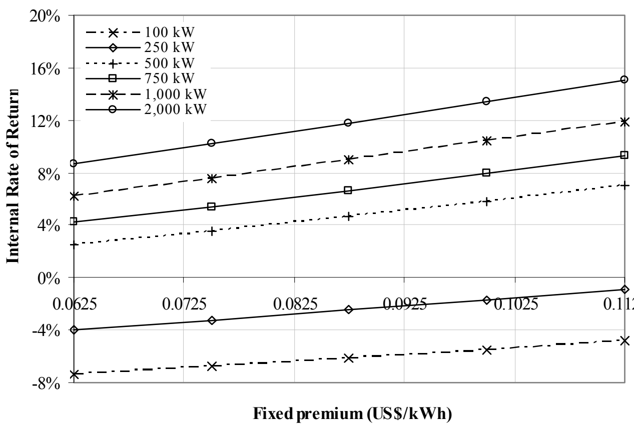

Fig. 4. Comparison of internal rates of return when duration of support is 7 years.

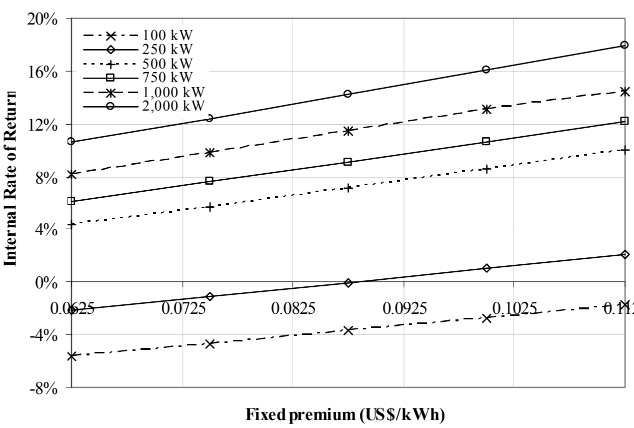

Fig. 5. Comparison of internal rates of return when duration of support is 10 years.

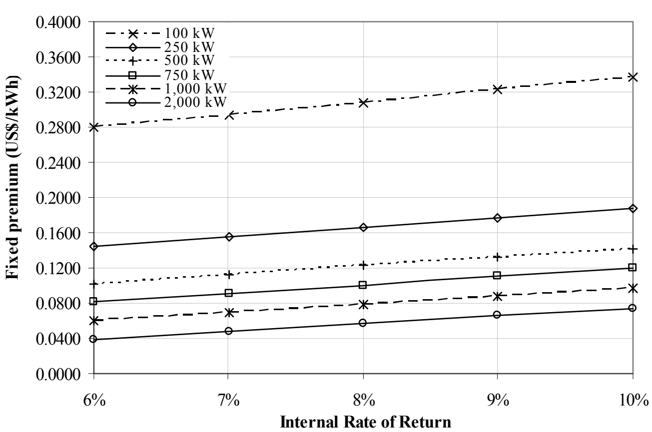

Fig. 6. Comparison of fixed premiums when duration of support is 7 years.

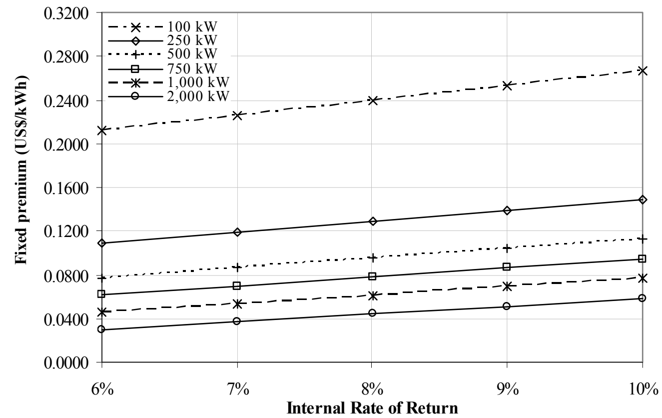

Fig. 7. Comparison of fixed premiums when duration of support is 10 years.

In Fig. 8, the Net Present Value (NPV) of subsidy cost in each wind turbine was calculated; given that the minimum attractive rates of return (MARRs) were varied from 6 to 10%, the fixed premium is 0.0875 US$/kWh, and the duration of support is 10 years. It was found that the NPVs of large wind turbines varied with the MARR, while the NPVs of small wind turbines were relatively constant.

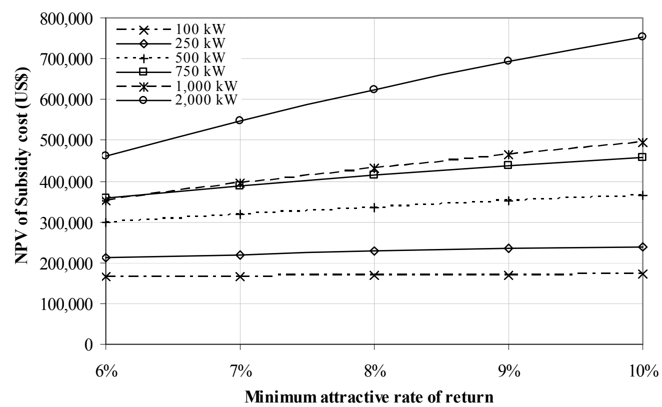

Fig. 8. Net present value of Subsidy cost in wind power generation.

B. Problem Formulation

The feed-in tariff design problem is proposed in this work to provide financial incentive for investment in wind energy generation. The objective function is to maximize the total generation capacities of wind power over time horizon. The constraints being considered are (a) budget limit for annual subsidy, (b) minimum capacity of wind power required each year, (c) minimum and maximum capacities of wind power available each year, and (d) lower and upper limits of the fixed premium. The lower limit of the fixed premium can be determined by computing the difference in the actual cost of generation and the purchasing electricity rate. The upper limit of the fixed premium can be determined by comparing the difference in the actual cost of generation and the electricity purchasing rate with the generation benefit of wind power. In general, the generation benefit can be quantified from avoided fuel cost, capacity credit, emission cost, etc.

The problem was formulated as a mixed-integer nonlinear programming and solved for optimum capacity and premium (price adder) of each wind turbine model. The time horizon was considered on an annual basis. In this work, the problem was solved by using Simple Branch and Bound (SBB®) solver under the General Algebraic Modeling System (GAMS®) environment [15], [16].

$$\text{Max} \sum_{t=1}^{T} \sum_{i=1}^{N} n_{it} G_i \tag{2}$$

$$\text{s.t.} \sum_{i=1}^{N} a_{it} n_{it} G_i (8760 \cdot \text{CF}) = S_t,\ \forall t \tag{3}$$

$$\sum_{\tau=1}^{t-1} S_\tau + \sum_{i=1}^{N} a_{it} n_{it} G_i (8760 \cdot \text{CF}) \le F_t,\ \forall t \tag{4}$$

$$\sum_{i=1}^{N} n_i G_i \ge R_t,\ \forall t \tag{5}$$

$$G^{min} \le \sum_{i=1}^{N} n_{it} G_i \le G^{max},\ \forall t \tag{6}$$

$$\text{Max}\left\{0, C_{it} - r_t\right\} \le a_{it} \le \text{Max}\left\{C_{it} - r_t, b_{it}\right\},\ \forall t\ \forall i \tag{7}$$

IV. Results and Discussion

A. Simulation Data

The typical wind data including potential area [17], [18] and electricity database of the Electricity Generating Authority of Thailand (EGAT) [19], [20] were inquired to formulate the feed-in tariff design problem of wind energy generation in Thailand. During 2010-2019, the maximum target for wind generation capacity was set for 10,000 kW each year or 100 MW over the 10-year period. The capacity factor of wind energy generation was averaged at 12% throughout the country. By using time series forecasting method, the electricity purchasing rate is 0.0786 US$/kWh in 2010 and increased by 0.0031 US$/kWh each year. The discount rate is 9 percent per annum and the economic life of all wind turbines is assumed to be 20 years. The budget limit for subsidizing wind energy generation is 10 million US$ per annum. The duration of support is 10 years. Given wind speed data in Thailand, there are 5 wind turbine models under consideration, i.e. 100, 250, 500, 750, and 1,000 kW. As a result, the average cost of wind energy generation from those wind turbines are 0.2403, 0.1602, 0.1356, 0.1232, and 0.1109 US$/kWh, respectively. The generation benefit of all wind turbines is set for 0.2286 US$/kWh, which is equal to the fixed premium provided for photovoltaic generation.

B. Optimum Time-Varying Premium

The optimization problem of feed-in tariff design was solved by using simulation data described earlier. The study period is 10 years (2010-2019). The results are shown in Tables I and II. In Table I, it can be seen that the optimum premiums are gradually decreasing with time because the electricity purchasing rate is higher and the average cost of wind power generation is lower in the future. By comparing among wind turbines, the premium is lower when the turbine capacity is higher. This is a direct effect of scale economies in wind energy generation. Given that the current premium for wind energy generation in Thailand is fixed at 0.0875 US$/kWh over a ten-year period, it would provide investment incentive for only large wind turbines (≥500 kW). Besides, it would be more beneficial to defer investment until later year. In contrary; if the time-varying premium scheme were implemented, it could provide investment incentive for both large and small wind turbines. The time-varying premium scheme would also encourage early investment as the premium decreases with time. But, it can be argued that the time-varying premium scheme does not provide incentive for both cost reduction and free competition. Thus, the implementation of fixed or time-varying premium is subject to further discussion.

TABLE I
Time-Varying Premiums for Different Wind Turbine Capacities

Year	Premium (US$/kWh)				
	100 kW	250 kW	500 kW	750 kW	1,000 kW
2010	0.1620	0.0820	0.0570	0.0450	0.0320
2011	0.1580	0.0780	0.0540	0.0410	0.0290
2012	0.1550	0.0750	0.0510	0.0380	0.0260
2013	0.1520	0.0720	0.0480	0.0350	0.0230
2014	0.1490	0.0690	0.0450	0.0320	0.0200
2015	0.1460	0.0660	0.0410	0.0290	0.0170
2016	0.1430	0.0630	0.0380	0.0260	0.0130
2017	0.1400	0.0600	0.0350	0.0230	0.0100
2018	0.1370	0.0570	0.0320	0.0200	0.0070
2019	0.1340	0.0540	0.0290	0.0170	0.0040

TABLE II
Optimum Solution of Investment in Wind Power Generation with Time-Varying Premium

Year	Number x Turbine capacity (kW)	Generation Capacity (kW)	NPV of Subsidy cost (M US$)	NPV of Generation cost (M US$)
2010	3x250+5x500 +5x750+3x1,000	10,000	0.4920	1.3180
2011	3x250+5x500 +5x750+3x1,000	10,000	0.8700	2.4180
2012	10x1,000	10,000	1.0280	3.2000
2013	10x1,000	10,000	1.1290	3.8360
2014	10x1,000	10,000	1.1830	4.3450
2015	10x1,000	10,000	1.1990	4.7440
2016	10x1,000	10,000	1.1840	5.0470
2017	10x1,000	10,000	1.1460	5.2680
2018	10x1,000	10,000	1.0910	5.4190
2019	10x1,000	10,000	1.0220	5.5080
	Total	100,000	10.3440	41.1030

In Table II, it is shown that only the 100-kW wind turbines were not feasible for optimum solution. If the budget limit or target capacity of wind power generation were higher, it would be possible for smaller wind turbines to be feasible. It is important to emphasize that that the subsidy cost shown in Table II is a financial burden over the duration of support, not just in the specified year. For instance, the NPV of subsidy cost of wind turbines installed in the first year is approximately US$ 0.4920 million per annum and must be taken into account for 10 years. Thus, the NPV of subsidy costs for wind turbine installation in subsequent years are higher because of the subsidy burden from the earlier years.

C. Optimum Fixed Premium

In case of fixed premium, the premium is not time-varying and constant for all wind turbine capacities. To perform simulations, the constraint in (7) was removed from the problem and the premium value in (3) and (4) was specified. In this work, the fixed premium was in the range of 0.0875-0.1663 US$/kWh.

It is shown in Fig. 9 that when the fixed premium was only 0.0875 US$/kWh, the target capacity of 100 MW for wind power generation can be obtained. Meanwhile, it is implied that the NPV of total subsidy costs are directly proportional to the fixed premium. When the fixed premium was greater than 0.0875 US$/kWh, the target capacity could not be obtained because the budget for subsidizing new generation capacity of wind power is limited at US$ 1 million per annum.

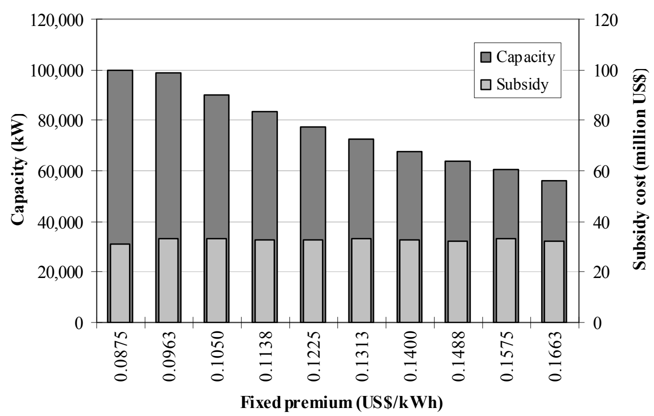

Fig. 9. Generation capacity and subsidy cost under fixed premium scheme.

Then, two simulations were performed by setting the fixed premium to be 0.0875 and 0.1663 US$/kWh. The results are shown in Tables III and IV accordingly. It is observed that, when the fixed premium was 0.0875 US$/kWh, the optimum capacities were exactly the same as those of Table II. But, the NPV of subsidy costs were much higher. In the early years, the optimum capacities are much less than the target capacity because the investment of small wind turbines is more expensive, when compared with large turbines. In addition, investment in small wind turbines requires more subsidy expenses that investment in large turbines. As a result, when the fixed premium was 0.1663 US$/kWh, the generation capacity over the 10-year period was dropped to 56.25 MW, which was far below the target capacity of 100 MW.

D. Comparison of Generation Profits

Finally, the NPV of generation profits from both time-varying and fixed premium schemes are compared in Table V. The NPV of generation profit of the time-varying premium scheme is the smallest, while the NPV of generation profit of the fixed premium of 0.1663 US$/kWh is the largest. When the premium is time-varying, it decreases with time and also varies with generation capacity so that the generation profit is marginal. Obviously, the generation profit could be considered as investment incentive. Although the fixed premium scheme provides more investment incentive but it requires higher subsidy costs, when compared with the time-varying scheme.

TABLE III
OPTIMUM SOLUTIONS OF INVESTMENT IN WIND POWER GENERATION WITH FIXED PREMIUM (0.0875 US$/KWH)

Year	Number x Turbine capacity (kW)	Generation Capacity (kW)	NPV of Subsidy cost (M US$)	NPV of Generation cost (M US$)
2010	3x250+5x500 +5x750+3x1,000	10,000	0.9200	1.3180
2011	3x250+5x500 +5x750+3x1,000	10,000	1.6880	2.4180
2012	10x1,000	10,000	2.3220	3.2000
2013	10x1,000	10,000	2.8410	3.8360
2014	10x1,000	10,000	3.2580	4.3450
2015	10x1,000	10,000	3.5870	4.7440
2016	10x1,000	10,000	3.8390	5.0470
2017	10x1,000	10,000	4.0250	5.2680
2018	10x1,000	10,000	4.1540	5.4190
2019	10x1,000	10,000	4.2350	5.5080
	Total	100,000	30.8700	41.1030

TABLE IV
OPTIMUM SOLUTIONS OF INVESTMENT IN WIND POWER GENERATION WITH FIXED PREMIUM (0.1663 US$/KWH)

Year	Number x Turbine capacity (kW)	Generation Capacity (kW)	NPV of Subsidy cost (M US$)	NPV of Generation cost (M US$)
2010	3x750+2x1,000	4,250	0.7430	0.5250
2011	1x250+3x750 +3x1,000	5,500	1.5630	1.1080
2012	6x1,000	6,000	2.3170	1.6050
2013	6x1,000	6,000	2.9360	2.0130
2014	6x1,000	6,000	3.4370	2.3420
2015	6x1,000	6,000	3.8350	2.6040
2016	6x1,000	6,000	4.1430	2.8050
2017	6x1,000	6,000	4.3750	2.9570
2018	2x750+4x1,000	5,500	4.4960	3.0440
2019	5x1,000	5,000	4.5270	3.0610
	Total	56,250	32.3730	22.0640

TABLE V
GENERATION PROFIT OF WIND POWER INVESTMENT

Year	NPV of generation profit (M US$)		
	Time-Varying premium	Fixed premium	
		0.0875 US$/kWh	0.1663 US$/kWh
2010	0.0000	0.4280	0.5700
2011	0.0330	0.8500	1.2270
2012	0.0820	1.3760	1.8950
2013	0.1500	1.8630	2.4770
2014	0.2300	2.3050	2.9770
2015	0.3200	2.7080	3.4060
2016	0.4110	3.0650	3.7650
2017	0.5050	3.3850	4.0650
2018	0.5820	3.6460	4.2480
2019	0.6730	3.8860	4.3690
Total	2.9860	23.5130	28.9990

V. CONCLUSION

The implementation of feed-in tariff and its implication on the promotion of wind energy generation are investigated in this paper. The tariff could provide investment incentive for wind energy generation by means of giving premium (price adder) to electricity purchasing rate over a certain period of time. The premium scheme could be either time-varying or fixed. The time-varying premium scheme could provide investment incentive for large wind turbines and takes generation cost of a wind turbine into account. The fixed premium scheme provides investment incentive for small (large) wind turbines when the premium value is high (low). The fixed premium is constant over time and independent of generation capacity of a wind turbine. In both schemes, it was found that the proposed premiums could effectively promote wind energy generation.

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VII. Biographies

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