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태양전지-연료전지 복합 전력시스템에 대한 환경평가에 관한 연구

(Environmental Evaluation for a Photovoltaic-Fuel Cell Hybrid Power System)

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요 약

본 논문은 태양전지-연료전지 복합 전력시스템에 대한 환경평가를 다목적함수의 해 선정 보조시스템의 하나인 이상점 기법을 통하여 다루고자 한다. 그에 대한 평가는 발전소 건설에 필요한 부지량과 건설에서 해체때까지의 이산화탄소 배출량의 관점에서 이루어지며 그 결과는 기존의 화석연료 발전시스템들과 비교되어진다. 연료전지 발전은 이미 변덕스러운 날씨하에서 극심한 태양전지의 출력량 변화를 보상하기 위한 적절한 발전기술임이 증명되었다. 가장 적은 부지량을 필요로 하는 연료전지 발전은 태양전지 발전시스템의 과도한 부지 필요량을 경감시킬 수 있으며 그 태양전지-연료전지 복합 전력시스템은 건설에서 해체때까지의 이산화탄소 배출량 면에서도 가장 적은 영향을 미치는 것으로 나타난다.

Abstract

This paper presents an overview of environmental evaluation for a photovoltaic-fuel cell hybrid power plant through the Ideal Point approach, which is one of multiobjective decision support systems. Its evaluation is carried out in terms of such two criteria as land requirement for plant construction and lifetime CO_2 emissions, and then compared with conventional fossil fuel power plants. Fuel cell power system has been proven a viable technology to back up severe PV power fluctuations under inclement weather conditions. Fuel cell power generation, containing small land use, is able to alleviate the heavy burden for large surface requirement of PV power plants. In addition, the PV-fuel cell hybrid power system shows a very little potential for lifetime CO_2 emissions.

1. Introduction

Renewable energy sources (solar, wind, tidal, and geothermal, etc.) are drawing more attraction as the worlds environmental concern about acid deposition and global warming increases. Among the renewable energy sources, solar photovoltaic (PV) energy has been widely utilized in small-size applications.

PV power generation, which directly converts solar radiation into electricity, contains many significant features such as inexhaustible, pollution-free, quiet, with no rotating parts and

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size-independent electricity conversion efficiency. Positive environmental effect of photovoltaics results in replacing electricity generated in more polluting way, or providing electricity where none was available before. Various anti-pollution apparatus can be operated by solar PV power; for example, water purification by electrochemical processing or stopping desert expansion supported with tree implantation [1].

A PV array experiences large power variations under intermittent weather conditions. It generates no (or very little) power during successive rainy or cloudy days. Those phenomena may cause operational problems in the system network, such as excessive frequency or voltage deviations and increased spinning reserve.

One method to overcome the above problem is to integrate a PV power plant with other power sources; for example, diesel backup [2], fuel cell backup [3, 4], battery backup [5 ,6, 7], and superconductive magnetic energy storage (SMES) backup [8]. The author has made a detailed comparison among those backup sources and concluded that the fuel cell power has most beneficial effects when operates with utility-connected PV power [9]. Due to the fast ramping capability of fuel cells, the PV-fuel cell hybrid system is able to solve the PVs inherent problem of fluctuating power generation. Thus, fuel cell power is a viable technology to support a weather-dependent PV power source.

On the other hand, solar photovoltaic and fuel cell power generations are not free from environmental impacts. The main disadvantage of PV power plants is that they require an extensive land for large-scale centralized power plant construction. Their indirect impacts on environment during production and disposal of the PV systems cannot be ignored since these materials contain some toxic elements. Fuel cell systems produce very little amounts of SO_2, NO_x and other particulates in the fuel reforming process since the fuel cell stack operates electrochemically at lower temperature than other thermomechanical power plants. Their high energy conversion efficiency may result in lower CO_2 emissions, which will help reduce the rate of global warming.

Land requirement for the power plant and its lifetime CO_2 emissions are considered as two major criteria for calculating environmental impacts of the PV-fuel cell hybrid system. An acquisition of land area would nearly soon be a crucial factor for power station construction in densely populated regions, particularly such as eastern U.S.A, Europe and East Asia. The worlds rising concern about the increasing CO_2 concentration in the atmosphere and its potential impact on global warming gives a suggestion that CO_2 emission rates be considered in selecting electricity generating technologies. The CO_2 emissions of the hybrid system are caused by fuel consumption during its life-long period and its construction, operation and maintenance.

2. Land Requirement

The land area required for each electric power plant varies over a significant range, depending upon factors such as individual utility design specifications, land costs, and the installed capacity. Photovoltaic modules that provide power for remote systems are useful with small land disturbance, but, when used for a grid-connected central power station, land requirement is a major consideration. A PV power plant requires the most extensive land due to the low energy density of solar radiation and low efficiencies of solar cells. It ranges from 20,000 to 30,000 m^2/MW [10].

The amount of land required for the installation of a fuel cell power plant may be relatively small like 500 - 1,000 m^2/MW owing to the capability of its modular construction [12]. This feature, together with very low environmental impact, may allow fuel cell power plants to be located close to the point of use, where its waste heat can be used in cogeneration applications. This site flexibility of the fuel cell power plants may not only permit a reduction in transmission and distribution loss but also provide for power control close to the load center. Therefore, it is able to make a utility defer transmission and distribution investments.

Table 1 summarizes the standard figures of land use for electricity generating power plants, including conventional fossil-fuel power sources [13]. The land requirement for PV power stations is 6-25 times higher compared to the other forms of power generation. Fuel cell power plants need the least land area for plant construction. When these two power plants are integrated, land requirement for the hybrid plant would decrease so that the PV power could get an applicable position to be located near highly populated area.

3. CO_2 Emissions

This section calculates the lifetime CO_2 emissions for polycrystalline silicon PV plants, phosphoric acid fuel cell plants, and three conventional fossil fuel (coal, oil and natural gas) power plants. Their 30-year lifetime CO_2 emissions are summarized in Table 2 [10, 15, 16, 17]. The total CO_2 amount generated during a power plants lifetime is calculated by adding the CO_2 produced during its construction to the CO_2 produced from burning fuels and from its operation and maintenance (O & M). Once the lifetime energy input for construction, operation and maintenance of a system is known, the CO_2 production can be calculated. More than 95% of CO_2 produced from fossil fuel-burning power plants is generated during their operation as a consequence of fuel combustion.

Table 1. Land requirement for electric power plants.

Power sources	Land use [m^2/MW]
Photovoltaics	20,000
Fuel cells	700
Coal	1,200*
Oil	900
Natural gas	800

* Includes land needed for solid waste disposal.

Table 2. CO_2 emissions for electric power plants with a 30-year lifetime.

Power sources	CO_2 from plant construction* [kg/MWh]	CO_2 from O & M [kg/MWh]	CO_2 from burning fuel [kg/MWh]	Total CO_2 emissions [kg/MWh]
PVs	81.8	9	·	90.8
Fuel cells	0.9	8	461.4	470.3
Coal	3.5	28	987.4	1018.9
Oil	6.4	16	738.5	760.9
Nat.gas	2.7	10	551.4	564.1

* For calculation, capacity factors for coal, oil, natural gas and fuel cell power plants are 65%, 25%, 25%, and 25%, respectively.

For a PV power plant, nearly 90% of CO_2 emissions result from the CO_2 generated during the plants construction stage. The CO_2 generated during its construction is calculated by multiplying the primary energy consumed by the CO_2 emission factor of the primary energy. The detailed calculations are illustrated in Appendix A.

Almost all of CO_2 production from a fuel cell power plant occurs during the fuel reforming process that reforms natural gas into hydrogen-rich gas. The CO_2 amount emitted from the fuel cell plant is calculated using heating value of natural gas and the plants electricity conversion efficiency. The whole calculations are shown in Appendix B.

From the Table 2, photovoltaic power plants produce 6-11 times less lifetime CO_2 gas than other power generating sources and the CO_2 emissions from fuel cell power plants also very little. So, the hybrid power plant has an excellent potential to reduce lifetime CO_2 emissions.

4. Evaluation of the PV-Fuel Cell Hybrid Power Plant

Environmental impacts of the PV-fuel cell (FC) hybrid power plant are going to be evaluated through the Ideal Point approach [11]. Six alternatives are considered, which are the above five power sources plus the PV-fuel cell hybrid system. Land requirement and life cycle CO_2 emissions are two criteria. Then the effect of alternative i according to criterion j is defined as x_{ji}. The effects table (X) can be organized using the Table 1 and 2.

Since the effect values for the criteria are calculated on different scales, they must be standardized to a common dimensionless unit, which is denoted as follow:

$$\hat{x}_{ji} = \frac{x_{ji}}{\max_i x_{ji}} \quad (1)$$

where $\hat{x}_{ji}$ is the normalized effect of alternative i with respect to criterion j.

Normalized effects table ($\hat{X}$) is illustrated in Table 3. Then the distance from each alternative to a hypothetically ideal point is calculated in the following equation. The ideal point is assumed the origin, which means that it produces zero CO_2 emissions and needs zero land area.

$$d_i = \left[\sum_{j=1}^{J} (w_j |\hat{x}_{ji} - 0|)^p \right]^{1/p} \quad (2)$$

where w_j is a weighted factor for criterion j, and p is a metric coefficient (p=2, in this study).

The smaller distance value, the more benign environmental impact each alternative represents. Table 4 shows the distances for the six alternatives with respect to different weighting factors. When the weighting factors, for example, are same, fuel cell power plants have the least value. The order of the rest alternatives for environmental deterioration is shown below.

FC < Gas < PV+FC < Oil < Coal < PV

According to Table 4, the evaluation ranking is significantly changed for different criterion priorities considered. Therefore, it should be noted that determining the weighting value for each criterion is a very crucial factor in the evaluation stage.

5. Conclusion

This paper discusses environmental impacts of a PV-fuel cell hybrid power plant through the Ideal Point approach. Its evaluation is performed in terms of land requirement for plant construction and lifetime CO_2 emissions, and compared with conventional fossil fuel power generating forms.

Table 3. Normalized effects table.

	$\hat{x}_{ji}$ (i →)	Coal	Oil	Gas	PV	FC	PV+FC
j	Land	0.06	0.045	0.04	1	0.035	0.517
	CO_2	1	0.747	0.553	0.089	0.461	0.275

Table 4. Distances of the alternatives with respect to different weighting factors.

d_i (i →)	Coal	Oil	Gas	PV	FC	PV+FC
w_1 =0.5, w_2 =0.5	0.501	0.374	0.277	0.502	0.231	0.293
w_1=0.2, w_2=0.8	0.8	0.598	0.442	0.212	0.369	0.243
w_1=0.8, w_2=0.2	0.206	0.154	0.115	0.8	0.096	0.417

Fuel cell power generation, having the least land use, is able to alleviate the heavy burden for large surface requirement of the PV power plants. It also has a fast-ramping capability to smoothen the fluctuating PV power outputs under varying weather conditions. Moreover, the hybrid power plant has a very little potential for lifetime CO_2 emissions because the photovoltaics and fuel cells are the power sources that produce the least lifetime CO_2 emissions.

Significant reduction of CO_2 emissions from energy generation could be achieved by improving the plants efficiency or shifting fossil fuel to renewable energy sources. The PV system produces considerably less CO_2 over a 30-year lifetime than the fossil-fuel power plants. When natural gas power systems are substituted for coal power plants as a method of CO_2 reduction, it could reduce the CO_2 production by 45%. However, this reduction could not achieve a long-time solution to global warming. Substituting PV technologies for coal-fired power plants could reduce CO_2 production over time.

Appendix-A. CO_2 Emissions from PV Power Plants

This section calculates estimates of the CO_2 emissions from both PV module fabrication and construction of the PV power plant, based on consumed energy analysis.

Accumulated energy requirements for construction of PV power plants are shown in Table A.1 [10]. The energy consumed for the photovoltaic modules and that for the remaining components such as supporting structures, cabling, power conditioning system, etc. constitute the accumulated energy for a PV power plant. The percentages by which electrical energy and raw fuel take charge out of the total energy consumption are 68.2% and 28.8%, respectively.

CO_2 emissions, involved in the construction process of the PV power plant by the consumption of electricity and fuels, can be estimated using the specific emission factors within an energy supply network. For the United States, 0.5984 kg/kWh for electrical energy and 0.48 kg/kWh for fossil fuels are calculated for their CO_2 emission factors. These calculations are based on the data that the percentage of electricity generated by coal is 54.6%, by oil 3.9%, and by natural gas 11.9%. The emission factors for coal, oil and natural gas power plants are 952.42 kg/MWh, 710.46 kg/MWh, and 466.36 kg/MWh, respectively. Table A.2 shows the amount of CO_2 emitted during the construction of the PV power plant and equivalent CO_2 emissions during the systems working life cycle.

Table A.1. Accumulated energy requirements for PV power plants [10].

Cell structure	η [%]	PV Modules [kWh/kW$_p$]	Remaining componens [kWh/kW$_p$]	Power station total [kWh/kW$_p$]
Single-crystalline	15.5	11,000	1,200	12,200
Poly-crystalline	13.5	7,500	1,500	9,000
Amorphous	8.0	5,500	2,000	7,500

- Size of power station = 1,500 kW$_p$
- Annual production capacity = 25 MW$_p$/yr

Table A.2. CO_2 emissions of PV power plants.

Cell structure	CO_2 emissions [kg CO_2/kW$_p$]	Equivalent CO_2 emissions [kgCO_2/MWh]
Single-crystalline	6,654.5	110.9
Poly-crystalline	4,909.1	81.8
Amorphous	4,090.9	68.2

- Working life cycle = 30 yrs
- Annual load durartion = 2,000 hrs

Appendix-B. CO_2 Emissions from Fuel Cell Power Plants

This section calculates CO_2 emissions during operation of phosphoric acid fuel cell power plants, which use natural gas as a fuel. Because the actual fuel of fuel cell stacks is hydrogen (H_2) gas rather than methane (CH_4), fuel reforming process is required to process CH_4 into H_2.

The fuel reforming system comprises three processes such as desulfurization, steam reforming, and CO shift. The reaction formula for those processes are written as

Steam reforming: $CH_4 + H_2O \rightarrow CO + 3H_2$ (B.1)

CO shift: $CO + H_2O \rightarrow CO_2 + H_2$ (B.2)

Overall: $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$ (B.3)

Therefore, about 80% H_2 and 20% CO_2 are supplied to the fuel cell stacks, assuming the fuel is reformed completely.

When the natural gas contains 100% CH_4 with a heating value of 23,861 Btu/lb, the CO_2 emission rate for fuel cell power plants is calculated as [16]

$$\frac{2.75lb \times 0.95}{23861Btu \times 0.45} = \frac{1.18346kg}{3.1439 \times 10^{-3} MWh} = 376.43kgCO_2 / MWh$$

assuming that the efficiencies of the reforming process and fuel cell power plant are 95% and 45%, respectively.

References

[1] M. Ohnishi and A. Takeoka, Advanced Photovoltaic Technologies and Residential Applications, Renewable Energy, Vol. 6, No. 3, pp. 275-282, 1995.

[2] T.M. Calloway, Autonomous Photovoltaic- Diesel Power System Design, Proc. IEEE PV Specialists Conference, Las Vegas, Nevada, October 1985, pp. 280-284.

[3] S. Rahman and K. Tam, A Feasibility Study of Photovoltaic-Fuel Cell Hybrid Energy System, IEEE Transactions on Energy Conversion, Vol. 3, No. 1, March 1988, pp. 50-55.

[4] K. Tam and S. Rahman, System Performance Improvement Provided by a Power Conditioning Subsystem for Central Station Photovoltaic-Fuel Cell Power Plant, IEEE Transactions on Energy Conversion, Vol. 3, No. 1, March 1988, pp. 64-70.

[5] K.C. Kalaitzakis and G.J. Vachtsevanos, On the Control and Stability of Grid Connected Photovoltaic Sources, IEEE Transactions on Energy Conversion, Vol. 2, No. 4, December 1987, pp. 556-562.

[6] B.H. Chowdhury and S. Rahman, Analysis of Interrelationships Between Photovoltaic Power and Battery Storage for Electric Utility Load Management, IEEE Transactions on Power Systems, Vol. 3, No. 3, August 1988, pp. 900-907.

[7] A. Chaurey and S. Deambi, Battery Storage for PV Power Systems: An Overview, Renewable Energy, Vol. 2, No. 3, pp. 227-235, 1992.

[8] K. Tam, P. Kumar and M. Foreman, Enhancing the Utilization of Photovoltaic Power Generation by Superconductive Magnetic Energy Storage, IEEE Transactions on Energy Conversion, Vol. 4, No. 3, September 1989, pp. 314-321.

[9] K. Ro and S. Rahman, Battery or Fuel Cell Support for an Autonomous Photovoltaic Power System, Renewable Energy, Vol. 13, No. 2, pp. 203-213, 1998.

[10] H. Schaefer and G. Hagedorn, Hidden Energy and Correlated Environmental Characteristics of PV Power Generation, Renewable Energy, Vol. 2, No. 2, pp. 159-166, 1992.

[11] R. Janssen, Multiobjective Decision Support For Environment Management, Kluwer Academic Publishers, 1991.

[12] L.J. Blomen and M.N. Mugerwa, Fuel Cell Systems, Plenum Press, New York, 1993.

[13] OECD, Environmental Effects of Electricity Generation, OECD Publications Office, 1985.

[14] A.J. Appleby, Fuel Cells: Trends in Research and Applications, Hemisphere Publishing Corporation, 1987.

[15] F. Kreith et al., A Comparison of CO2 Emissions From Fossil and Solar Power Plants in the United States, Energy, Vol. 15, No. 12, pp. 1181-1198, 1990.

[16] G. Marland, Carbon Dioxide Emission Rates for Conventional and Synthetic Fuels, Energy, Vol. 8, No. 12, pp. 981-992, 1983.

[17] H. Waku and I. Tamura, Life Cycle Analysis of Fossil Power Plant with CO2 Recovery and Sequestering System, Energy Convers. Mgmt, Vol. 36, No. 6-9, pp. 877-880, 1995.

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