

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 CO₂ 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 CO₂ 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. CO₂ Emissions

This section calculates the lifetime CO₂ 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 CO₂ emissions are summarized in Table 2 [10, 15, 16, 17]. The total CO₂ amount generated during a power plants lifetime is

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. CO₂ 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.

calculated by adding the CO₂ produced during its construction to the CO₂ 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 CO₂ production can be calculated. More than 95% of CO₂ produced from fossil fuel-burning power plants is generated during their operation as a consequence of fuel combustion.

For a PV power plant, nearly 90% of CO₂ emissions result from the CO₂ generated during the plants construction stage. The CO₂ generated during its construction is calculated by multiplying the primary energy consumed by the CO₂ emission factor of the primary energy. The detailed calculations are illustrated in Appendix A.

Almost all of CO₂ production from a fuel cell power plant occurs during the fuel reforming process that reforms natural gas into hydrogen-rich gas. The CO₂ 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 CO₂ gas than other power generating sources and the CO₂ emissions from fuel cell power plants also very little. So, the

hybrid power plant has an excellent potential to reduce lifetime CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions, and compared with conventional fossil fuel power generating forms.

Table 3. Normalized effects table.

		<i>i</i>					
		Coal	Oil	Gas	PV	FC	PV+FC
<i>j</i>	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.

		<i>i</i>					
<i>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 CO₂ emissions because the photovoltaics and fuel cells are the power sources that produce the least lifetime CO₂ emissions.

Significant reduction of CO₂ 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 CO₂ 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 CO₂ reduction, it could reduce the CO₂ 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 CO₂ production over time.

Appendix-A. CO₂ Emissions from PV Power Plants

This section calculates estimates of the CO₂ 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.

CO₂ 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

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

electrical energy and 0.48 kg/kWh for fossil fuels are calculated for their CO₂ 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 CO₂ emitted during the construction of the PV power plant and equivalent CO₂ emissions during the systems working life cycle.

Appendix-B. CO₂ Emissions from Fuel Cell Power Plants

This section calculates CO₂ 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 (H₂) gas rather

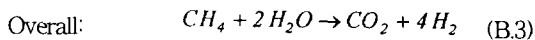
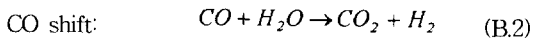
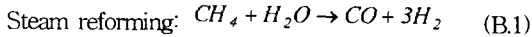
Table A.2. CO₂ emissions of PV power plants.

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

than methane (CH₄), fuel reforming process is required to process CH₄ into H₂.

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



Therefore, about 80% H₂ and 20% CO₂ are supplied to the fuel cell stacks, assuming the fuel is reformed completely.

When the natural gas contains 100% CH₄ with a heating value of 23,861 Btu/lb, the CO₂ emission rate for fuel cell power plants is calculated as [16]

$$\frac{2.75\text{lb} \times 0.95}{23861\text{Btu} \times 0.45} = \frac{1.18346\text{kg}}{3.1439 \times 10^3 \text{MWh}} = 376.43\text{kgCO}_2 / \text{MWh}$$

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

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