Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews 13 (2009) 736–749
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Economic analysis of power generation from floating solar chimney power plant

Xinping Zhou [a,*], Jiakuan Yang [b], Fen Wang [c], Bo Xiao [b]

[a] School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan, Hubei 430074, PR China
[b] School of Environmental Science and Engineering, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan, Hubei 430074, PR China
[c] Wuhan Gatway Science and Technology Co., Ltd., Wuhan, Hubei 430074, PR China

Received 22 January 2008; accepted 8 February 2008

Abstract

Solar chimney thermal power technology that has a long life span is a promising large-scale solar power generating technology. This paper performs economic analysis of power generation from floating solar chimney power plant (FSCPP) by analyzing cash flows during the whole service period of a 100 MW plant. Cash flows are influenced by many factors including investment, operation and maintenance cost, life span, payback period, inflation rate, minimum attractive rate of return, non-returnable subsidy rate, interest rate of loans, sale price of electricity, income tax rate and whether additional revenue generated by carbon credits is included or not. Financial incentives and additional revenue generated by carbon credits can accelerate the development of the FSCPP. Sensitivity analysis to examine the effects of the factors on cash flows of a 100 MW FSCPP is performed in detail. The results show that the minimum price for obtaining minimum attractive rate of return (MARR) of 8% reaches 0.83 yuan $(\mathrm{kWh})^{-1}$ under financial incentives including loans at a low interest rate of 2% and free income tax. Comparisons of economics of the FSCPP and reinforced concrete solar chimney power plant or solar photovoltaic plant are also performed by analyzing their cash flows. It is concluded that FSCPP is in reality more economical than reinforced concrete solar chimney power plant (RCSCPP) or solar photovoltaic plant (SPVP) with the same power capacity.

Keywords: Renewable energy; Floating solar chimney; Thermal power plant; Economic analysis

Contents

* Corresponding author. Tel.: +86 27 62250811; fax: +86 27 87542231.
E-mail address: zhxpmark@hotmail.com (X. Zhou).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2008.02.011

1. Introduction

In recent years, utilization of fossil fuels together with net deforestation [1] has led to global greenhouse effect and subsequently produces many potential negative effects [2]. Until now, fossil fuels have also been the main energy source, which are being exhausted at a fast rate and will be difficult to satisfy the energy needs in future. It is urgent to develop the technologies utilizing renewable and clean energy source to solve the above problems.

Solar energy [3] is an abundant renewable and clean energy source free of greenhouse gases (GHG) emissions. Solar chimney power technology is a promising large-scale power generating technology [4–7]. The technology was first described in a publication by Günter in 1931 and tested with the 50 kW Manzanares prototype plant in the early 1980s [8,9]. The solar chimney power generating technology combines three familiar components: a solar collector, a chimney situated in the center of the collector, and wind turbine generators. It works on the principle that the turbines are driven by airflow produced by buoyancy derived from hot air heated by the collector. However, the conversion efficiency of a solar chimney thermal power plant is low as determined by the thermal performance of the system. The conversion efficiency of a solar chimney thermal power plant increases with the height of the chimney. For commercial power plants producing energy economically, not only is a large collector area necessary for collecting solar energy, but also a high gigantic chimney is required to house a big turbine and to obtain a large driving force. Furthermore, a higher conversion efficiency for large-scale solar chimney thermal power systems will also lead to a reduction in the energy cost. The most suitable construction sites of solar chimney power plants are therefore located in vast desert regions where the land may be free [10]. Recently, the Australia government decided to support the construction of a prototype solar chimney electric power generating plant with a 1 km chimney in Mildura, Australia. The proposed solar power plant can produce 200 MW of electricity [11].

With the diminishing of fossil fuel and aggravation of greenhouse effect, many countries addressed strategies and provided economic incentives for the development of solar power systems such as solar photovoltaic system (SPVS). The incentives and strategies include granting a non-returnable subsidy, a payment per kWh of electricity produced and sold, enhanced feed-in tariffs, soft loans and favourable income tax waivers [12–17]. The Netherlands government and the California State government, respectively, offer a subsidy at 3.5 Euros Wp^{-1} and 3.80 US\$ ACW^{-1} installed [12]. Recently, the Institute for Diversification and Saving of Energy (IDAE) and local government of Spain offered non-returnable subsidies, which can be as much as 40% of the installation cost [13]. In 2004, an average value at 27% of the cost of the installations of less than 100 kW power capacity was subsidized by IDAE, and 11% for installations of more than 100 kW [14]. Interest rate on loans to SPVS has been lowered to 2% in some countries such as the USA, Germany and Spain, for example. The electricity price sold to the utility in the USA and Australia reached 0.457 and 0.6 Euro (-kWh)$^{-1}$, respectively, figures several times more than the local market price [12]. The electricity price sold to the utility in Spain is given as 5.75 times more than the market price in the first 25 years of the installation, and 4.6 times in further years [14]. In the cost estimate of solar power systems [12–23], e.g. SPVS, solar chimney power system, income tax is considered to be free (Fig. 1).

Not long ago, solar electric power generating costs of the plants were estimated by some investigators. Schlaich et al. [18,19] estimated the costs of plants with different power capacities whose collector roofs were made of plastic. Bernardes [20] estimated the cost of a 100 MW plant with plastic collector roof. Fluri et al. [21] carried out a detailed estimate of the cost of 100 MW plants, proposed by Schlaich et al. [18] and Bernardes [20]. In the analysis plastic roofs of the collector were replaced with glass cover. The ecomonic analysis for the first time includes additional revenue generated by carbon credits. Papageorgiou [22] estimated the cost of the components of a 100 MW FSCPP excluding the additional revenue generated by carbon credits whereas Zhou and Yang [23] estimated the electricity cost of potential FSCPPs supported by high mountains in the deserts in

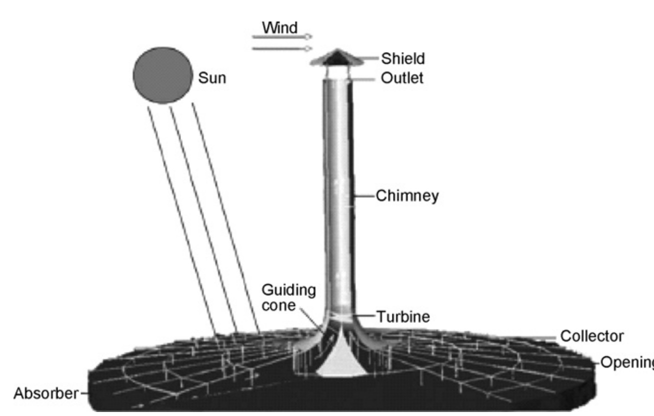

Fig. 1. Schematic diagram of solar chimney power system.

Northwest China and also excluded the additional revenue generated by carbon credits in their analysis.

In this paper, an economic analysis of power generation from FSCPP, whose service period is far more than the life span of FSC, is performed in detail by looking at cash flows during the service period of FSCPP. The analysis includes additional revenue generated by carbon credits. Comparisons of economics of the FSCPP and reinforced concrete solar chimney power plant (RCSCPP) or solar photovoltaic plant (SPVP) are also performed by analyzing their cash flows. The following conversion rates for yuan, Euro and US$ are used in this paper: Euro 1 = US$ 1.2 and US$ 1 = 8 yuan.

2. Floating solar chimney power plant (FSCPP)

The conventional solar chimney electric power generating plant is constructed by reinforced concrete. Although it has a long life span, the reinforced concrete solar chimney, whose height is needed to be high as possible in order to improve the efficiency of solar chimney power plant [4,24], has some disadvantages. The disadvantages include high construction cost and limited height because of the technological constraints and restrictions on the construction materials. There are also external limitations such as possible earthquakes which can easily destroy very high chimneys. Based on these facts, Papageorgiou [25] proposed a floating solar chimney (FSC) concept to be used for solar chimney power plant.

FSC is consists of three parts as shown in Fig. 2: main chimney, heavy base and the folding lower part. The main chimney whose wall is full of gases is composed of cylindrical balloon rings tied up to each other with the help of supporting rings. The main chimney is fastened to the seat of the heavy base and the folding lower part is fastened to the lower part of the base, which can withstand the exterior winds by letting the air enter and come out freely from its rings so that FSC can receive any suitable declination resulting from the winds.

The idea of using floating solar chimney technology is to avoid two major problems which appear in the design of usual concrete solar chimney. The problems arise due to their heavy weight and the wind. Backström observes that the floating solar chimney could behave as slender and fairly limp kelp (seaweed) whose stem stay upright even in the presence of tides and currents [26] as opposite to the huge massive concrete solar chimney which may buckle under its own weight.

Compared to the reinforced concrete solar chimney located in a steady geology region, the construction cost of FSC is less although its life span is shorter.

The novel FSC can in principle extend several thousands of meters [7,13,14,23,26]. This would substantially improve the energy conversion efficiency of the power system and eliminate the difficulty and the danger of constructing gigantic vertical reinforced concrete chimneys.

3. Investment

Total investment of FSCPP includes the investments on the collector, FSC and a power conversion unit (PCU).

3.1. Cost of collector

Generally, there are two kinds of collector cover materials: glass and plastic film. We consider a glass cover because a plastic film would easily age and readily be destroyed in deserts where the weather is usually bad. The collector simply consists of glass, column system and support matrix. The cost of the collector includes the costs of materials, transportation costs as well as construction costs. In this work, construction cost and transportation costs are assumed to be 15% of the costs of materials and 180 yuan tonne^{-1}, respectively. An average transportation distance of 300 km is assumed. The prices of steel and 4 mm thick float glass used are 4000 yuan tonne^{-1} and 18.23 yuan m^{-2}, respectively. Land covered by large solar collector in the desert regions in Northwest China [23,27] is therefore considered to be free.

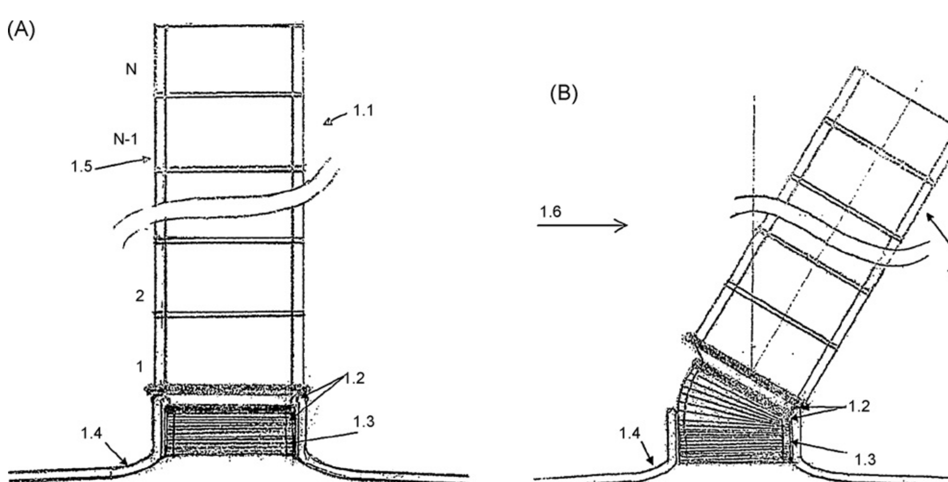

Fig. 2. Schematic diagram of floating solar chimney [19]. (1.1) Main chimney; (1.2) heavy base; (1.3) folding lower part; (1.4) seat; (1.5) $(N-1)$ the part of the main chimney; (1.6) wind. (A) Under the conditions of no wind and (B) under the conditions of wind.

3.2. Cost of FSC

The shape of wall, buoyant gas, and materials of supporting rings for FSC are selective. There can be three shapes A, B or C for wall construction with a combination of helium or NH_3 for non-flammable buoyant gas, and reinforced glass, aluminum or composite material for supporting rings. Papageorgiou [22] estimated specific costs of FSC with different combinations of materials and shapes of wall construction by including the costs of materials, transportation costs and construction costs. We have chosen to use helium which is a non-flammable and environment-friendly buoyant gas. There are four economical combinations for large FSCPP which arise by integrating shape B or C for wall construction with reinforced glass or aluminum for supporting rings. The specific costs are presented in Table 1 [22]. The mean of the four figures calculated as 945.75 US\$ kW^{-1} is used as the specific cost of FSCPP in estimating the cost of FSC. In China, helium is a commercial product obtained from the international market. High-performance fibers, which are needed to prevent UV radiation damage and the effect of cold atmosphere are usually imported from abroad or produced in China but with the use of foreign technology. In this paper, the cost of FSC is based on Papageorgiou's [22] estimate performed according to international price of materials.

3.3. Cost of PCU

PCU includes turbines, generators, electronic control equipment and grid feed-in apparatus. The turbines and generators are expensive items in China with their prices several times more than the international market prices. These items are, however, now being produced locally in China and their prices will gradually compare favourably with the international prices when the market is fully developed. The cost of PCU is therefore calculated according to the specific cost of the PCU at 488.4 US\$ kW^{-1} estimated by Fluri et al. based on wind turbine costs in the year 2002 [21].

4. Expense and revenue analysis

The economic analysis carried out in this work is based on comparison of expense which is cash outflow and revenue which is cash inflow. Generally, the life span of collector and PCU, N, which is also the whole service period of FSCPP, is far longer than that of FSC, N_{FSC}. The whole service period of FSCPP is divided into n_p phases with $n_p = N/N_{FSC}$. FSC will be renewed at the end of a phase. The number of years since the first year of operation is denoted by n.

Table 1
Specific cost of FSCs with different combinations of materials and shapes of wall construction [22] (US\$ kW^{-1})

	Helium, reinforced glass supporting rings	Helium, aluminum supporting rings
Shape B	880	978
Shape C	915	1010

Investment in the first phase P_{inve}, which is equal to the sum of present value (PV) of loans, P_{loan}, and PV of a non-returnable subsidy, $P_{subsidy}$, is expressed as

$$P_{inve} = P_{loan} + P_{subsidy} \tag{1}$$

4.1. Revenue analysis

Cash inflow, i.e. revenue received for FSCPP include revenue of selling electricity to the utility and additional revenue generated by carbon credits because of lessening GHG emissions.

The PV of the cash inflow from the system by selling electricity to the utility is related to financial incentives of government. Generally, most of the electricity E_l is sold to the utility at a given price p_{solar} above the market level p_m, while the remaining electricity E_s is consumed in situ [12]. PV of the annual cash inflow from the system by selling electricity to the utility can therefore be given by

$$C_{cash1,n} = p_{solar}E_l(1+\varepsilon_{solar})^{(n-1)} + p_m E_s (1+\varepsilon_m)^{(n-1)} \tag{2}$$

where ε_{solar} and ε_m are the annual increasing rate of p_{solar} and p_m, respectively. When p_{solar} is m times more than p_m, Eq. (2) becomes

$$C_{cash1,n} = (mE_l + E_s)\, p_m (1+\varepsilon_m)^{(n-1)} \tag{3}$$

When all the electricity E is sold to the utility, Eq. (3) becomes

$$C_{cash1,n} = p_{solar}E(1+\varepsilon_{solar})^{(n-1)} \tag{4}$$

Unlike conventional coal-fired power plant, nearly no GHG is released in the operation of FSCPP. Carbon dioxide (CO_2) equivalent released from coal-fired power plant is calculated to be 0.95 kg CO_2 emissions kWh^{-1} of electricity from coal as reported in 1999 [28]. According to a carbon credit price of 21.4 Euros $tonne^{-1}$ CO_2 [29] and the conversion rate for yuan to Euro at 10.63:1 [30] as reported on October 3, 2007, cash inflow generated by carbon credits in the first year of operation is estimated by

$$C_{cash2,1} = E \times 0.95 \times 21.4 \times 10.63 \tag{5}$$

Cash inflow generated by carbon credits after the first year of operation for FSCPP will gradually increase with inflation. The revenue generated by carbon credits is not included in the calculation of income tax.

4.2. Expense analysis

Schlaich et al. [18] estimated the operation and maintenance cost of a 100 MW reinforced concrete solar chimney power plant to be 1.9 million Euros in the first year of operation. The cost is used for operation and maintenance of components mainly including the collector and PCU. Papageorgiou [22] assumed the operation and maintenance costs of FSC to be 0.5 million Euros in the cost estimate of a 100 MW FSCPP. In this work, the operation and maintenance cost in the first year of operation NC_{OM1st} is assumed to be (1.9 + 0.5) million Euros. This amount is assumed to cover the cost of maintenance of the whole system and include jobs as clearing dusts from the roof of the collector, mending the roof, maintaining electronic equipments, mending the fiber wall of FSC, replenishing buoyant gases and paying for management staff. The annual operation and maintenance cost after the first year of operation increases year by year, and can be expressed by the following equation:

$$C_{OM,n} = C_{OM,1}(1+\varepsilon_{OM})^{(n-1)} \tag{6}$$

where ε_{OM} is the annual increasing rate of operation and maintenance costs and is assumed to be equal to inflation rate in our model.

Insurance and reinsurance including losses of equipments and lost revenues with premium rate in the first year of operation is usually assumed to be less than 1% of investment [14,16]. In this work, we consider a lower value of 0.8% [16]. The insurance in the first year of operation is therefore

$$C_{insu,1} = 0.008P_{inve} \tag{7}$$

The annual insurance $C_{insu,n}$ after the first year of operation increases year by year with inflation.

Annual cash flows before paying income tax are expressed as

$$BCF_n = C_{cash1,n}(1+f)^n - C_{OM,n} - C_{insu,1} \tag{8}$$

where f is defined as the inflation rate.

When inflation is included in the economic model, the annual equivalent discount rate becomes

$$i_p = i + f + if \tag{9}$$

where i is expected or optional discount rate.

Annual cash flows after paying income tax are

$$ACF_n = BCF_n - C_{pay,n} - (BCF_n - C_{payint,n} - C_{d,n})\eta_{tax} + C_{cash2,n} \tag{10}$$

where η_{tax} is income tax rate and $C_{d,n}$ is annual depreciation expense.

Power capacity is kept constant when the main body of FSC has been used for its life span and replaced with a new main body under the assumed same meteorologic conditions. Usually, the heavy base, supporting rings, some buoyant gases, can further be used for a new FSC. Therefore, residual values after capital depreciation are included in the cost estimate. In this work, the residual values are calculated by using double-declining-balance method of depreciation. Annual depreciation expense can be given by

$$C_{d,n} = C_{inve,n}d \tag{11}$$

where $d = 2/N$ and $2/N_{FSC}$ are double-declining-balance depreciation rate of collector and PCU, and that of FSC, respectively, and $C_{inve,n}$ is the residual value at the end of the nth year. The residual value at the end of the nth can further be expressed as

$$C_{inve,n} = C_{inve,n-1}(1-d) = C_{inve,n-1} - C_{d,n-1} \tag{12}$$

with $C_{inve,N}$ being the residual value of collector and PCU at the end of service period, is negligible because their service period is too long. $C_{inve,N_{FSC}}$ is the residual value of FSC at the end of service period in different phases.

C_{pay} is defined as the annual paid-pack principal and interest of loans calculated using annuity method and $C_{payint,n}$ is the annual paid-pack interest of loans. They can be expressed as

$$C_{pay} = P_{load}\left(\frac{i_0(1+i_0)^{N_{FSC}}}{(1+i_0)^{N_{FSC}}-1}\right) \tag{13}$$

$$C_{payint,n} = C_{load,n}i_0 \tag{14}$$

where i_0 is interest rate of loans and $C_{load,n}$ is the debt after paying back the principal and interest in the nth year. $C_{load,n}$ is given by

$$C_{load,n} = C_{load,n-1} - (C_{pay} - C_{payint,n-1}) \tag{15}$$

with $n \le N_{FSC}$, the debt after paying back principal and interest in the first year when $C_{load,1}$ is equal to P_{load}.

Annual net present value (NPV) after paying income tax is given by

$$P_{Atax,n} = ACF_n(1+i_p)^{-n} \tag{16}$$

Total NPV after paying income tax during the whole service period of FSCPP is expressed as

$$TP_{Atax} = \sum_{1}^{N} P_{Atax,n} - P_{load}(1+i_p)^{-n} + C_{inve,N_{FSC}}(1+i_p)^{-n} \tag{17}$$

If i is an expected value and TP_{Atax} is bigger than 0, the plant will be profitable. Otherwise non-profitable.

Accumulative present value (APV) is the sum of PV and non-returnable subsidy, which is equal to accumulative net present value (ANPV) without non-returnable subsidy.

5. Results and discussion

To state the problem clearly, we have carried out economic analysis of an FSCPP by considering a 100 MW FSCPP whose dimension (collector diameter is 4300 m and height above the ground is 9.2 m) is similar to that of the Schlaich et al.'s 100 MW reinforced concrete solar chimney power plant [18] and replaced the reinforced concrete chimney with a FSC.

Details of costs of components for the 100 MW FSCPP proposed in China are presented in Table 2.

In Table 2, the investment reaches 3125.5 million yuan with the cost of collector, chimney, and PCU being 1978.1, 756.6, and 390.7 million yuan, respectively.

Cash flows are determined by many factors, including investment, operation and maintenance cost, life span, payback period, inflation rate, minimum attractive rate of return (MARR), non-returnable subsidy rate, interest rate of loans, sale price of

Table 2
Detailed costs of components of the proposed 100 MW FSCPP (million yuan)

Cost of component	Material	Construction	Transport	Total
Glass	264.7	52.9	14.4	332.1
Column system	83.7	16.7	12.6	113.0
Support matrix	1230.8	246.2	56.0	1533.0
Collector	1579.3	315.9	83.0	1978.2
FSC				756.6
PCU				390.7
Investment				3125.5

electricity, income tax rate and whether additional revenue generated by carbon credits is included or not [31].

RCSCPP can be used for more than 100 years [4]. Fluri et al.'s [21] cost estimate is based on payback period of 80 years. Papageorgiou [22] estimated the cost of FSC based on conservative payback period of 12 years. In fact, FSC made of high-performance materials can be used for more than 15 years. In this work, the life span of collector and PCU and that of FSC are, respectively, assumed as: $N = 90$ and $N_{FSC} = 15$. Annual global solar radiation at the potential construction site is assumed to be 1800 kWh m^{-2} year^{-1} because the most suitable construction sites are located in desert regions in Northwest China [23] where annual global solar radiation is usually more than 1800 kWh m^{-2} year^{-1}. Based on these and ref. [19], power output of a 100 MW FSCPP is calculated to be 250.4 GWh year^{-1}.

A standard MARR of solar power industry is usually 8% [15]. Olivier et al. [15] carried out economic analysis using annual increasing rate of market price of electricity varying from 3% to 5% to 7% and MARR from 4% to 8%. Talavera et al. [12] assumed the annual increasing rate of price of electricity from SPVS ranging from −10% to 10%. Default values of MARR and annual increasing rate of market price of electricity are set at 8% and 5%, respectively.

Schlaich et al. [18,19] and Fluri et al. [21] assumed inflation rate of 3.5% whereas Bernardes et al. [20] used a lower value of 3.25%. Although the inflation rate has recently been low in China, a value of 4% is used in the work. All these investigators used the annuity method to calculate the cost of electricity. Talavera et al. [12] and Chandrasekar and Kandpal [17] calculated the principal and interest of loans using the annuity method. In this work, we also calculate the principal and interest of loans using the annuity method.

Presently, non-returnable subsidy rate for solar power plant with small power capacity focuses on the values ranging from 0% to 40%, and have a declining trend for large power capacity [14]. China is a large developing country, where non-returnable subsidy rate for large-scale solar power plant is not realistic. Non-returnable subsidy rate is therefore assumed to take a default value of zero.

According to the legislation in China, income tax is not paid until the following year when loans are paid off. The Chinese government always gives income tax-free or low-tax incentives to some corporations in order to stimulate and encourage the development of a new, significant industry. Income tax for FSCPP in China is considered to be free.

Double-declining-balance method of capital depreciation, an economic technique in all depreciation of capital used in China, is employed.

Revenue generated by carbon credits is included in the analysis due to climate change induced by GHG emissions had drew the world's high attention with the release of the Stern Review [32].

Market price of electricity differs in different regions [33]. An intermediate value of 0.7 yuan (kWh)$^{-1}$ is selected as the local market price of electricity for industrial use in the first year of operation in the calculation.

Based on the above references, values of economic parameters of FSCPP used in calculating cash flows are given in Table 3.

Table 4 presents detailed cash flows during six phases during the whole service period of a 100 MW FSCPP which is calculated using the economic model. Table 5 is a simplified version of Table 4.

Under the influence of the annual equivalent discount rate, with an increase in the number of phase, PV gradually decreases as seen from Tables 4 and 5. The ratio of NPV to PV of the investment in any later phase after the first phase is far more than that in the first phase. Unlike in the first phase, the investments in the other phases indicate higher benefits only for FSC. The ratio of NPV to PV of the investment first subtly decreases from a value of 11.8 in the second phase to a value of 11.4 in the third phase, and finally increases to 18.1 in the sixth phase. This shows the benefit basically continues rising with the number of phase. The decreases in PV of the investment and NPV in other phases are influenced by the annual equivalent discount rate.

The sum of the NPV in the first two phases is much more than the first investment. This shows the FSCPP is economical under the financial conditions shown in Table 3. Without doubt, the electricity sale price can be lowered, thus increasing competitiveness of FSCPP with conventional fossil fuel combustion plants and other renewable energy systems such as biofuel system and SPVS.

By analyzing cash flows, the minimum sale price of electricity is found to give MARR in the first phase when

Table 3
Values of economic parameters of FSCPP used in calculating cash flows

Parameter	Value
Interest rate of loans (%)	2
Inflation rate (%)	4
MARR (%)	8
Annual increasing rate of market price of electricity (%)	5
Multiple of price of solar electricity as market price:	
In the first 25 years of operation	5.75
In further years after the first 25 years of operation	4.6
Whether revenue generated by carbon credits is included or not	Yes
Income tax rate (%)	0
Non-returnable subsidy rate in the first phase (%)	0
Market price of electricity in the first year of operation (yuan (kWh)$^{-1}$)	0.7

Table 4
Cash flows

Time (Year)	Revenue of carbon credits	Revenue of electricity	O & M	Insurance	BCF	Debts	Annuity	Interest of loans	Depreciation	Income tax	ACF	PV
For FSCPP I (million yuan)												
0					−3125.5						−0	−0
1	54.1	1,008.0	23.0	25.0	960.0	3,125.5	243.2	62.5	153.5	0.0	770.8	686.3
2	56.3	1,058.4	24.0	26.0	1,008.4	2,944.7	243.2	58.9	138.9	0.0	821.5	651.2
3	58.5	1,111.3	24.9	27.0	1,059.4	2,760.4	243.2	55.2	126.1	0.0	874.7	617.3
4	60.9	1,166.9	25.9	28.1	1,112.8	2,572.4	243.2	51.4	114.9	0.0	930.5	584.6
5	63.3	1,225.2	27.0	29.3	1,169.0	2,380.6	243.2	47.6	105.0	0.0	989.1	553.3
6	65.8	1,286.5	28.0	30.4	1,228.0	2,184.9	243.2	43.7	96.4	0.0	1,050.6	523.3
7	68.5	1,350.8	29.2	31.6	1,290.0	1,985.4	243.2	39.7	88.7	0.0	1,115.3	494.5
8	71.2	1,418.4	30.3	32.9	1,355.1	1,781.9	243.2	35.6	82.0	0.0	1,183.1	467.1
9	74.1	1,489.3	31.5	34.2	1,423.5	1,574.3	243.2	31.5	76.1	0.0	1,254.4	440.9
10	77.0	1,563.7	32.8	35.6	1,495.4	1,362.5	243.2	27.2	70.8	0.0	1,329.1	415.9
11	80.1	1,641.9	34.1	37.0	1,570.8	1,146.5	243.2	22.9	66.2	0.0	1,407.7	392.2
12	83.3	1,724.0	35.5	38.5	1,650.1	926.2	243.2	18.5	62.0	0.0	1,490.1	369.6
13	86.6	1,810.2	36.9	40.0	1,733.3	701.5	243.2	14.0	58.3	0.0	1,576.7	348.2
14	90.1	1,900.7	38.4	41.6	1,820.7	472.3	243.2	9.4	55.0	0.0	1,667.6	327.9
15	93.7	1,995.8	39.9	43.3	1,912.6	238.5	243.2	4.8	52.0	0.0	1,763.1	308.6
NPV												7,196.1
APV												7,196.1
For FSCPP II (million yuan)												
16	97.5	2,095.6	41.5	45.0	2,009.0	0.0	0.0	0.0	219.3	0.0	2,106.5	328.3
17	101.4	2,200.3	43.2	46.8	2,110.4	0.0	0.0	0.0	194.2	0.0	2,211.7	306.9
18	105.4	2,310.4	44.9	48.7	2,216.8	0.0	0.0	0.0	172.4	0.0	2,322.2	286.9
19	109.6	2,425.9	46.7	50.7	2,328.5	0.0	0.0	0.0	153.4	0.0	2,438.2	268.2
20	114.0	2,547.2	48.5	52.7	2,445.9	0.0	0.0	0.0	136.8	0.0	2,560.0	250.7
21	118.6	2,674.5	50.5	54.8	2,569.3	0.0	0.0	0.0	122.4	0.0	2,687.8	234.3
22	123.3	2,808.3	52.5	57.0	2,698.8	0.0	0.0	0.0	109.8	0.0	2,822.1	219.0
23	128.3	2,948.7	54.6	59.3	2,834.8	0.0	0.0	0.0	98.8	0.0	2,963.1	204.8
24	133.4	3,096.1	56.8	61.6	2,977.7	0.0	0.0	0.0	89.2	0.0	3,111.1	191.4
25	138.7	3,250.9	59.1	64.1	3,127.8	0.0	0.0	0.0	80.8	0.0	3,266.5	178.9
26	144.3	2,730.8	61.4	66.7	2,602.7	0.0	0.0	0.0	73.4	0.0	2,747.0	134.0
27	150.0	2,867.3	63.9	69.3	2,734.1	0.0	0.0	0.0	67.0	0.0	2,884.1	125.2
28	156.1	3,010.7	66.4	72.1	2,872.1	0.0	0.0	0.0	61.3	0.0	3,028.2	117.1
29	162.3	3,161.2	69.1	75.0	3,017.1	0.0	0.0	0.0	56.3	0.0	3,179.4	109.4
30	168.8	3,319.3	71.9	78.0	3,169.4	0.0	0.0	0.0	51.9	0.0	3,338.2	102.3
NPV												2,823.6
APV												10,019.7
For FSCPP III (million yuan)												
31	175.5	3,485.2	74.7	81.1	3,329.4	0.0	0.0	0.0	354.0	0.0	3,504.9	95.6
32	182.6	3,659.5	77.7	84.3	3,497.4	0.0	0.0	0.0	309.8	0.0	3,680.0	89.4
33	189.9	3,842.4	80.8	87.7	3,673.9	0.0	0.0	0.0	271.4	0.0	3,863.8	83.5
34	197.5	4,034.6	84.1	91.2	3,859.3	0.0	0.0	0.0	238.1	0.0	4,056.7	78.1
35	205.4	4,236.3	87.4	94.9	4,054.0	0.0	0.0	0.0	209.1	0.0	4,259.4	73.0
36	213.6	4,448.1	90.9	98.7	4,258.5	0.0	0.0	0.0	184.0	0.0	4,472.1	68.2
37	222.1	4,670.5	94.6	102.6	4,473.4	0.0	0.0	0.0	162.1	0.0	4,695.5	63.8
38	231.0	4,904.0	98.3	106.7	4,699.0	0.0	0.0	0.0	143.1	0.0	4,930.0	59.6
39	240.2	5,149.2	102.3	111.0	4,936.0	0.0	0.0	0.0	126.6	0.0	5,176.2	55.7
40	249.8	5,406.7	106.4	115.4	5,184.9	0.0	0.0	0.0	112.2	0.0	5,434.8	52.1
41	259.8	5,677.0	110.6	120.0	5,446.4	0.0	0.0	0.0	99.6	0.0	5,706.2	48.7
42	270.2	5,960.9	115.0	124.8	5,721.0	0.0	0.0	0.0	88.7	0.0	5,991.2	45.5
43	281.0	6,258.9	119.6	129.8	6,009.5	0.0	0.0	0.0	79.2	0.0	6,290.5	42.6
44	292.3	6,571.9	124.4	135.0	6,312.4	0.0	0.0	0.0	70.9	0.0	6,604.7	39.8
45	304.0	6,900.5	129.4	140.4	6,630.6	0.0	0.0	0.0	63.7	0.0	6,934.6	37.2
NPV												859.3
APV												10,879.0
For FSCPP IV (million yuan)												
46	316.1	7,245.5	134.6	146.1	6,964.9	0.0	0.0	0.0	608.4	0.0	7,281.0	34.8
47	328.8	7,607.8	140.0	151.9	7,315.9	0.0	0.0	0.0	529.4	0.0	7,644.7	32.5
48	341.9	7,988.2	145.6	158.0	7,684.6	0.0	0.0	0.0	460.9	0.0	8,026.6	30.4
49	355.6	8,387.6	151.4	164.3	8,071.9	0.0	0.0	0.0	401.5	0.0	8,427.5	28.4

Table 4 (*Continued*)

Time (Year)	Revenue of carbon credits	Revenue of electricity	O & M	Insurance	BCF	Debts	Annuity	Interest of loans	Depreciation	Income tax	ACF	PV
50	369.8	8,807.0	157.4	170.9	8,478.7	0.0	0.0	0.0	349.9	0.0	8,848.5	26.5
51	384.6	9,247.3	163.7	177.7	8,905.9	0.0	0.0	0.0	305.2	0.0	9,290.5	24.8
52	400.0	9,709.7	170.3	184.8	9,354.6	0.0	0.0	0.0	266.4	0.0	9,754.6	23.2
53	416.0	10,195.2	177.1	192.2	9,825.9	0.0	0.0	0.0	232.8	0.0	10,241.9	21.7
54	432.6	10,704.9	184.2	199.9	10,320.9	0.0	0.0	0.0	203.5	0.0	10,753.5	20.3
55	450.0	11,240.2	191.6	207.9	10,840.7	0.0	0.0	0.0	178.2	0.0	11,290.7	18.9
56	467.9	11,802.2	199.2	216.2	11,386.8	0.0	0.0	0.0	156.2	0.0	11,854.7	17.7
57	486.7	12,392.3	207.2	224.8	11,960.3	0.0	0.0	0.0	137.0	0.0	12,446.9	16.6
58	506.1	13,011.9	215.5	233.8	12,562.6	0.0	0.0	0.0	120.4	0.0	13,068.7	15.5
59	526.4	13,662.5	224.1	243.2	13,195.2	0.0	0.0	0.0	106.0	0.0	13,721.6	14.5
60	547.4	14,345.6	233.1	252.9	13,859.7	0.0	0.0	0.0	93.5	0.0	14,407.1	13.5
NPV												316.0
APV												11,195.0
For FSCPP V (million yuan)												
61	569.3	15,062.9	242.4	263.0	14,557.5	0.0	0.0	0.0	1,074.9	0.0	15,126.8	12.6
62	592.1	15,816.0	252.1	273.6	15,290.4	0.0	0.0	0.0	933.1	0.0	15,882.5	11.8
63	615.8	16,606.8	262.1	284.5	16,060.2	0.0	0.0	0.0	810.2	0.0	16,676.0	11.0
64	640.4	17,437.2	272.6	295.9	16,868.7	0.0	0.0	0.0	703.6	0.0	17,509.1	10.3
65	666.0	18,309.0	283.5	307.7	17,717.8	0.0	0.0	0.0	611.2	0.0	18,383.8	9.7
66	692.7	19,224.5	294.9	320.0	18,609.6	0.0	0.0	0.0	531.1	0.0	19,302.3	9.0
67	720.4	20,185.7	306.7	332.8	19,546.2	0.0	0.0	0.0	461.6	0.0	20,266.6	8.4
68	749.2	21,195.0	318.9	346.1	20,529.9	0.0	0.0	0.0	401.4	0.0	21,279.1	7.9
69	779.2	22,254.8	331.7	360.0	21,563.1	0.0	0.0	0.0	349.2	0.0	22,342.2	7.4
70	810.3	23,367.5	345.0	374.4	22,648.2	0.0	0.0	0.0	303.9	0.0	23,458.5	6.9
71	842.8	24,535.9	358.8	389.3	23,787.8	0.0	0.0	0.0	264.6	0.0	24,630.5	6.4
72	876.5	25,762.7	373.1	404.9	24,984.6	0.0	0.0	0.0	230.6	0.0	25,861.1	6.0
73	911.5	27,050.8	388.0	421.1	26,241.6	0.0	0.0	0.0	201.0	0.0	27,153.2	5.6
74	948.0	28,403.3	403.6	438.0	27,561.8	0.0	0.0	0.0	175.4	0.0	28,509.8	5.3
75	985.9	29,823.5	419.7	455.5	28,948.3	0.0	0.0	0.0	153.1	0.0	29,934.2	4.9
NPV												116.1
APV												11,311.1
For FSCPP VI (million yuan)												
76	1,025.3	31,314.7	436.5	473.7	30,404.5	0.0	0.0	0.0	1,921.0	0.0	31,429.8	4.6
77	1,066.3	32,880.4	454.0	492.6	31,933.8	0.0	0.0	0.0	1,665.9	0.0	33,000.2	4.3
78	1,109.0	34,524.4	472.1	512.4	33,540.0	0.0	0.0	0.0	1,444.9	0.0	34,649.0	4.0
79	1,153.4	36,250.7	491.0	532.9	35,226.8	0.0	0.0	0.0	1,253.2	0.0	36,380.2	3.8
80	1,199.5	38,063.2	510.6	554.2	36,998.4	0.0	0.0	0.0	1,087.2	0.0	38,197.9	3.5
81	1,247.5	39,966.3	531.1	576.3	38,858.9	0.0	0.0	0.0	943.2	0.0	40,106.4	3.3
82	1,297.4	41,964.7	552.3	599.4	40,813.0	0.0	0.0	0.0	818.4	0.0	42,110.3	3.1
83	1,349.3	44,062.9	574.4	623.4	42,865.1	0.0	0.0	0.0	710.2	0.0	44,214.4	2.9
84	1,403.2	46,266.0	597.4	648.3	45,020.4	0.0	0.0	0.0	616.5	0.0	46,423.6	2.7
85	1,459.4	48,579.3	621.3	674.2	47,283.8	0.0	0.0	0.0	535.2	0.0	48,743.2	2.5
86	1,517.7	51,008.3	646.1	701.2	49,661.0	0.0	0.0	0.0	464.7	0.0	51,178.7	2.3
87	1,578.5	53,558.7	672.0	729.2	52,157.5	0.0	0.0	0.0	403.6	0.0	53,736.0	2.2
88	1,641.6	56,236.7	698.8	758.4	54,779.4	0.0	0.0	0.0	350.6	0.0	56,421.0	2.0
89	1,707.3	59,048.5	726.8	788.7	57,532.9	0.0	0.0	0.0	304.7	0.0	59,240.2	1.9
90	1,775.5	62,000.9	755.9	820.3	60,424.7	0.0	0.0	0.0	264.9	0.0	62,200.3	1.8
NPV												42.6
APV												11,353.6

Table 5
Simplified cash flows (million yuan)

End of phase (year)	Inve	Inve PV	Ratio of inve PV to APV (%)	NPV	APV	Residual PV	Ratio of NPV to inve PV
0	3,125.5	3,125.5	100.0	3,125.5	3,125.5	15.5	
15	1,362.6	238.5	7.6	7,196.1	7,196.1	4.9	2.3
30	2,454.0	75.2	1.0	2,823.6	10,019.7	1.5	11.8
45	4,419.4	23.7	0.2	859.3	10,879.0	0.5	11.4
60	7,959.2	7.5	0.1	316.0	11,195.0	0.2	13.3
75	14,334.0	2.4	0.0	116.1	11,311.1	0.1	15.5
90				42.6	11,353.6		18.1

Table 6
Minimum electricity sale price at obtaining MARR of 8% and the relevant NPV in the first phase

	Minimum electricity sale price at obtaining MARR of 8% (yuan $(kWh)^{-1}$)	NPV in the first phase (million yuan)	APV during the whole service period (million yuan)
Without needing any loan other than the first year	0.83	243	952.6
Needing loan other than the first year	0.72	3.6	577.1

NPV = 0. Table 6 presents minimum electricity sale price at 0.72 yuan for obtaining MARR of 8% and the relevant NPV in the first phase. However, NPV of 3.6 yuan is less than PV of the second investment at 238.5 million yuan, which is only 1.51% of PV of the first investment. In order to simplify economic estimate, NPV in the first phase is considered to be enough to satisfy the need of the investment of FSC in the second phase, a criteria that assures no reloaning during the whole service period. In Table 6, the minimum electricity sale price at 0.83 yuan for obtaining MARR of 8% during the whole service period of FSCPP is presented. NPV at 243 yuan in the first phase is more than PV of the second investment at 238.5 million yuan.

It is thus reasonable to state that electricity from FSCPP is competitive with other renewable energy utilizing systems such as biofuel systems and SPVS.

5.1. Sensitivity analysis

NPV in any phase is influenced by many factors including investment, operation and maintenance cost, life span, payback period, inflation rate, MARR, non-returnable subsidy rate, interest rate of loans, sale price of electricity, income tax rate, whether additional revenue generated by carbon credits being included or not, etc.

All the factors will influence cash flows and economics of project. In this paper, we examine the effect of various factors on the cash flows by keeping default values of other parameters equal and changing the value of one parameter at a time. As shown in Table 6, the minimum electricity sale cost for obtaining MARR of 8% during the whole service period of FSCPP is far less than the default value of electricity sale price at (0.7×5.75) yuan $(kWh)^{-1}$. An intermediate value of 2 yuan $(kWh)^{-1}$ is selected as the electricity sale price in the sensitivity analysis. Table 7 presents simplified cash flows during the whole service period of FSCPP at the electricity sale price of 2 yuan $(kWh)^{-1}$ by keeping default values of other economic parameters constant. In the table, APV during the whole service period of FSCPP at the electricity sale price of 2 yuan $(kWh)^{-1}$ reaches 4946.2 million yuan, which accounts for 43.6% of the total value by keeping the multiple of sale price of solar electricity as market price in the first 25 years of operation and after the first 25 years of operation as 5.75 and 4.6, respectively.

5.2. Effect of inflation rate

With inflation, prices rise and currencies are devaluated. This will result in bigger values of cash flows in the service periods of projects. Fig. 3 presents the variations of NPV in the first phase and APV during the whole service period with inflation rate from 2% to 10%. In the figure, the NPV gradually decreases with the increase in inflation rate. This results from the fact the effect of currency devaluation increases with bigger inflation rate.

5.3. Effect of MARR

The intention of any investment is to obtain maximum benefits. There are usually many choices for an investment. When they invest a sum of capital, investors always expect to obtain a benefit for the capital of an investment that is more than the MARR in the service period of the project. Fig. 4 presents the variations of NPV in the first phase and APV during the whole service period with MARR increasing. With an increase in MARR, PV gradually decreases.

5.4. Effect of non-returnable subsidy

Some developed countries granted non-returnable subsidy to support the development of renewable energy power generating technologies, whose cost are usually high. Based on the reference where non-returnable subsidy is granted to support projects of SPVP in the developed countries, non-returnable

Table 7
Simplified cash flows (million yuan) during the whole service period of FSCPP at the electricity sale price of 2 yuan $(kWh)^{-1}$

End of phase (year)	Inve	Inve PV	Ratio of inve PV to APV (%)	NPV	APV	Residual PV	Ratio of NPV to inve PV
0	3,125.5	3,125.5	100.0	3,125.5	3,125.5	15.5	
15	1,362.6	238.5	7.6	2,789.2	2,789.2	4.9	0.9
30	2,454.0	75.2	2.7	1,366.0	4,155.2	1.5	5.7
45	4,419.4	23.7	0.6	507.7	4,662.9	0.5	6.8
60	7,959.2	7.5	0.2	188.1	4,851.0	0.2	7.9
75	14,334.0	2.4	0.0	69.5	4,920.5	0.1	9.3
90				25.6	4,946.2		10.9

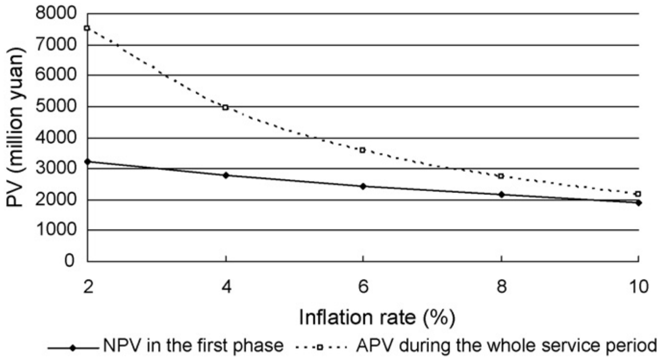

Fig. 3. Variations of NPV in the first phase and APV during the whole service period with inflation.

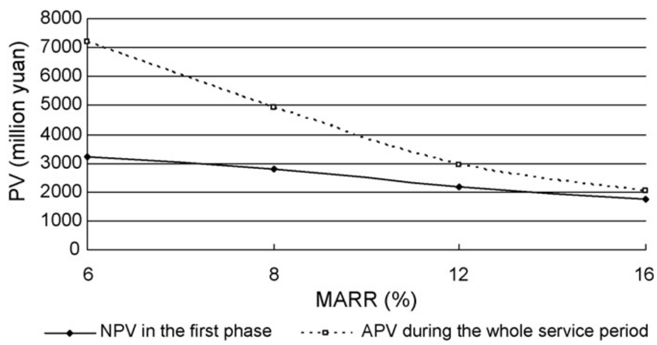

Fig. 4. Variations of NPV in the first phase and APV during the whole service period with MARR.

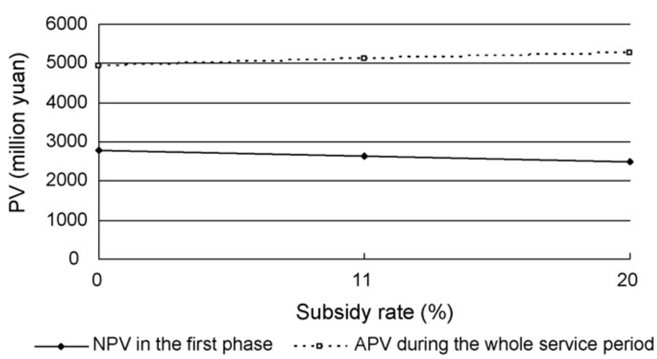

Fig. 5. Variations of NPV in the first phase and APV during the whole service period with non-returnable subsidy rate.

subsidy rate granted to FSCPP changed from 0% to 11% to 20% in the economic analysis.

Fig. 5 shows the variations of NPV in the first phase and APV during the whole service period with non-returnable subsidy rate increasing. With an increase in non-returnable subsidy rate, the principle and interest of loans will drop off, producing bigger PV, as presented in Table 8.

5.5. *Effect of interest rate of loans*

The magnitude of interest rate of loans determinates the widening level of capital. The annual paid-back principal and interest of loans are calculated using annuity method.

Fig. 6 shows the variations of NPV in the first phase and APV during the whole service period with interest rate of loans increasing. The figure shows that an increase in interest rate of loans causes a decrease in PVs. This depends on more interest of loans with bigger interest rate should be paid back, decreasing NPV in the first phase from 2789.2 million yuan at interest rate of loans of 2% to a low value of 1972.9 million yuan at interest rate of loans of 8% and APV during the whole service period. It is concluded that low interest rate of loans is needed in order for FSCPP to compete favourably with other energy power generating systems.

5.6. *Effect of income tax rate*

An income tax is a tax levied on the financial income of persons, corporations, or other legal entities. The common income tax rate of corporations is 33% in China [31]. The Chinese government usually gives incentives to the development industry whose cost is high by reducing or exempting the relevant corporations from income tax. According to legislation, income tax is not paid until the following year when loans are paid off. In our work, income tax is assumed to be paid from the first year in the second phase of project.

Fig. 7 shows the variations of NPV in the first phase and APV during the whole service period with income tax rate increasing. With an increase in income tax rate from 0% to 20%, NPV in the first phase shows a little decrease, and APV during the whole service period decreases from 4946.2 million to 3939.1 million yuan returning a decease of 20.4%. This shows that the effect of income tax rate on economics of the project is considerable.

5.7. *Effect of electricity sale price*

With fossil fuels being exhausted and the influence of inflation and living standards of people being improved, the market price of electricity without doubt increases year by year. In this paper, we have taken the sale price of electricity from FSCPP at the market price multiplied by a given multiple with the assumption that there is the same annual increasing rate as the market price.

By keeping other parameters constant and changing the increasing rate of market price of electricity and electricity price sold to the utility in the first year, variations of NPV in the first phase and APV during the whole service period with annual electricity sale price are investigated.

Figs. 8 and 9, respectively, show the variations of NPV in the first phase and APV during the whole service period with annual increasing rate of market price of electricity at a given electricity sale price of 2 yuan $(\text{kWh})^{-1}$ in the first year of operation and with a given electricity sale price in the first year at annual increasing rate of electricity market price of 4%. In the two figures, both the given sale price of electricity in the first year and annual increasing rate of electricity market price can directly increase the revenue received for FSCPP and its PV. PV is calculated according to the given sale price of electricity (denoted by a *) being 5.75 times more than the market price in

Table 8
NPV in the first phase and APV during the whole service period at different non-returnable subsidy rates

Subsidy rate	Subsidy	NPV in the first phase	APV in the first phase	APV during the whole service period	Diff of NPV without subsidy in the first phase	Diff of APV without subsidy during the whole service period
0	0	2789.2	2789.2	4946.2	0.0	0.0
11	343.8	2624.6	2968.4	5125.3	164.6	179.2
20	625.1	2489.9	3115.0	5271.9	134.7	325.8

the first 25 years of operation and 4.6 times after the first 25 years of operation with market price of electricity being 0.7 yuan $(kWh)^{-1}$ as shown in Fig. 9. This is only slightly less than the corresponding value calculated according to the given sale price of electricity at 4 yuan $(kWh)^{-1}$ in the first year.

5.8. Effect of revenue generated by carbon credits

In the recent years, GHG emissions have acquired much importance, and the cost of dismissing GHG emissions start to be included in the economic analysis of projects.

Table 9 presents comparisons of NPV in the first phase and APV during the whole service period whether revenue generated by carbon credits due to decrease in GHG emissions is included or not. In the table, the revenue generated by carbon credits reaches 445.4 million yuan in the first phase and 649.9 million yuan during the whole service period. This account for 19% and 15.1% of NPV excluding revenue generated by carbon credits in the first phase and APV during the whole service period, respectively. This shows that the economics of lessening GHG emissions is very crucial.

5.9. Effect of depreciation on capital

There are many depreciation methods of capital including slow depreciation methods and fast depreciation methods. Four basic methods exist in China for computing depreciation which are: straight-line, units-of-production, double-declining-balance, and sum-of-years'-digits [31]. In this work, straight-line depreciation method and double-declining-balance method of depreciation are used in calculating the capital depreciation. Fig. 10 compares the variations of cash values and their PV in the second phase with time using different depreciation methods of capital. The residual value using straight-line depreciation method of capital is assumed to be equal to that using depreciation method of capital. In the figure, depreciation rate using double-declining-balance method shows gradual

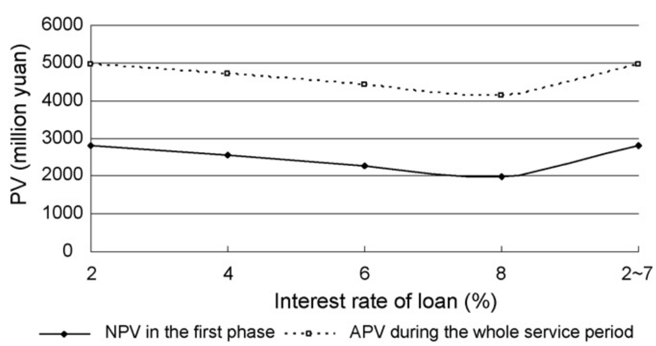

Fig. 6. Variations of NPV in the first phase and APV during the whole service period with interest rate of loans.

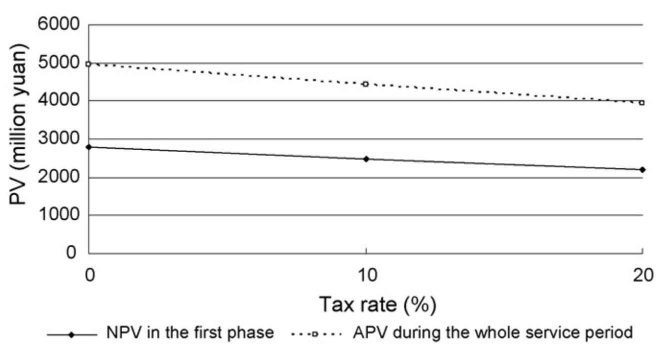

Fig. 7. Variations of NPV in the first phase and APV during the whole service period with income tax rate.

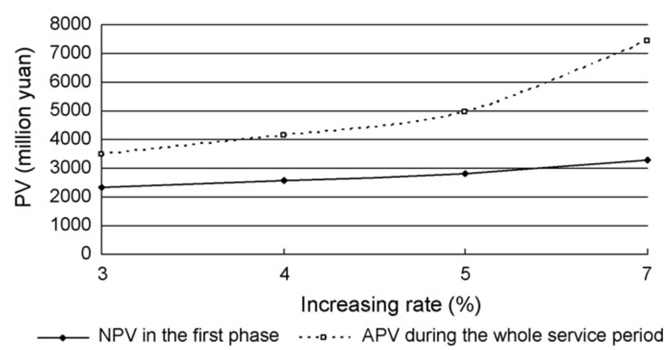

Fig. 8. Variations of NPV in the first phase and APV during the whole service period with annual increasing rate of market price of electricity.

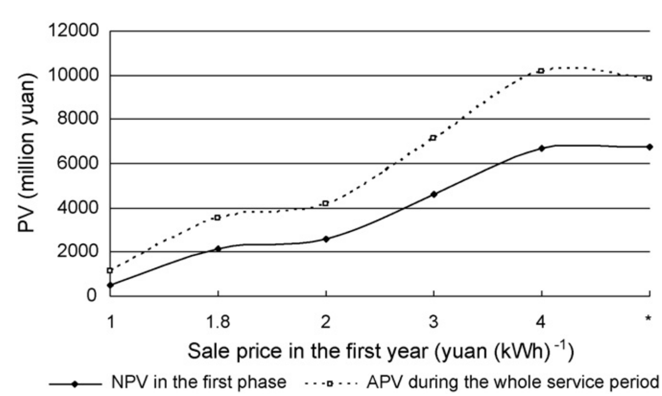

Fig. 9. Variations of NPV in the first phase and APV during the whole service period with electricity sale price in the first year.

Table 9
Comparisons of NPV in the first phase and APV during the whole service period whether revenue generated by carbon credits is included or not

	NPV in the first phase	APV during the whole service period
Including revenue generated by carbon credits (million yuan)	2789.2	4946.2
Not including revenue generated by carbon credits (million yuan)	2343.8	4296.3
Difference (million yuan)	445.4	649.9
Percent of difference to calculation not including revenue generated by carbon credits (%)	19.0	15.1

decrease while that using straight-line method is maintained constant.

In Table 10, NPVs in the first phase and APVs during the whole service period using different depreciation method of capital at income tax rate of 10% are compared. Difference of the APVs using straight-line depreciation method of capital and double-declining-balance depreciation method reaches 7.7 million yuan, which only accounts for 0.2% of the APV using double-declining-balance depreciation method. As shown in Fig. 10 and Table 10, double-declining-balance depreciation method is more economical in calculating the cash flows than straight-line depreciation method, although just a slight increase in PV by decreasing income tax.

6. Comparison of FSCPP with reinforced concrete solar chimney power plant

Although it can be used for more than 100 years, the cost of RCSCPP is high with a long payback period. This study is carried out to compare the economics of the proposed 100 MW FSCPP with that of a 100 MW RCSCPP whose collector cover is made of glass in line with the investment estimate by Fluri et al. [21].

The assumptions for estimate of the cost of the 100 MW RCSCPP are summarized as: operation and maintenance cost and insurance in the first year of 1.9 million Euros; life span and payback period of loans of 90 years; multiple of the given sale price of electricity as the market price in the first 25 years of operation and after the first 25 years of operation being 5.75 and 4.6, respectively; the market price of electricity of 0.7 yuan $(\mathrm{kWh})^{-1}$; and default values of other economic parameters in the cost estimate of the RCSCPP being similar to those for the FSCPP.

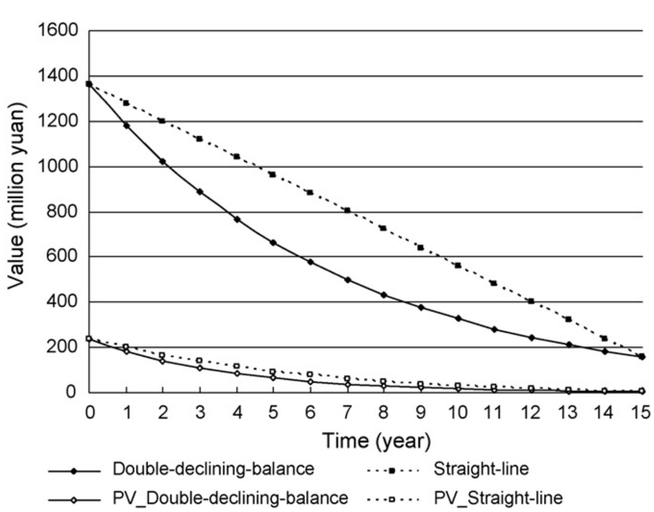

Fig. 10. Variations of future value and PV in the second phase with time using different depreciation method of capital.

Fig. 11 shows the variations of APVs of a 100 MW FSCPP and a RCSCPP with inflation rate and interest rate of loans. By changing inflation rate from 2% to 12%, the APVs of the 100 MW FSCPP at an interest rate of 2% on loans is always higher than that of the 100 MW RCSCPP at an interest rate of 8% on the loans. The APVs for FSCPP at an interest rate of 2% on loans and inflation rate of less than 4% is higher than the corresponding values for the 100 MW RCSCPP at an interest rate of 6% on loans. As a basic principle, interest rate on loans increases with longer payback period. The value of 2% seems low for interest rate on loans for RCSPP in a payback period of 90 years but at this interest rate, it is feasible for FSCPP in 15 years compared to SPVP for more than 25 years with a low interest rate of 2%.

As shown in Fig. 11, APVs of the 100 MW FSCPP and RCSCPP decrease with the increase in interest rate of loans or inflation rate.

By keeping interest rate constant at 2% on loans for a 100 MW FSCPP but changing the interest rate on loans for a 100 MW RCSCPP, a minimal interest rate on loans for the 100 MW RCSCPP is obtained to allow APV of a 100 MW FSCPP to be equal to that of a 100 MW RCSCPP.

Fig. 12 shows the variation of the minimal interest rate of loans at different inflation rates when APV of a 100 MW FSCPP is equal to that of a 100 MW RCSCPP. As shown in Fig. 12, the minimal interest rate of loans for RCSCPP reaches 6.4% at an inflation rate of 4%. That is to say, based on the same financial incentives, when interest rate on loans is more than 6.4%, there is a bigger APV for FSCPP. This is more economical, otherwise the economics of RCSCPS is better. The minimal interest rate of loans also increases with bigger inflation rate, and reaches 7.3% at inflation rate of 8%. The value of 7.3%, which is lower than the more than five-year bank lending rate at 7.83% in China [35], also seems low for interest rate on loans for RCSPP in payback period of 90 years. Since inflation rate is low in China, FSCPP in reality provides better-savings than RCSCP as a whole.

Fig. 13 shows the variation of the maximum interest rate of loans with time by keeping inflation rate constant at 4% when PV of FSCPP whose interest rate of loans is maintained constant at 2% is equal to that of RCSCPS. In the figure, the maximum interest rate rises with time, and is less than 2% for a time period less than 15 years showing that the benefits are better with time.

Table 10
Comparisons of NPV in the first phase and APV during the whole service period using different depreciation methods of capital (million yuan)

	Double-declining-balance		Straight-line		NPV diff	APV diff	Ratio of diff to NPV double-declining-balance (%)	Ratio of diff to APV double-declining-balance (%)
End of phase (year)	NPV	APV	NPV	APV				
0	3,125.5	3,125.5	3,125.5	3,125.5	0.0	0.0		
15	2,492.7	2,492.7	2,485.1	2,485.1	7.7	7.7	0.3	0.3
30	1,236.2	3,728.9	1,236.2	3,721.2	0.0	7.7	0.0	0.2
45	458.3	4,187.2	458.3	4,179.6	0.0	7.7	0.0	0.2
60	169.6	4,356.9	169.6	4,349.2	0.0	7.7	0.0	0.2
75	62.6	4,419.5	62.6	4,411.8	0.0	7.7	0.0	0.2
90	23.1	4,442.6	23.1	4,434.9	0.0	7.7	0.0	0.2

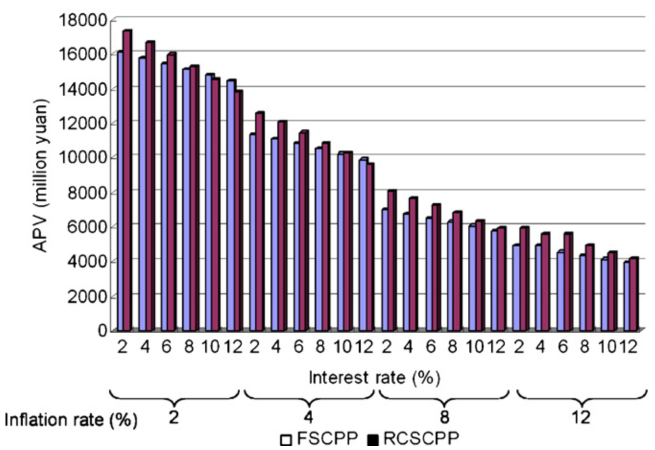

Fig. 11. Variations of APV of the 100 MW FSCPP and RCSCPP with inflation rate and interest rate of loans.

7. Comparison of FSCPP with solar photovoltaic plant

Solar photovoltaic technology is one of the earliest and most popular solar power generating technologies to first be commercialized. SPVP can be used for more than 30 years and its economic analysis is usually based on service period of 25 years [12–17,34]. This service period is much shorter compared to that of solar chimney power plant. We will compare the economics of the proposed 100 MW FSCPP and a

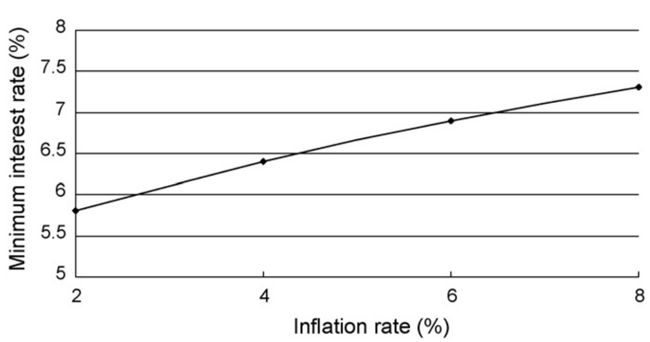

Fig. 12. Variation of the maximum interest rate of loans for RCSCPP with different inflation rates when APV of FSCPP whose interest rate of loans is maintained constant at 2% is equal to that of RCSCPS.

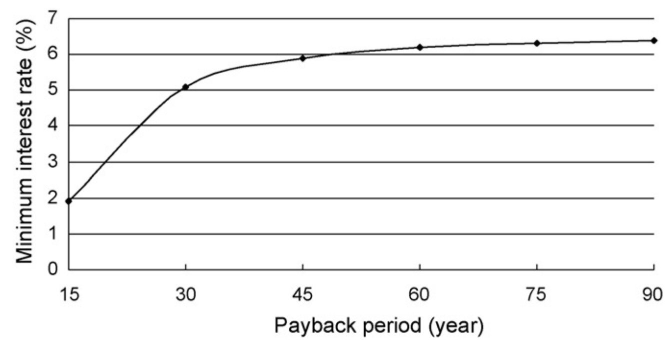

Fig. 13. Variation of the maximum interest rate of loans for RCSCPP with time by keeping inflation rate at 4% when APV of FSCPP whose interest rate of loans is maintained constant at 2% is equal to that of RCSCPS.

SPVP with the same annual power capacity by analyzing their cash flows.

The assumptions for estimating the cost of the SPVP are summarized as: investment of 7 Euros Wp^{-1} [14]; annual power of 1314 kWh kWp^{-1} $year^{-1}$ (27% of solar radiation is assumed to be lost [23]); operation and maintenance cost and insurance in the first year accounting for 0.2% [16] and 0.8% [12] of investment, respectively; payback period is 25 years; and default values of other economic parameters in cost estimate of the SPVP being similar to those of the FSCPP. The investment of the SPVP is calculated to be 12,807.6 million yuan.

By assuming the sale price of electricity from the SPVP to be 5.75 times more than the market price, APV for obtaining MARR of 8% from the SPVP during the whole service period reaches 5511.3 million yuan, which is far lower than the value of 7196.1 million yuan for the 100 MW FSCPP in the first 15 years. We concluded that FSCPP is more economical than SPVP.

8. Conclusions

In this paper, economic analysis of power generation from FSCPP that has a long service period is performed by analyzing cash flows during its service period. By neglecting the externalities for sulphur dioxide (SO_2), nitrogen oxides (NO_x) and particles which may amount to 203.8 mEuro $(kWh)^{-1}$ in the conventional thermo-electric power plants using sub-bituminous coal like in Spain [14], cost-effectiveness for FSCPP may be achieved under the available financial incentives in China. The results show that the minimum price for obtaining MARR of 8% is 0.83 yuan $(kWh)^{-1}$ under the financial incentives including loans at an interest rate of 2%, free income tax, and collection of additional revenue generated by carbon credits.

Under the same financial incentives, the FSCPP is more economical than RCSCPP or SPVP with the same power capacity. Based on low inflation rate, the APV of a 100 MW FSCPP with loans at low interest rate is usually more than the value for a 100 MW RCSCPP with loans at high interest rate of 6.4%. APV for obtaining MARR of 8% from a 100 MW SPVP is far low than the value for a SPVP with the same annual power capacity in the first 15 years.

We believe that if taken into consideration, this economic analysis based on the practice in China will accelerate the development of FSCPP in the country (China).

Acknowledgements

Many thanks to Dr. Reccab M. Ochieng's help in reviewing this paper.

References

[1] Gullison RE, Frumhoff PC, Canadell JG, Field CB, Nepstad DC, Hayhoe K, et al. Tropical forests and climate policy. Science 2007;316:985–6.
[2] Zhou XP, Xiao B, Ochieng RM, Yang JK. Utilization of carbon-negative biofuels from low-input high-diversity grassland biomass for energy in China. Renewable Sustain Energy Rev 2009;13:479–85.
[3] Service RF. Is it time to shoot for the sun? Science 2005;309:548–51.
[4] Schlaich J. The solar chimney: electricity from the sun. Stuttgart, Germany: Edition Axel Menges; 1995.
[5] Dennis C. Solar energy: radiation nation. Nature 2006;443:23–4.
[6] Woody T. Tower of power. In: The 31 best business ideas in the world. Business 2.0 2006;7:94–102.
[7] Papageorgiou CD. Floating solar chimney: the link towards a solar future. In: Proceedings of the ISES 2005 Solar World Congress Conference; August 2005.
[8] Zhou XP, Yang JK, Xiao B, Hou GX. Experimental study of the temperature field in a solar chimney power setup. Appl Therm Eng 2007;27:2044–50.
[9] Ketlogetswe C, Fiszdon JK, Seabe OO. Solar chimney power generation project—the case for Botswana. Renewable Sustain Energy Rev 2008;12: 2005–12.
[10] Zhou XP, Yang JK, Xiao B, Hou GX, Shi XY. Special climate around a commercial solar chimney power plant. J Energy Eng Trans ASCE 2008;134:6–14.
[11] Available at: http://www.enviromission.com.au/faqs/faqs.htm.
[12] Talavera DL, Nofuentes G, Aguilera J, Fuentes M. Tables for the estimation of the internal rate of return of photovoltaic grid-connected systems. Renewable Sustain Energy Rev 2007;11:447–66.
[13] Line of financing ICO-IDAE for Renewable Energies and Power Efficiency projects. Addressed at: http://www.idae.es; 2004.
[14] Bernal-Agustín JL, Dufo-López R. Economical and environmental analysis of grid connected photovoltaic systems in Spain. Renewable Energy 2006;31:1107–28.
[15] Olivier JR, Harmsa TM, Esterhuyse DJ. Technical and economic evaluation of the utilization of solar energy at South Africa's SANAE IV base in Antarctica. Renewable Energy 2008;33:1073–84.
[16] Trieb F. Competitive solar thermal power stations until 2010—the challenge of market introduction. Renewable Energy 2000;19:163–71.
[17] Chandrasekar B, Kandpal TC. Effect of financial and fiscal incentives on the effective capital cost of solar energy technologies to the user. Solar Energy 2005;78:147–56.
[18] Schlaich J, Bergermann R, Schiel W, Weinrebe G. Sustainable electricity generation with solar updraft towers. Struct Eng Int 2004;3.
[19] Schlaich J, Bergermann R, Schiel W, Weinrebe G. Design of commercial solar updraft tower systems-utilization of solar induced convective flows for power generation. J Solar Energy Eng 2005;127:117–24.
[20] dos S. Bernardes MA. Technische, ökonomische und ökologische Analyse von Aufwindkraftwerken, Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart; 2004.
[21] Fluri TP, Pretorius JP, van Dyk CP, von Backström TW, Kröger DG, van zijl GPAG. Cost analysis of solar chimney power plants. In: Proceedings of the EuroSun Conference; 2006.
[22] Papageorgiou CD. Optimum design for solar power stations with floating solar chimneys. In: Proceedings of the 32nd National Heat Transfer Conference; 2004. p. 763–72.
[23] Zhou XP, Yang JK. A novel solar thermal power plant with floating chimney stiffened onto a mountain-side and potential of the power generation in China's deserts. Heat Transfer Eng, in press.
[24] Zhou XP, Yang JK, Xiao B, Hou GX. Simulation of solar chimney power equipment. Renewable Energy 2007;32:1637–44.
[25] Papageorgiou CD. Floating solar chimney. PCT/GR03/00037/27-03-2003; 2003.
[26] Communication with Dr. Denis D.; 2007.
[27] Papageorgiou CD. Floating solar chimney technology: a solar proposal for China. In: Proceedings of the ISES 2007 Solar World Congress Conference; 2007. p. 172–6.
[28] U.S. Energy Information Administration. Available at: http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html#electric; 2006.
[29] PointCarbon. Accessed at: http://www.pointcarbon.com/; October 3, 2007.
[30] Conversion rate for yuan and Euro. Accessed at: http://www.99199.com.cn/forex/1949/; October 3, 2007.
[31] Yu HX.In: Engineering economics. Beijing: China Planning Press; 2002.
[32] Stern N. The economics of climate change: the Stern Review. Cambridge, UK: Cambridge University Press; 2007.
[33] Price of electricity and water for industrial purposes in several cities in China. Addressed at: http://www.hnpi.net/jbwd-1.htm; February 2007.
[34] Shaahid SM, Elhadidy MA. Economic analysis of hybrid photovoltaic-diesel-battery power systems for residential loads in hot regions—a step to clean future. Renewable Sustain Energy Rev 2008;12:488–503.
[35] People's Bank of China. Chinese unit of currency (CNY) lending rate table. http://www.boc.cn/cn/common/rmbcredit.jsp?category=ROOT%3-E%D6%D0%D0%D0%D7%DC%D0%D0%3E%D0%D0%C7%E9%-B7%D6%CE%F6%CA%D2%3E%B4%E6%BF%EE%A1%A2%B4%-FB%BF%EE%C0%FB%C2%CA&ratecolumn=2, 21 December, 2007.