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# NEXUS OF WATER-ENERGY AND THE POTENTIAL EMISSION REDUCTION BENEFIT OF PHOTOVOLTAIC PUMPING SYSTEM IN NORTH CHINA PLAIN

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## ABSTRACT

The North China Plain (NCP) is the largest groundwater irrigation area in China, with about 6.5 million hectares of cultivated land and more than 1 million irrigation wells. Totally there are about 20 billion $m^3$ of groundwater that pumped for irrigation each year. The exploitation of groundwater in NCP leads to the continuous decrease of groundwater level. The average depth of groundwater is more than 20 m, and the deepest groundwater level is 100m beneath the ground surface. As the groundwater level is low, the energy use for pumping in NCP is huge, which leads to high carbon emission. This paper reveals the nexus of water-energy in NCP based on the experiments of agricultural irrigation wells. The volume of the pumped water and the energy is measured, and the correlations between the water and energy are established for irrigation wells of different depth. Based on the groundwater level of NCP and the location of irrigation wells, the total energy use for agricultural pumping is calculated. As a comparative study, this paper calculates the potential benefit of $CO_2$ emission reduction, assuming the groundwater is pumped by a photovoltaic system instead of the state power grid. The results show that the photovoltaic pumping system can reduce $CO_2$ emission by 1.87 million ton/year, comparing to the state power grid. The surplus electricity could replace thermal power and bring additional 2.67 million ton of emission reduction benefit per year.

**Keywords:** nexus of water-energy, photovoltaic pumping, emission reduction, groundwater irrigation, North China Plain

## 1. INTRODUCTION

With the rapid development of the world, a large amount of non-renewable energy is consumed. The problem of energy source is becoming more and more serious. Since energy storage is not able to meet the growing demand, many countries in the world are seeking alternative energy sources and developing clean energy. The clean energy includes solar, wind, and nuclear energy, and solar power technology has been widely used in the world. The photovoltaic pumping system is one of the typical applications of solar energy resource. It uses solar power to pump groundwater to irrigate crops. Some researches on photovoltaic pumping system worldwide are reviewed. Ghoneim [1] developed a computer program to simulate a photovoltaic power device that meets the local climate of Kuwait. With the program, the best combination of components in amorphous silicon solar energy was also found, so that the device has the highest efficiency. Amer and Younes[2] experimentally obtained the non-linear relationship between discharge and solar radiation. The long-term performance of battery-free photovoltaic pumping system was assessed based on the relationship and the error between the experimental and actual average discharge of the system was estimated. Based on the electric pump subsystem model of the photovoltaic pumping system, Ould-Amrouch et al. [3] introduced a method to estimate the savings of carbon dioxide ($CO_2$) emissions using photovoltaic pumping system (i.e., photovoltaic array) rather than a diesel-driven generator. Gao et al. [4]

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assessed the feasibility and performance of photovoltaic pumping system in a demonstration area in Qinghai, China. Based on the analysis of the supply-demand balance of solar energy, the design parameter of the photovoltaic pumping system in the study area was determined. It was concluded that the photovoltaic pumping system had better economic and ecological benefits compared with the diesel-driven system. The North China Plain (NCP), with a large cultivated land area, is one of the leading grain producing areas in China. It has the largest groundwater irrigation area as well. The electricity consumption for farmland irrigation is increased due to the decrease in the groundwater level. As a result, energy consumption and $CO_2$ emission are increased. Therefore, the application of photovoltaic is necessary for NCP area.

## 2. OVERVIEW OF THE NCP

China has a vast territory, most of which lies between temperate and subtropical zones, which are rich in solar resources. The annual radiation is over 5000 MJ/m$^2$, and over two-thirds of the territory has the sunshine duration of 2,200 hours per year. The sunshine energy in the terrestrial area is equivalent to 2.4*1012 tons of coal. The NCP is one of the three major plains in China and an essential part of the Great Plain in Eastern China. It is located at 32° - 40° N, 114° - 121° E. The annual solar radiation decreases from the northern to the southern area, which is between 4,800 and 6,400 MJ/m$^2$. The average value is approximately 5,700 MJ/m$^2$. However, the radiation is higher in a few areas.

The NCP is the main grain-producing area in China, with about 16 million acres of arable land, which meets the huge annual water demand for crop growth. Up to 20 billion cubic meters of groundwater each year is applied for irrigation due to the insufficient rainfall and surface water resources in the NCP. Because of the over-exploitation of the groundwater, the groundwater level decreases, leading to the groundwater funnels. The average groundwater depth in the NCP is over 20 meters, and the maximum depth can reach 100 meters. The 3D image of groundwater depth in the NCP is shown in Figure 1 below. In order to meet the demand for irrigation, pumps with a higher power are applied, resulting in more consumption of electricity. Also, other energy consumption, such as the carbon emission is indirectly increased because of the mainly applied thermal power in China.

## 3. METHODOLOGY

### *3.1 Survey*

Handan, China is one of the groundwater

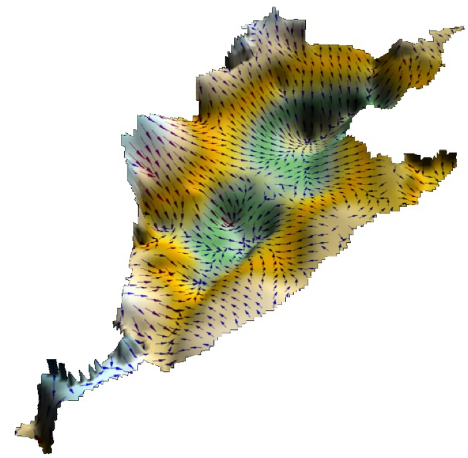

Fig 1. 3D Image of Groundwater Depth in the NCP

exploitation project areas in the NCP. The massive amount of groundwater exploitation in Handan causes a decrease of groundwater level and the increase of groundwater depth. To meet the demand for farmland irrigation, high-power pumps are applied which consume more electricity. In this study, the relationship between the flow rate of wells, groundwater depth, and electricity consumption was determined. By using the relationship between the flow rate of the well corresponding to unit electricity consumption and the groundwater depth, the total electricity consumption in the NCP area was calculated. One hundred thirty-two wells for farmland irrigation with different groundwater depth were selected in Handan. The discharge corresponding to unit electricity consumption and the groundwater depth of each well are measured using hand-held ultrasonic flowmeter. The distribution of

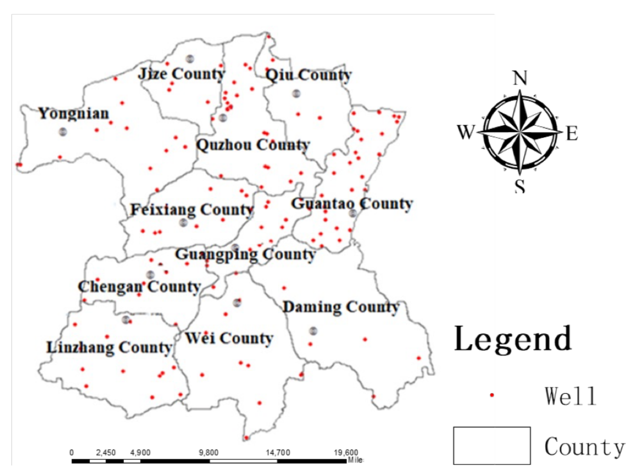


Fig 2. Distribution of Experimental Points


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experimental points is shown in Figure 2 below.

The wells are divided into eight groups. The average discharge per unit electricity consumption ($m^3$/kWh) of each group is calculated and summarized in Table 1 below. It shows a negative correlation between the discharge per unit electricity consumption and the groundwater depth, as shown in Figure 3.

Table 1. Groundwater Depth and Discharge per Electricity Consumption

| Groundwater Depth (m) | 45 | 50 | 60 | 65 | 67 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|
| Discharge per Electricity ($m^3$/kWh) | 2.1 | 2.4 | 1.1 | 1.9 | 2.6 | 1.3 | 1.7 | 1.8 |

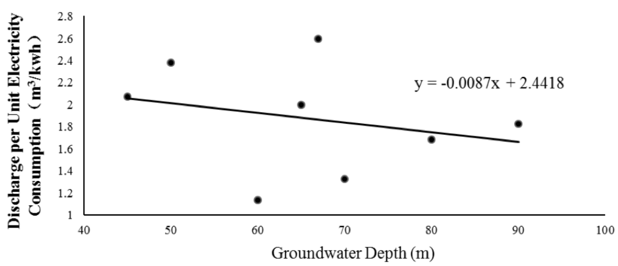


Fig 3. Relationship Between Discharge per Unit Electricity Consumption and Groundwater Depth

### *3.2 Energy Consumption of Irrigation*

#### 3.2.1 Thermal Power

The main power generation methods in China are thermal power and hydroelectric power, of which thermal power accounts for more than 70%. According to statistics, the coal-fired power plants with 600 MkW or more installed capacity of central units is approximately 305 g/kWh. The primary pollution comes from $CO_2$, which are 1,118 g /kWh. [5] The electric well irrigation is dominant in the NCP area. The annual water demand of the crops, which is 20 billion cubic meters, is met by groundwater extraction and exploitation. Along with the decrease of groundwater level, additional electricity is consumed annually to meet irrigation needs. The electricity consumption is calculated by Equation (1) below.

$$\mathrm{E} = \frac{\rho g V h}{\alpha \eta} \quad (1)$$

Where E is electricity consumption, J; ρ is density of water, kg/$m^3$; g is gravitational acceleration, m/$s^2$; V is volume of water, $m^3$; h is the water head of the pump, in NCP, h=20 m; α is electricity conversion factor, α=3600000 J/kWh; $\eta$ is the efficiency coefficient of the pump, in this study $\eta$=0.65.

The monthly electricity consumptions for irrigation in the NCP are calculated by Equation (1), and the results are summarized in Table 2 below.

According to Table 2, annual electricity consumption in the NCP is 1,675.21 MkWh. 510.9 kilo-tons of coal is consumed, with corresponding 1,873 kilo-tons of $CO_2$ emission. The monthly water and electricity consumption for irrigation is shown in Figure 4 below.

Table 2. Monthly Water Consumption and Electricity Consumption

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Water Consumption ($Mm^3$) | 417 | 342 | 1632 | 2467 | 2277 | 3112 | 3188 | 2846 | 1101 | 1290 | 797 | 531 |
| Electricity Consumption (MkWh) | 34.93 | | 28.65 | 136.70 | 206.64 | 190.72 | 260.66 | 267.03 | 238.38 | 92.22 | 108.05 | 66.76 |

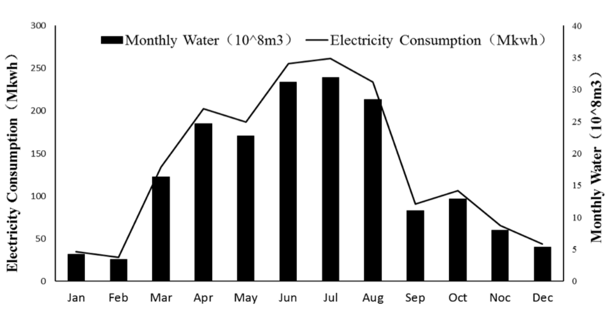


Fig 4. Monthly Water and Electricity Consumption

#### 3.2.2 Photovoltaic Pumping System

China is a country with abundant solar energy resources. The annual total radiation is between 860 and 2080 kWh/$m^2$, the annual direct radiation is between 230 and 1500 kWh/$m^2$, the annual average direct radiation ratio is between 0.24 and 0.73, and the annual sunshine hour is between 870 and 3570 hours. [6] According to the Assessment Method for Solar Energy Resources, the solar energy resource regions in China are divided based on the total annual solar radiation of


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the region. The detailed standards are summarized in Table 3 below.

Table 3. Division of Solar Energy Resource Region

| Level | Zone | Annual Total Radiation (MJ/m²) | Annual Total Radiation (kWh/m²) | Average Daily Radiation (kWh/m²) |
|---|---|---|---|---|
| Most Abundant | I | ≥6300 | ≥1750 | ≥4.8 |
| Abundant | II | 5040-6300 | 1400-1750 | 3.8-4.8 |
| Less Abundant | III | 3780-5040 | 1050-1400 | 2.9-3.8 |
| Normal | IV | <3780 | <1050 | <2.9 |

The NCP is located in Zone II, with the annual total radiation between 1450 and 1500 kWh/m$^2$. The annual sunshine hour is between 2400 and 3000 hours, which provides abundant solar energy resource. The photovoltaic pumping system is suitable for this area, mitigating the energy consumption and pollution in North China. The intensity of sunshine and the average monthly sunshine hour are relatively high in spring and summer in the NCP, showing a trend of first increase and then decrease. The monthly sunshine intensity and duration are shown in Figure 5 below.

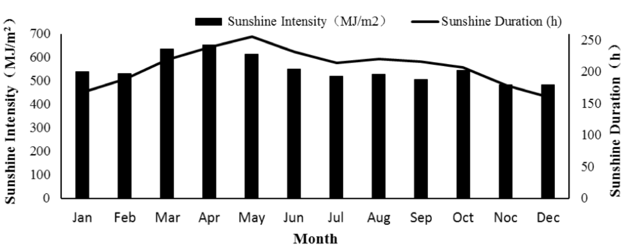


Fig 5. Monthly Sunshine Intensity and Duration

The photovoltaic pumping system includes solar panels, inverters, and pumps. The large-scale produced single-crystal silicon solar panel has a high power generation efficiency of about 18% - 24%. The inverter has an efficiency of 96%, and the energy conversion efficiency of the pump is measured to be approximately 50% by experiment. There is attenuation in the life cycle of solar panels due to some technical limits. The initial attenuation is significant, while gradually becomes stable later. The maximum attenuation in 25 years can be limited to less than 20% with current technology. Even though the photovoltaic system is clean, it has a high cost, which requires large investment including annual capital investment, operation, maintenance, and replacement. [7] Besides, the annual investment of the photovoltaic pumping system is calculated based on the data provided by the manufacturer.

In this study, the prices of the photovoltaic module, the inverter and the pump are $1.5/Wp, $1.5/Wp, and $0.5/Wp, respectively [7]. The operation and maintenance costs are equal to 2% of the annual investment. Assuming pumps and inverters are replaced every eight years, the operation, maintenance, and replacement costs are 4% of annual investment. To meet the annual demand of crops in the NCP area, approximately 20 billion cubic meters of groundwater is extracted annually, which consumes about 1675.21 MkWh of electricity. In order to meet the irrigation demand of crops during the whole life cycle of solar panels, the scale of solar panels was estimated based on the year when the solar panels were decayed by 20% after 25 years of operation. The monthly water consumption and the photovoltaic power generation are summarized in Table 4 below.

Table 4. Monthly Water Consumption and Photovoltaic Power Generation

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Water Consumption (Mm³) | 417 | 342 | 1632 | 2467 | 2277 | 3112 | 3188 | 2846 | 1101 | 1290 | 797 | 531 |
| Photovoltaic Power Generation (MkWh) | 266.34 | 292.97 | 410.91 | 458.62 | 460.47 | 373.97 | 326.89 | 340.65 | 320.54 | 330.85 | 253.11 | 228.62 |

### *3.3 Investment and Benefits*

Based on calculations, the power of photovoltaic pumping system is 2.0 MkWp and the initial annual investment is $7.00 billion, including $3.00 billion for PV module, $3.00 billion for the inverters and $1.00 billion for pumps. The operation cost is approximately $0.14 billion per year. In the 9th and 17th year, an additional investment of 3.12 is needed for renew the inverters. The annual investment of PV pump system in NCP is shown in figure 6. Assuming the social discount rate is 5%, the net present value of the 25-year investment is $12.47 billion.


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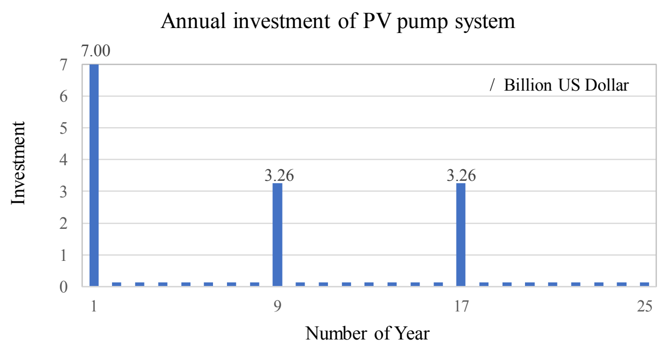

Fig 6. Annual Investment of PV pump system

The annual electricity consumption for crop irrigation in the NCP area is 1675.21 MkWh. After meeting the irrigation demand in the base year, the annual additional power generation is 2388.73 MkWh. The photovoltaic pumping system can be directly incorporated in the national grid. When the daily demand for irrigation is met, the remaining power can be sold directly to the national grid for profit so that the capital investment during construction can be recovered as soon as possible. According to national photovoltaic power station benchmarking tariff, the photovoltaic power is about $0.13/kWh. As a result, the photovoltaic pumping system can make a profit of at least $0.31 billion after meeting the annual irrigation demand. According to the full power generation (4063.94 MkWh/a), the net present value of electricity bill income is $7.81 billion. The net investment that deducts income from investment is $4.66 billion ($12.47 billion minus $7.81 billion). The most important benefit is $CO_2$ emission reduction. The less the thermal power is used, the less coal will be consumed, and the fewer greenhouse gases such as $CO_2$ are emitted. During 25 years of operation, the carbon dioxide emissions can be reduced by 113.6 Mt when using PV pump system instead of traditional irrigation system. It will cost $41 to reduce one ton of carbon emissions averagely.

## *4. CONCLUSIONS*

The solar energy is one of the primary clean energy sources in the world, which is abundant in most areas in China. Taking advantage of solar energy contributes to decreasing energy consumption and the emission of greenhouse gases such as $CO_2$ in the NCP area. Huge amount of electricity is consumed on crop irrigation each year. Compared to thermal-power generation which is the traditional method, the photovoltaic pumping system is not only conducive to energy saving and emission reduction but also creating economic benefits by utilizing surplus electricity based on satisfying irrigation demand.

## ACKNOWLEDGEMENT

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