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Application of Life Cycle Assessment to Policy Environmental Impact Assessment—A Clean Energy Action Plan Case Study in Qinghai Region

Yuan Li [1], Paul P. J. Gaffney [2], Fang Zhao [1], Xiangbo Xu [3] and Mingbo Zhang [1,*]

1 Environmental Development Center of the Ministry of Ecology and Environment, Beijing 100029, China; yuan.li19890228@hotmail.com (Y.L.); zhaofang@edcmep.org.cn (F.Z.)
2 Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; gafppj@igsnrr.ac.cn
3 Key Laboratory of Ecosystem Network Observation and Modelling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; ydxu.ccap@igsnrr.ac.cn
* Correspondence: zhangmingbo@edcmep.org.cn

Abstract: Due to significant political and environmental decisions regarding clean energy, rapid adoption of solar photovoltaic (PV), wind power, and hydropower is taking place. In China, policy environmental impact assessment (EIA) plays an important role in pollution prevention, while its practice is relatively limited due to insufficient methodologies and weak legislative enforcement. Taking the clean energy action plan (CEAP) in the Qinghai region as a case study, this study explored the application of life cycle assessment (LCA) to evaluate the potential environmental impacts imposed by the installment capability of 70,000 MW solar PV in pristine areas. It was found that the CO_2 emissions of solar PV are less than 3% of that of clean coal-fired power, while the emissions of pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter only account for about 18~27% of coal-fired power. Meanwhile, from the full life cycle perspective, 4.61 million tons of solar PV panel waste will be generated, and 4172 square kilometers of land surface area will be occupied. Herein, implications for policy are proposed, including (1) advance planning of local waste disposal capacity and processing facilities, (2) the integration of clean energy planning with legal ecological environment protection schemes, and (3) rational planning of upstream and downstream solar PV industries.

Keywords: policy environmental impact assessment; life cycle assessment; solar photovoltaic power

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1. Introduction

In order to effectively achieve carbon neutralization targets and sufficiently limit the negative impacts of human activities on the environment, China has been experiencing a critical energy transition, swiftly shifting away from the use of traditional fossil fuels towards cleaner renewable forms of energy [1–4]. Politically, the promotion and application of renewable energy have been integrated into the national energy strategy, which is not only a response to address environmental challenges, including a reduction in pollutant emissions and an enhancement of global leadership in the commitment to international climate agreements, but also a move to secure national energy independence and obtain economic development goals [5].

Substantial policies, strategies, and action plans have been formulated to obtain adequate renewable energy, especially in economically underdeveloped areas where traditional fuels are still widely used [6,7]. With the implementation of renewable energy policies, the installment of solar photovoltaic (PV), wind turbines, hydropower, and biomass energy is numerically simulated, and newly installed capacity of renewable energy in China has accounted for almost half of the world's total new renewable energy capacity in 2022 [8–10]. According to the International Renewable Energy Agency (IRENA), the installed capacity of renewable energy in China was 1.45×10^6 MW in 2023, accounting for approximately one-third of the world's total installed capacity (3.86×10^6 MW) [11–13]. Taking solar PV as an example, the worldwide capability has reached 1.42×10^6 MW in 2023 and is predicted to expand to over 2×10^6 MW in 2024, which is double that of 2022 (1.07×10^6 MW) [14]. In China, the capacity of solar PV energy reached 6.09×10^5 MW in 2023, experiencing a growth rate of 50% [15]. The installation of renewable energy in China is often distributed in remote areas with lower population density, where the ecological system is still pristine [16]. Qinghai, located at the juncture of the Qinghai–Tibet plateau and the northwestern desert region, plays a pivotal role in renewable energy development due to its rich solar and wind energy resources and the lack of electricity in higher altitude regions [17]. Qinghai authorities aspire to sustain 100% renewable energy generation, cultivating solar PV and wind turbine industries and manufacturing geothermal lithium battery production [18].

However, such renewable energy is not absolutely "clean", as the associated industrial supply chains produce significant emissions; processes such as raw material production and power station construction still consume unsustainable energy and produce emissions [19–25]. Given the drastic increasing interest in developing renewable energy, it is imperative to evaluate the potential environmental impacts of such energy systems and take necessary environmental precautions. Attempts have been made to assess the environmental impacts of renewable energy, including air pollution and carbon emissions, and some recommendations have been given to certain technology systems; however, the environmental impact assessment from the perspective of renewable energy policies is limited [26,27]. The unprecedented upsurge in renewable energy capability is the result of robust policy instruments. Approximately 20,000 renewable energy policies have been issued in China in the last 70 years [28]. Supportive and deliberate government policies thus play a crucial role in promoting the application of renewable energy, while research gaps remain in the environmental impact assessment of such policies to achieve better environmental outcomes. The environmental impact assessment (EIA) process has evolved as an important pollution prevention tool in the national environmental governance system, which is gauged to effectively reduce the adverse impacts of plans, projects, and programs (PPPs) [29]. Policy EIA can be a useful instrument to incorporate in addressing environmental issues, as it entails the assessment of proposed actions from the front side of the decision-making procedure. In the area of policy EIA, the progress in China is lagging behind in comparison with the US, Canada, Denmark, and Germany, where the environmental assessment of policies and even legislative proposals is required [30]. Article 14 of China's Environmental Protection Law (2014) clearly states, "In formulating economic and technological policies, the relevant departments under the State Council, and the people's governments of provinces, autonomous regions and municipalities shall fully consider the impacts on the environment". This is the legislative support for policy EIA in China, which can play an important role in the prevention of environmental pollution. Even though there remained no provisions for policy EIAs in China, exploration in this field has been carried out. To establish an effective methodological system of policy EIA suitable for China, some research has been conducted considering its necessity, theoretical basis, procedure indicators, principle content, basic framework, and public participation [31,32]. At present, China's policy EIA study mainly focuses on theoretical research, while the exploration of technical assessment methods and the exploration of practical cases are insufficient [33,34].

This can be attributed to the wide-ranging, regional, accumulative, and long life span characteristics of policies, which can also be affected by various changing factors during the policy implementation process. Attempts for case studies of policy EIA in China have been made for trade policy and agricultural and wastewater resource utilization policies [35–39]. However, most studies are inclined to macro-trend analysis and qualitative evaluation; the exploration of quantitative or semi-quantitative methodologies is limited, especially in relation to emerging issues like CO_2 emissions and ecological effects [40–42]. Considering that renewable energy policy may cause direct and indirect environmental impacts, EIA on renewable energy policy, especially in delicate ecological areas, is of the utmost urgency among economic and technological policies. At present, there are no standardized assessment procedures, and proper methodological systems specific to policy EIA need to be established via pilot practical exploration [43].

Life cycle assessment (LCA) is a scientific and quantitative methodology used to assess resource consumption and environmental impacts of a product (or activity) integrated with different industrial chains along the whole life cycle [44]. It has been proven to be an effective approach to improve process level management and reduce the emissions of pollutants and CO_2 [45,46]. Although LCA has been widely used to assess the impact of products, projects, and regional planning, its application to policy EIA is still limited [43,47–49]. The exploration of applying LCA to policy EIA is needed to systematically assess potential environmental impacts throughout the entire life cycle and propose effective strategies to mitigate adverse environmental impacts introduced by policy implementation.

The objective of this research is to evaluate the potential environmental impacts imposed by the clean energy action plan (CEAP) by utilizing LCA as a quantitative method (for policy EIA) in the Qinghai region where the largely pristine ecological environment is fragile. The CEAP aims to build the province as a national hub for the renewable energy industry, setting up goals of boosting the installed capacity of clean energy to 145.2 million kilowatts (AC) in 2030 from 36.4 million kilowatts (AC) in 2020, with solar PV capacity alone increasing to 70 million kilowatts (AC) from 15.8 million kilowatts (AC). With the significant number of renewable energy goals and the delicate ecological systems in the region, Qinghai presents a unique case for evaluating the renewable energy development strategies in northwest China within the constraints of policy EIA. Through the CEAP policy EIA case study, we aim to illustrate the environmental impacts of solar PV power in this pristine region (which is a special high-altitude ecological function area) from the point of how to proceed with EIAs on renewable-energy-based policies and how to promote the policy EIA practice. The framework of this paper is to (1) introduce the policy's main content and identify the scope and boundary of LCA systems; (2) evaluate the energy consumption, pollutants, and CO_2 emissions in comparison to traditional coal-fired power generation throughout the entire life cycle; (3) analyze the potential ecological environmental impacts imposed by the CEAP based on the LCA results; and (4) consider relevant policy implications to mitigate the adverse environmental impacts. This study is of vital importance for source pollution prevention in clean-energy-relevant policies, providing useful practice for policy EIA in China and enhancing the methodologies in policy EIA.

2. Materials and Methods

2.1. Policy Overview and Local Environmental Conditions

The CEAP aims to increase the proportion of clean energy in the Qinghai region to 100% by 2030. The total power generation will increase (by a factor of 2.6) from 94.8 billion kilowatt hours to 246 billion kilowatt hours. The inter-provincial transmission capacity (AC) will develop 5.3-fold, from 27.3 billion kilowatt hours to 145 billion kilowatt hours.

The installment of photovoltaic capacity will increase to 70 million kilowatts (AC) from 15.8 million kilowatts (AC), a 4.4-fold increase. Solar PV is taken as the most effective solar energy utilization method, which is vigorously promoted by local government and is expected to be the primary energy source of the region [50,51]. The policy will apply in areas with a mean elevation over 4000 m above sea level, extending over 729,119 square kilometers. This region is also the source of three important Asian rivers, the Yangtze, Yellow, and Lancang, harboring unique global biological resources. It is, therefore, a special ecological function area, where the ecosystem is both fragile and of outstanding conservation value [52]. Under the dual influence of climate change and human activities, the structure and function of its ecosystem have undergone serious challenges [53]. This study will systematically evaluate the environmental impacts of the most applied clean energy solar PV power imposed by the CEAP in such a pristine and fragile ecological environment.

2.2. Life Cycle Assessment Analysis

In this study, the conventional LCA procedure was conducted to evaluate the potential environmental impacts of the CEAP following the methodology described in ISO14040:2006 and GB/T24040 standards [54–56], which comprises goal and scope definition, life cycle inventory analysis (LCI analysis), life cycle inventory assessment (LCIA), and results interpretation, as shown in Figure 1. Following the LCA framework, the system boundaries were first set up. In the LCA analysis, environmental indicators, i.e., energy consumption, pollutants, and CO_2 emissions, were calculated for the electricity generated by solar PV in comparison to coal-fired power based on the data collected from the literature and field surveys [57–62]. The functional unit is defined as 1 kW·h of electricity. Finally, the environmental impacts of solar PV power compared to coal-fired power were assessed and interpreted by the CEAP using the LCIA results.

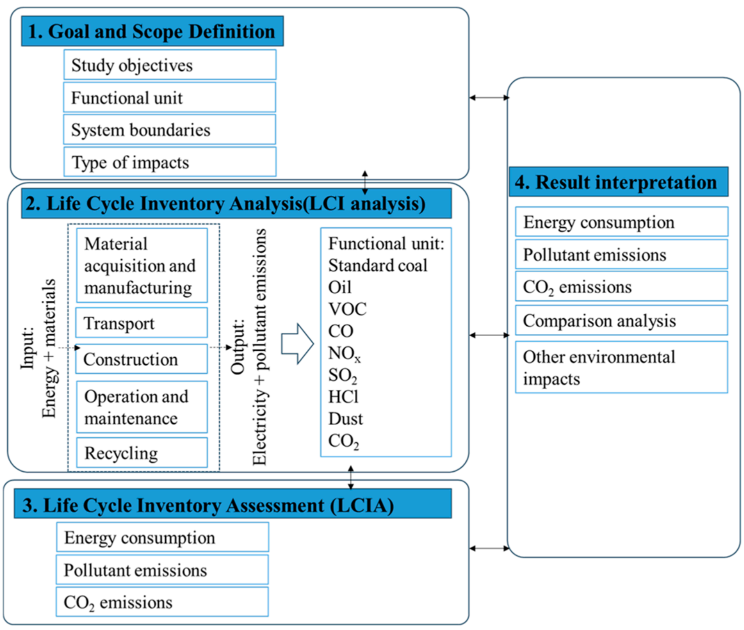

Figure 1. LCA framework flowchart.

2.2.1. Goal and Scope Definition

The goal and scope definition are used to understand the unit processes and specify the boundaries of energy and material inputs to the power system. A solar PV power system generally consists of arrays and combinations of PV panels, a charge controller (DC to DC), an inverter (DC to AC), a power meter, a breaker, and batteries [63]. The solar PV panels generate DC, which is regulated by the charge controller and stored in batteries, and it is then inverted to AC through the inverter for AC loads or directly supporting DC loads [26]. This study took the most widely applied solar PV technology, polycrystalline silicon cells, as the research subject, and the system boundaries are depicted in Figure 2 [64–66].

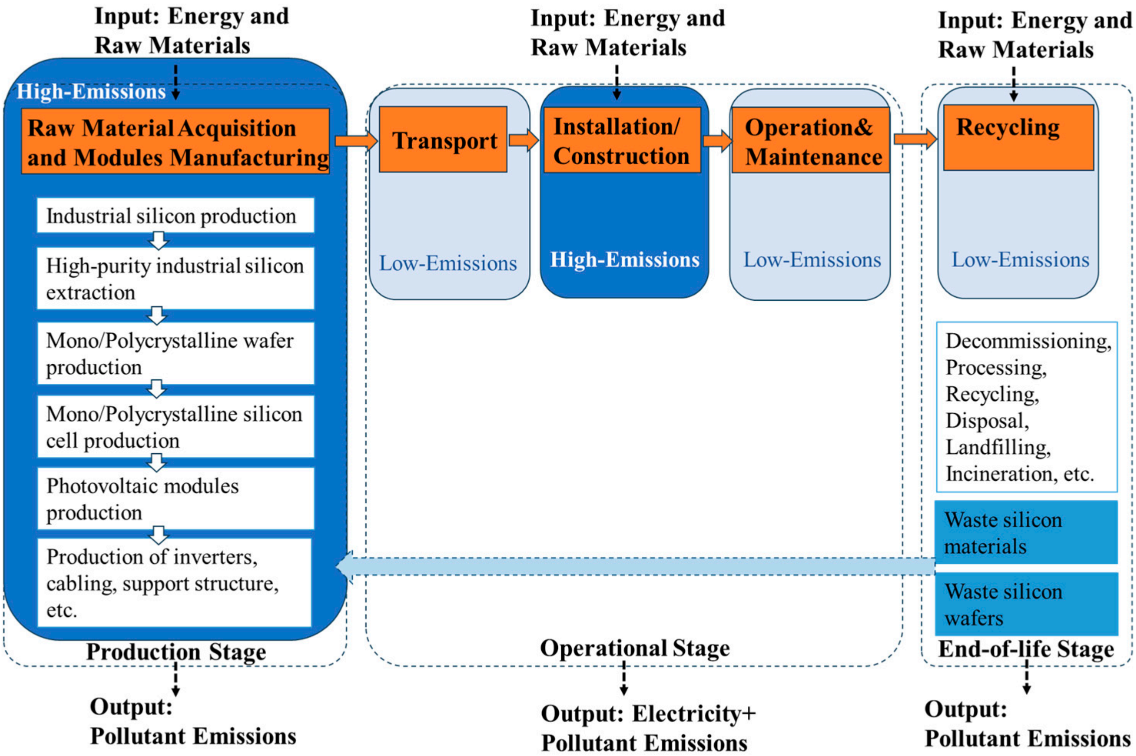

Figure 2. The life cycle of solar PV polysilicon power system boundaries. Note: the dashed line represents the system boundary, raw materials and energy are the inputs of this system, and pollutant emissions and electricity are the outputs.

The whole life cycle can be divided into three stages: (1) the production stage, referring to raw material acquisition and module manufacturing; (2) the operational stage, referring to transport, construction, and operation; and (3) the end-of-life stage, referring to equipment recycling. The core part of the life cycle is the manufacturing of monocrystalline/polycrystalline silicon and silicon cells. The emissions at transport, operation, and maintenance are less than 10% of the full life cycle, and most enterprises currently reuse waste silicon materials and silicon wafers [60,67]. It has been revealed that the recovery rate of the PV module waste materials (such as glass, silicon, aluminum, steel, copper, tellurium, and lead) ranged from 85% to 98%, and the recoveries of steel, copper, tellurium, and lead can be over 95% [68]. One case study has found that the manufacturing of solar PV modules accounted for over 80% of total energy consumption and emissions in the full life cycle, while metal recycling and transport stages distributed 7.5% and 0.5%, respectively [60,67]. As the share of the recycling stage is low and some scholars have undertaken research considering the life cycle assessment of PV modules specifically during the recycling process [69,70], the LCA evaluation in this study mainly focused on the processes of raw materials acquisition, module manufacturing, and the construction of power stations. This study considers a functional unit, generating 1 kW·h electricity, for which the mass of solar PV panels corresponded to ~90 kg/kW [71].

To better evaluate the environmental impacts of the CEAP, this study took coal-fired systems, which are the traditional applied energy generating systems in China, for comparison. The system boundaries of the coal-fired power systems are presented in Figure 3. Most emissions occur during the processes of power plant construction, operation and maintenance, and decommissioning, which are specifically analyzed in the LCA evaluation.

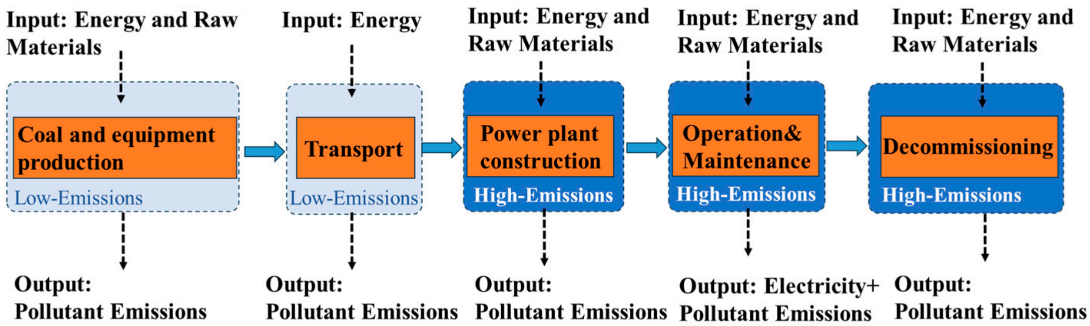

Figure 3. The full life cycle of coal-fired power system boundaries.

2.2.2. Life Cycle Inventory Analysis (LCI Analysis)

During this step, the environmental inventories were classified and characterized considering energy consumption and the emission of pollutants along with CO_2 emissions [72]. LCI analysis for key commercial PV technologies, such as functional units, life expectancy, and environmental effects, were compiled using data from the International Energy Agency (IEA), the literature, and regional surveys [57–62]. Across the life cycle, there are two main components of energy production: (1) material production and (2) direct energy inputs. To calculate the consumption of energy during the production of materials, we used Equation (1) as follows:

$$CM = \sum_i^n CM_i = \sum_i^n \sum_j^m CQ_{ij} \times CF_j \quad (1)$$

where CM represents the total energy consumption from material production over the whole life cycle, CM_i is the energy consumption of the life cycle stage i, CQ_{ij} is the raw material quantity (type j) consumed in the life cycle stage i,; and CF_j is the energy consumption coefficient for raw material type j (kilograms of standard coal equivalent per ton, kg_{ce}/t).

Furthermore, we calculated direct energy inputs, which are an integral component of energy consumption associated with power generation across the full life cycle, by converting them into the standard coal equivalent using Equation (2) as follows:

$$CE = \sum_i^n CE_i = \sum_i^n \sum_r^m CE_{ir} \times CV_r \quad (2)$$

where CE is the amount of energy consumed from direct energy inputs over the entire life cycle, CE_i is the direct energy inputs at the life cycle stage i, CE_{ir} is the quantity of energy (type r) at the life cycle stage i, and CV_r is the factor for conversion from physical units of fuel type r into the coal equivalent.

Therefore, the total energy consumption of solar PV power is calculated following Equation (3).

$$C = CM + CE \quad (3)$$

Utilizing the energy consumption formula (Equation (1)), we can calculate various pollutant emissions following Equation (4).

$$EM_k = \sum_i^n EM_{ik} = \sum_i^n \sum_j^m CQ_{ij} \times EF_{jk} \quad (4)$$

where EM_k is the quantity of pollutant type k produced over the whole life cycle, EM_{ik} is the quantity of pollutant k produced in the life cycle stage i, CQ_{ij} is the quantity of raw material (type j) consumed during the life cycle stage i, and EF_{jk} is the emission factor associated with pollutant type k produced by raw material j.

Additionally, the direct energy inputs from each life cycle process also produce emissions. We calculated emissions associated with direct energy inputs using Equation (5).

$$EE_k = \sum_i^n EE_{ki} = \sum_i^n \sum_r^m CE_{ir} \times CV_{rk} \quad (5)$$

where EE_k is the quantity of the pollutant (type k) produced by direct energy inputs over the whole life cycle, EE_{ki} is the quantity of the pollutant (type k) produced in the life cycle stage i, CE_{ir} is the energy quantity (type r) consumed in the life cycle stage i, and CV_{rk} is the emission coefficient of pollutant type k produced by energy type r.

Therefore, the total quantity of pollutant emissions from solar PV power was calculated based on Equation (6) as follows:

$$E_k = EM_k + EE_k \quad (6)$$

The calculation of solar PV panel waste was based on Equations (7) and (8) as follows:

$$m_r = \frac{M_r}{C} \times C_{CEAP} \quad (7)$$

where m_r is the amount of solar PV wastes produced by the implication of the CEAP under the regular loss scenario, M_r is the amount of solar PV wastes generated in China in 2050 based on the regular loss scenario, C is the cumulative installed capacity of solar PV in 2020, and C_{CEAP} is the cumulative installed capacity of solar PV based on the goals of the CEAP.

$$m_e = \frac{M_e}{C} \times C_{CEAP} \quad (8)$$

where m_e is the amount of solar PV wastes produced by the implication of the CEAP under the early loss scenario, M_e is the amount of solar PV wastes generated in China in 2050 based on the early loss scenario, C is the cumulative installed capacity of solar PV in 2020, and C_{CEAP} is the cumulative installed capacity of solar PV based on the goals of CEAP.

Solar PV systems are installed at the optimum azimuth and slant angle, at which the system can obtain maximum solar power and reach peak-rated annual generation. Annual power generation (APG) was obtained by Equation (9) as follows:

$$APG = PRH \times C \times SE \quad (9)$$

where PRH is the annual peak radiation hours of the photovoltaic module, C is the solar power capacity of the PV system, and SE is the system efficiency of grid-connected PV systems, which is affected by a combination of the efficiency of the PV array, the temperature loss influence factor of the PV system, the efficiency of the PV grid-connected inverter, and the dust shielding effect factor of the wide PV square. The PRH value used in this study is 80% [73].

An average CO_2 emission of 890 g/kW·h of the (Chinese) national grid is applied for the calculation above [74]. In 2022~2023, the largest source of the national energy grid—coal—accounted for ~61% of the total energy supply, which has decreased compared to past times, indicating that the average CO_2 emissions of the national grid are decreasing over time [75,76]. As China is shifting toward more renewable sources, the average CO_2 emission will continue to drop in the future when more renewable energy is applied to the national grid.

3. Results

3.1. Life Cycle Inventory Assessment (LCIA) of Solar Photovoltaic (PV) Power Generation

This section aims to calculate energy consumption, pollutants, and CO_2 emissions for generating 1 kW·h of electricity produced by 1 MW of solar polysilicon PV power. If the solar PV cells are installed at the best local inclination angle, the local annual sunshine utilization time is 3000 h, and the average annual power generated is 1.44×10^6 kW·h. Taking the life span of solar PV power as 25 years, electricity generated over the full lifetime is 3.59×10^7 kW·h. Distributing the total electricity generated by each process in the full life cycle of the solar polysilicon PV system, the energy consumption, pollutants, and CO_2 emissions for generating every kW·h was calculated, as shown in Table 1.

Table 1. Energy consumption, pollutants, and CO_2 emissions of the solar PV polysilicon system; data are compiled from References [57–62].

Category	Stage	Production Stage (kg/kW·h)					Installation (kg/kW·h)	Total (kg/kW·h)
	Processes	Industrial Silicon Production	High-Purity Polysilicon Extraction	Polycrystalline Wafer Production	Polycrystalline Silicon Cell Production	Photovoltaic Module Production	Power Plant Construction	
Energy consumption [1]	Standard coal	1.29×10^{-3}	5.56×10^{-3}	3.83×10^{-4}	5.84×10^{-5}	1.27×10^{-3}	1.75×10^{-4}	8.73×10^{-3}
	Oil	/	/	/	/	9.88×10^{-6}	8.75×10^{-6}	1.86×10^{-5}
Pollutant and CO_2 emissions	VOC	8.55×10^{-9}	8.84×10^{-8}	1.53×10^{-9}	4.51×10^{-9}	6.10×10^{-10}	1.01×10^{-9}	1.05×10^{-7}
	CO	4.78×10^{-5}	7.59×10^{-7}	6.03×10^{-8}	1.76×10^{-7}	2.39×10^{-8}	3.99×10^{-8}	4.89×10^{-5}
	NO_X	7.78×10^{-6}	4.26×10^{-5}	3.37×10^{-6}	9.88×10^{-6}	1.33×10^{-6}	2.22×10^{-6}	6.71×10^{-5}
	SO_2	2.24×10^{-5}	4.61×10^{-5}	3.65×10^{-6}	1.07×10^{-5}	1.44×10^{-6}	2.41×10^{-6}	8.67×10^{-5}
	HCl	4.91×10^{-7}	5.98×10^{-7}	0	1.36×10^{-6}	/	/	2.45×10^{-6}
	N_2O	1.05×10^{-8}	1.81×10^{-8}	1.44×10^{-9}	4.21×10^{-9}	5.69×10^{-10}	9.53×10^{-10}	3.58×10^{-8}
	CO_2	3.70×10^{-3}	1.53×10^{-2}	1.20×10^{-3}	3.54×10^{-3}	4.78×10^{-4}	7.98×10^{-4}	2.50×10^{-2}
	COD	/	2.57×10^{-5}	1.49×10^{-5}	5.87×10^{-6}	4.65×10^{-6}	/	5.11×10^{-5}
	Solid wastes	/	4.22×10^{-6}	1.74×10^{-6}	8.75×10^{-7}	7.31×10^{-7}	/	7.57×10^{-6}
	Particulate matter	4.71×10^{-5}	6.92×10^{-6}	5.48×10^{-7}	1.61×10^{-6}	2.18×10^{-7}	3.61×10^{-7}	5.67×10^{-5}

[1] Energy consumption calculated as kg of standard coal and oil required to produce 1 kW·h of electricity.

According to the LCIA results, for 1 kW·h of electricity produced by solar PV power, the CO_2 emissions of the full life cycle were 2.5×10^{-2} kg, among which the high-purity polysilicon extraction process was 1.53×10^{-2} kg, accounting for 61%. The CO_2 emissions of industrial silicon and polysilicon module production were 3.7×10^{-3} and 3.54×10^{-3} kg, respectively, approximately 14% of the full life cycle CO_2 emissions. The CO_2 emissions (per kW·h) for solar PV power in the Qinghai region were slightly lower than those of some European developed countries, such as Spain (Barcelona; 3.7×10^{-2} kg), Italy (Palermo; 3.26×10^{-2} kg), and The Netherlands (Utrecht; 3.2×10^{-2} kg), which can be attributed to the higher ground solar radiation in the studied (high-altitude) area [77–79]. The solar radiation intensity in Qinghai province is 4.71 kW·h/(m^2·d), which confirms the effectiveness of implementing solar energy utilization systems here [80]. We suggest that this is one factor resulting in lower CO_2 emissions compared to the referenced European countries, where solar radiation intensities are lower (e.g., central Europe ~3.04 kW·h/(m^2·d)) [81]. Considering other parts of the world, the CO_2 emissions of distributed solar PV systems installed in New York State, USA, were found to range from 2.5×10^{-2} to 8.9×10^{-2} g/kW·h with a mean of 4.6×10^{-2} g/kW·h [82]. This figure is similar to the calculated (average) CO_2 emissions from solar PV systems in Pakistan of 4.2×10^{-2} kg/kW·h [83]. Thus, the CO_2 emissions from solar PV in Qinghai are comparatively low, which is likely (in addition to high solar radiation intensity) due to technological improvements and the use of efficient silicon panel materials in the CEAP, along with the energy mix of the power grid. There are four different solar technologies dominant on the market, which are crystalline silicon (mono and poly), amorphous silicon, cadmium tellurium cells (CdTes), and Copper Indium Gallium Selenium cells (CIGS). Among them, the carbon emissions of CdTe and CIGS technologies, which are more state of the art, have been found to be at the same level or slightly lower than those of the other two types [84]. At present, silicon-based solar panels have been found to dominate the market (92%), while CdTe and CIGS technology have taken a share of 7%, which may increase over time [85,86]. Another study has reported that CO_2 emissions from a solar PV plant in Aotearoa (New Zealand) were 26.2~40.4 g/kW·h, where a transport process from manufacture in China to New Zealand has been included [87].

3.2. Life Cycle Inventory Assessment (LCIA) of Coal-Fired Power

Utilizing LCIA enables a consistent comparison between solar PV power and coal-fired power systems that can perform the same function. Following the current commercial applications of coal-fired power technology in China, we utilized a subcritical clean coal-fired power plant with an installment capacity of 300 MW as the research objective, in which the net efficiency was 36.5% and the energy consumption rate was 6.5% [88,89]. The removal efficiency of particulate matter, desulfurization, and denitrification was 99%, 90%, and 75%, respectively. Taking the service life span of clean coal-fired power plants as 30 years, the LCIA of clean coal-fired power systems was calculated (Table 2).

Table 2. Energy consumption, pollutants, and CO_2 emissions of coal-fired power; data compiled from References [59,72,88].

Category	Processes	Construction Stage (kg/kW·h)	Operation Stage (kg/kW·h)	Decommission Stage (kg/kW·h)	Total (kg/kW·h)
Energy consumption [1]	Standard coal	6.18×10^{-4}	3.20×10^{-1}	2.24×10^{-7}	3.21×10^{-1}
	Oil	1.10×10^{-4}	3.75×10^{-3}	5.52×10^{-6}	3.87×10^{-3}
Pollutants and CO_2 emissions	Natural gas	2.31×10^{-5}	1.93×10^{-7}	4.43×10^{-12}	2.33×10^{-5}
	CO	2.73×10^{-5}	7.88×10^{-1}	9.17×10^{-8}	7.88×10^{-1}
	NO_x	5.40×10^{-6}	3.50×10^{-4}	2.87×10^{-8}	3.55×10^{-4}
	SO_2	1.74×10^{-4}	1.75×10^{-4}	$1.27E \times 10^{-8}$	3.49×10^{-4}
	HCl	2.11×10^{-7}	/	/	2.11×10^{-7}
	CO_2	2.73×10^{-3}	8.60×10^{-1}	8.89×10^{-6}	8.63×10^{-1}
	COD	3.01×10^{-7}	8.84×10^{-7}	1.20×10^{-11}	1.19×10^{-6}
	Solid wastes	7.03×10^{-4}	1.36×10^{-1}	/	1.37×10^{-1}
	Particulate matter	1.42×10^{-4}	7.00×10^{-5}	/	2.12×10^{-4}

[1] Energy consumption calculated as kg of standard coal and oil required to produce 1 kW·h of electricity.

4. Discussion

Our study demonstrates the ability of LCA to evaluate policy EIA, taking the case of the Qinghai CEAP, where potential environmental impacts of the policy are assessed. Here, we apply LCA to evaluate the impact of a 70,000 MW solar PV installation by evaluating energy consumption, potential ecological impacts, and other implications of the CEAP policy. Further, the environmental impacts of solar PV systems were compared to that of coal-fired power systems (which at present account for 61% of the electricity generation in China [75,76]). The following sections discuss the LCA of solar PV power generation, coal-powered systems, and then the CEAP itself, followed by considering its environmental and ecological impacts. Finally, policy implications and suggestions for reducing environmental impacts are given in this section.

4.1. Life Cycle Analysis (LCA) of Solar Photovoltaic (PV) Power Generation

The proportion of energy consumption, pollutants, and CO_2 emissions in different processes of solar PV power generation is shown in Figure 4. The order of energy consumption in the full life cycle of solar PV power is high-purity polysilicon extraction > industrial silicon production > photovoltaic module production > polycrystalline wafer production > power plant construction > polycrystalline silicon cell production. The energy consumption of the high-purity polysilicon extraction process accounts for more than 50% of the full life cycle, while the highest portion of pollutant discharge has been found during this process. At present, the energy consumption and carbon emissions of the high-purity polysilicon extraction process in China are relatively high compared to those of European countries [90], which may be attributed to the production techniques applied. For industrial silicon production, the carbon–thermal reduction method was the most commonly used technique in China, which has high energy consumption and carbon emissions [91]. Therefore, upgrading relevant production processes and pollutant treatment technologies during high-purity polysilicon extraction and industrial silicon production are key for mitigating pollutant and CO_2 emissions for the life cycle of solar PV power.

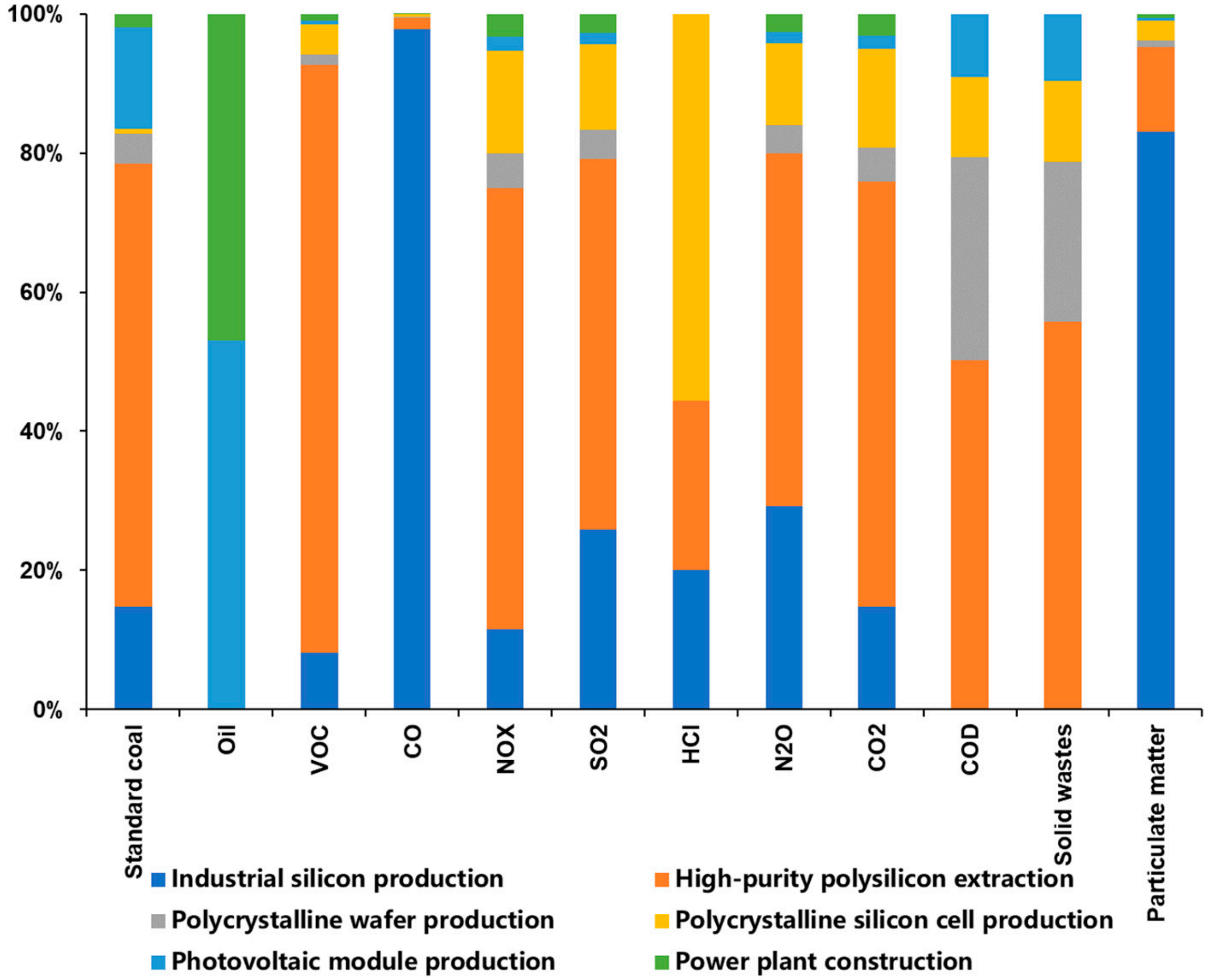

Figure 4. The proportion of energy consumption, pollutants, and CO_2 emissions at different processes of solar PV power during the full life cycle.

4.2. Life Cycle Analysis (LCA) Comparison with Coal-Fired Power

Based on the LCIA results of solar PV power (Table 1) and clean coal-fired power (Table 2), the energy consumption (standard coal and oil) of solar PV power was 2.7% of that of coal-fired power, and CO_2 emissions of solar PV power were 2.9% of those from coal-fired power. The emission of pollutants like sulfur dioxide, nitrogen oxides, and particulate matter from solar PV power was 24.8%, 18.9%, and 26.8% of that of coal-fired power, respectively. For every kW·h of electricity generated, solar PV power can save 312 g of standard coal and reduce the emissions of CO_2, sulfur dioxide, nitrogen oxide, and particulate matter by 838 g, 0.262 g, 0.288 g, and 0.212 g, respectively, compared to the clean coal-fired power system (Table 3).

Table 3. The LCIA comparison between solar PV power and coal-fired power.

Emissions per Unit of Electricity Generation (g/kW·h)	Standard Coal	NOx	SO_2	CO_2	Particulate Matter	HCl
The whole life cycle of coal-fired power	3.21×10^2	0.36	0.35	8.63×10^2	0.21	2.1×10^{-4}
The whole life cycle of solar PV power	8.73	6.71×10^{-2}	8.67×10^{-2}	25	5.67×10^{-2}	2.45×10^{-3}
Emission reduction in solar PV power compared to coal-fired power	3.12×10^2	0.29	0.26	8.38×10^2	0.16	-2.24×10^{-3}
The ratio of solar PV power to coal-fired power	2.72%	18.90%	24.84%	2.90%	26.75%	1166.67%

4.3. The Application of Life Cycle Analysis (LCA) to Policy Environmental Impact Assessment (EIA) (Case Study)

4.3.1. LCIA of the Clean Energy Action Plan

Following the scope of the CEAP for Qinghai province, 70,000 MW (AC) of solar PV cells are targeted to be installed by 2030. The theoretical electricity generating capacity can be calculated as the multiplication product of annual radiation hours of the solar PV module bevel peak (h), the efficiency of the solar PV power systems, and the installation capacity (MWp). The annual radiation hours of the solar PV module level peak in Xining (the provincial capital city) were 2670.56 h. Accordingly, the theoretical electricity generating capacity of the installed photovoltaic power (assuming that the 70,000 MW target capacity, AC, equals 77,000 MW, DC) was 1.64×10^8 MW·h/year. Considering that the aging of polycrystalline silicon cells can lead to a decrease in battery efficiencies over time, a battery efficiency attenuation coefficient of 3% was taken for the first year, and an annual battery efficiency attenuation coefficient of 0.7% for the rest of the life span [92]. Over the whole life span (25 years), the total electricity generated by the installed solar PV power was about 3.7×10^9 MW·h (correspondingly 1.48×10^8 MW·h/year).

Based on the LCIA results of solar PV systems, the energy consumption, pollutants, and GHG emissions imposed by the CEAP (for the Qinghai region) are presented in Table 4. For the full life cycle, the emissions of sulfur dioxide, nitrogen oxides, and particulate matter were 1.28×10^4, 9.94×10^3, and 8.39×10^3 tons per year, respectively.

Table 4. Energy consumption, pollutants, and CO_2 emissions of the solar PV polysilicon system imposed by the CEAP (annual average).

Category	Processes (ton/yr)	Industrial Silicon Production	High-Purity Polysilicon Extraction	Polycrystalline Wafer Production	Polycrystalline Silicon Cell Production	Photovoltaic Module Production	Power Plant Construction	Total
Energy consumption [1]	Standard coal	1.91×10^5	8.22×10^5	5.67×10^4	8.65×10^3	1.87×10^5	2.59×10^4	1.29×10^6
	Oil	/	/	/	/	1.46×10^4	1.29×10^3	2.76×10^3
Pollutants and CO_2 emissions	VOC	1	1.3×10^1	/	1	/	/	1.5×10^1
	CO	7.08×10^3	1.12×10^2	9	2.6×10^1	4	6	8.24×10^3
	NO_x	1.15×10^3	6.29×10^3	4.99×10^2	1.46×10^3	1.98×10^2	3.28×10^2	9.94×10^3
	SO_2	3.32×10^3	6.83×10^3	5.4×10^2	1.58×10^3	2.13×10^2	3.57×10^2	1.28×10^4
	HCl	7.3×10^1	8.9×10^1	/	2.01×10^2	/	/	3.63×10^2
	N_2O	2	3	/	1	/	/	5
	CO_2	5.48×10^5	2.26×10^6	1.78×10^5	5.23×10^5	7.08×10^4	1.18×10^5	3.69×10^6
	COD	/	3.79×10^3	2.21×10^3	8.68×10^2	6.88×10^2	/	7.56×10^3
	Solid wastes	/	6.25×10^2	2.58×10^2	1.3×10^2	1.08×10^2	/	1.12×10^3
	Particulate matter	6.97×10^3	1.04×10^3	8.1×10^1	2.39×10^2	3.2×10^1	5.3×10^1	8.39×10^3

[1] Energy consumption calculated as tons/yr of standard coal and oil required to produce the electricity target imposed by the CEAP.

4.3.2. Comparison to Coal-Fired Power

To generate the same amount of electricity produced by the solar PV system during the full life cycle (3.7×10^9 MW·h), the energy consumption, pollutants, and CO_2 emissions by the coal-fired power system are presented in Table 5. The emissions of pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter during the whole life cycle were 4.31×10^4, 4.38×10^4, and 2.62×10^4 tons per year, which were three times higher than that of solar PV systems. We note here that the decommissioning process (of coal-fired power) has not been analyzed in this section, as the emissions in this process are relatively low (Table 2).

Table 5. The energy consumption, pollutants, and CO_2 emissions of the whole life cycle for coal-fired power (annual average).

Category	Processes (ton/yr)	Construction Stage	Operation Stage	Total
Energy consumption [1]	Standard coal	7.62×10^4	3.95×10^7	3.95×10^7
	Oil	1.35×10^4	4.63×10^5	4.77×10^5
Pollutants and CO_2 emissions	Natural gas	2.85×10^3	2.4×10^1	2.87×10^3
	CO	3.37×10^3	9.72×10^7	9.72×10^7
	NO_x	6.66×10^2	4.32×10^4	4.38×10^4
	SO_2	2.15×10^4	2.16×10^4	4.31×10^4
	HCl	2.6×10^1	-	2.6×10^1
	CO_2	3.37×10^5	1.06×10^8	1.06×10^8
	COD	3.7×10^1	1.09×10^2	1.46×10^2
	Solid wastes	8.67×10^4	1.68×10^7	1.69×10^7
	Particulate matter	1.75×10^4	8.63×10^3	2.62×10^4

[1] Energy consumption calculated as tons/yr of standard coal and oil required to produce the electricity target imposed by the CEAP.

Based on the LCIA results of solar PV power compared to coal-fired power, the implementation of the CEAP can bring significant environmental benefits. The installment of 70,000 MW of solar PV power will reduce the use of standard coal by 4.62×10^4 k tons per year and decrease the emissions of CO_2, particulate matter, sulfur dioxide, and nitrogen oxide by 1.24×10^5, 2.3×10, 3.88×10, and 4.27×10 k tons/yr, respectively (Table 6).

Table 6. The reduction in energy consumption, pollutants, and GHG emissions for solar PV power imposed by the CEAP.

Processes (k ton/yr)	Standard Coal	Oil	CO	NO_x	SO_2	CO_2	Particulate Matter
Reduction	4.62×10^4	5.69×10^2	1.17×10^5	4.27×10^1	3.88×10^1	1.24×10^5	2.3×10^1

4.3.3. Further Assessment of Potential Ecological Environmental Impacts Imposed by the CEAP

The LCIA results suggested that implementation of the CEAP will have positive environmental impacts by reducing energy consumption, pollutants, and CO_2 emissions. However, our study also aimed to identify potential ecological impacts resulting from the policy. Therefore, to further evaluate the potential environmental impacts imposed by the CEAP, this section considers local environmental conditions to assess the potential effects on the ecological system, environmental quality, and climate change from a full life cycle perspective.

The ecological and environmental impacts of solar PV power are complex with many interacting mechanisms [93]. On one side, the installment of solar PV power has been found to play an important role in wind reduction, humidification, and reduction in wind-blown sand, while helping to regulate the local microclimate due to its occlusion effects [94]. On the other hand, the construction of solar PV power can also affect the soil's physical–chemical properties and temperature, owing to the surface disturbance [95]. Generally, solar PV power is a low-density form of clean energy, consisting of different functional areas. The land occupied by different functional areas followed the order of area of solar panels along with the station road (97.85%) > area of the fence boundary (1.56%) > management and control area (0.35%) > living area of construction workers (0.24%). A local key solar PV project (2000 MW) occupied 119.3 km^2, corresponding to a density coefficient of 59.6 km^2/GW. Accordingly, the total solar PV land occupation area of the CEAP will increase from 940 km^2 to 4172 km^2 by 2030 (Figure 5). The density coefficient is higher than reported values (20~32 km^2/GW) in other research, as the planned area in the region is combined with sand fixation areas and special vegetation protection areas, where it is not possible to install the solar PV panels intensively [96].

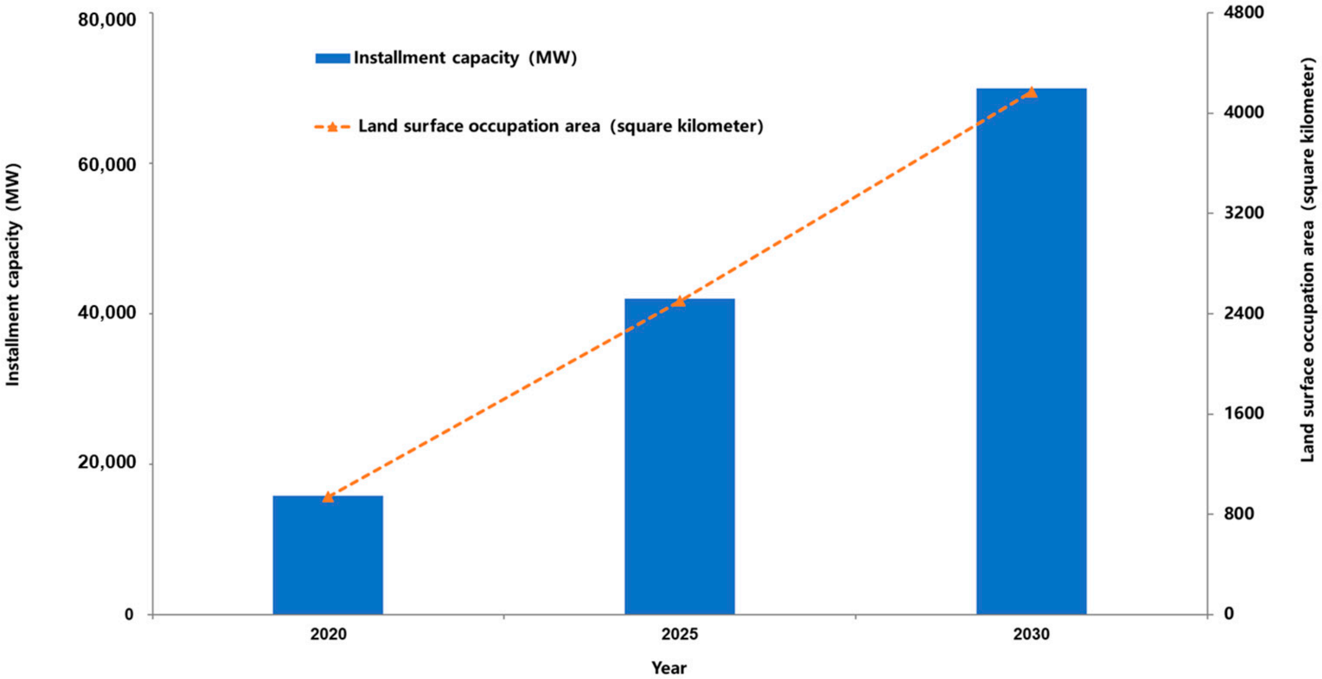

Figure 5. The land occupation area of solar PV power imposed by the CEAP.

Although solar PV panels are designed to withstand extreme conditions, such as high winds, large hailstones, and extreme temperatures [97,98], it has been reported that during high-temperature periods, power generation may be reduced by up to 30% [99]. There have been some reports that the expected 25-year life span for solar PV panels can be shortened due to extreme climate conditions, while poor maintenance is another factor that can reduce the solar PV life span [100]. Solar PV-related solid waste is created at the end of life (EOL) of PV power generation, which may occur sooner under circumstances where panels are scrapped early due to extreme climate conditions. Even though silicon-based materials are often recycled, the processing capability and treatment facilities for discarded PV panels in the CEAP region may need to be improved.

Based on the initial assumptions in the LCA analysis, ~90 tons of solar PV panels can be expected for each MW. We acknowledge that our estimate of waste volumes may be slightly conservative, as the mass of panels may decrease over time. However, over the CEAP timescale from 2020 to 2030 (when the installation is complete), very limited changes in panel power-to-weight ratios will likely occur [101]. Instead, we conducted the calculation for solar PV panel wastes for two scenarios (early loss and regular loss) based on an approach used by the International Renewable Energy Agency (IRENA) [101]. Using the IRENA PV panel waste model, cumulative solar PV panel waste of between 1.7 and 8 million tons by 2030 and 60–78 million tons by 2050 was estimated [101]. The IRENA model converts installed capacity (GW) to panel mass (tons) to calculate EOL waste quantities, while taking into account that panels become more powerful and lighter over time by applying a dynamic weight–power ratio correction. The upper estimates also include waste during panel production, transportation, installation, and operation by considering probable estimates of losses and failure during the life cycle (early loss scenario), while the lower estimate is based on installed capacity and life span (regular loss scenario). In China alone, a cumulative total of between 13.5 and 20 million tons of cumulative solar PV panel waste may be generated by 2050 [101], which corresponds to a cumulative installed capacity of 205 GW [102,103]. In our study of the Qinghai CEAP, in which the installment capacity goal of solar PV is 70,000 MW in 2030, we estimate that a cumulative total of 6.83 million tons of solar PV panel waste will be generated in the early loss scenario (97.6 tons/MW) and 4.61 million tons of solar PV panel waste will be generated in the regular loss scenario (65.9 tons/MW), as shown in Figure 6. The waste coefficient from the regular loss scenario is consistent with the results from other research (which correspondingly applied the coefficient between the installed capacity of a PV power station and the quantity of waste generated), estimated at 60–75 tons/MW [104,105].

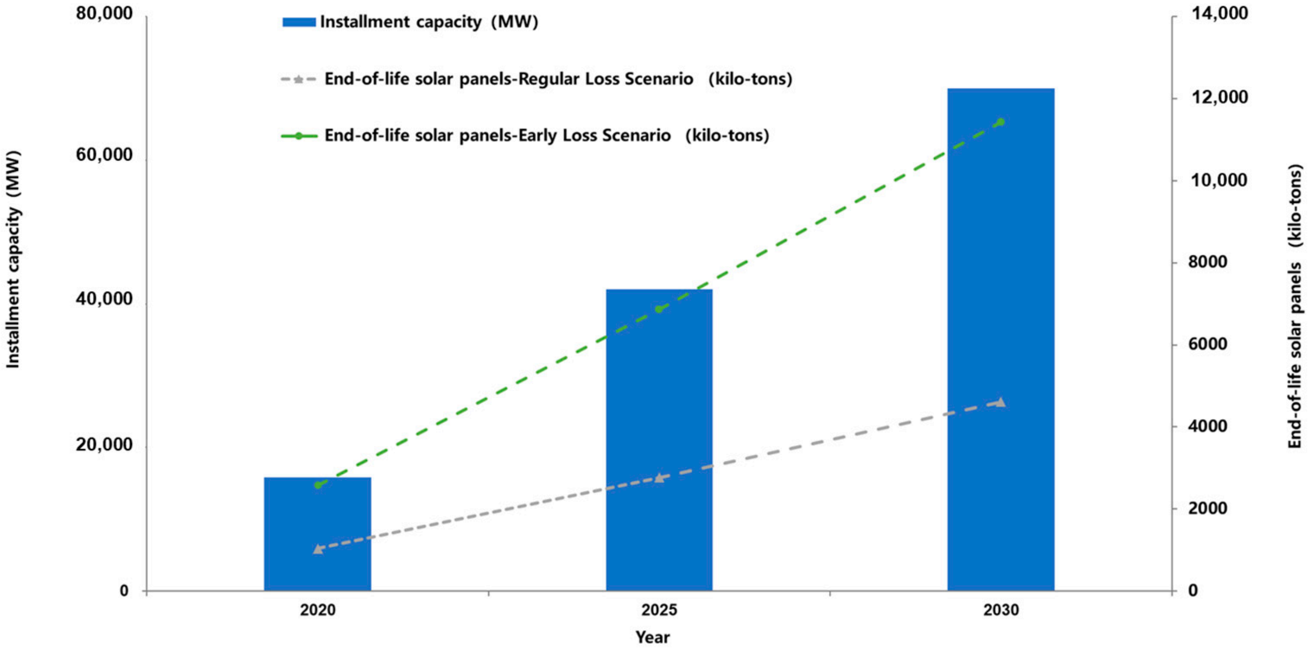

Figure 6. The amount of EOL solar PV panels imposed by the CEAP.

Solar PV panels contain zinc, lead, mercury, arsenic, cadmium, selenium, indium, gallium, fluorine, and other elements, which pose environmental risks if they are not processed and disposed of properly [106]. In China, there is a lack of regulations relating to solar panel recycling compared to other countries that have adopted solar panel waste directives, in which the producers and importers have to accept responsibility for the recycling and disposal of EOL solar PV materials [107]. It is, therefore, necessary to enhance recycling in China, which has been shown to significantly reduce pollutant and CO_2 emissions (15–40% and 25% reductions, respectively) while reducing mineral resource scarcity by ~90% [71].

Finally, we consider the potential reduction in CO_2 emissions from the CEAP in comparison to coal-fired power (Figure 7). The CO_2 emission coefficient of solar PV power in the Qinghai region was calculated as 2.5×10^{-2} kg/kW·h, while clean coal-fired power was 8.6×10^{-1} kg/kW·h. In terms of the efforts to contribute towards climate change mitigation by reducing CO_2 emissions, the CO_2 emission reduction potential is about 8.35×10^{-1} kg/kW·h, indicating the huge potential of solar PV power compared to coal generation. The reduction in CO_2 emissions from solar PV power imposed by the CEAP will reach a maximum of 1.25×10^5 k tons/year in 2030 (Figure 7).

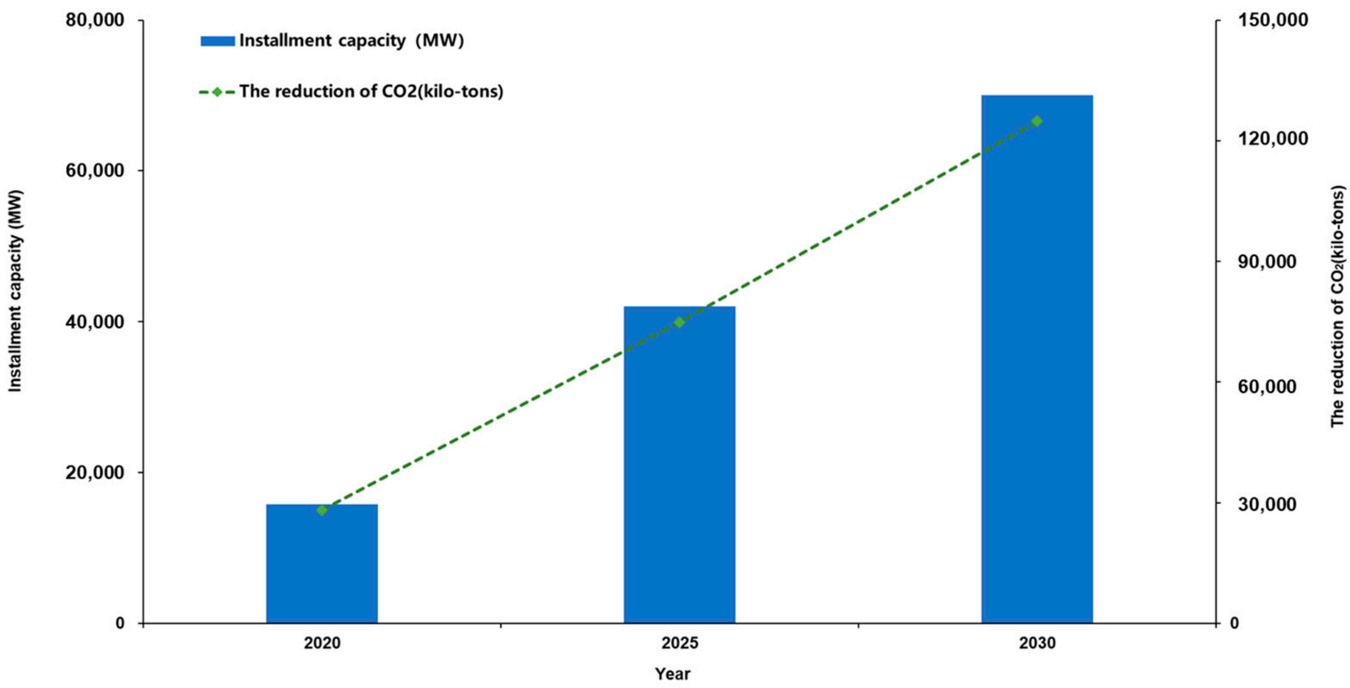

Figure 7. The reduction in CO_2 emissions for solar PV power imposed by the CEAP.

5. Conclusions

The potential environmental impacts of solar PV power generation imposed by the CEAP in the Qinghai region were evaluated in a regional, accumulative, and comprehensive way. By employing the LCA method, energy consumption and emissions of pollutants and GHGs from solar PV power were compared with clean coal-fired power systems. The main findings are summarized as follows:

(1) Solar PV power will significantly improve energy consumption, pollutants, and CO_2 emissions. Over a full life cycle, the CO_2 emissions of solar PV power were 2.9% of those from clean coal-fired power, while pollutant emissions including sulfur dioxide, nitrogen oxides, and particulate matter accounted for approximately 18–27% of those from coal-fired power. The installment of solar PV power introduced by the CEAP will reduce the use of standard coal by 4.62×10^4 k tons per year and decrease the emissions of CO_2, particulate matter, sulfur dioxide, and nitrogen oxide by 1.24×10^5, 2.3×10, 3.88×10, and 4.27×10 k tons/yr, respectively.

(2) From the perspective of a full life cycle, the application of solar PV power (in Qinghai) will result in 6.83/4.61 million tons of EOL solar PV panels under early/regular loss scenarios, which contain numerous hazardous materials. Additionally, as a low-density energy, solar PV power installation may cause an ecological disturbance due to considerable land occupation. The solar PV power included in the CEAP will occupy a land surface area of 4172 km^2 by 2030 from the current 940 km^2.

(3) The high-purity polysilicon extraction stage of production was found to be responsible for more than half of the energy consumption, pollutants, and CO_2 emissions.

The successful application of LCA in the CEAP indicates that LCA can be used as an effective tool for the qualitative and quantitative analysis of policy EIA, enriching the methodologies for policy EIA in China. Further application of LCA in policy EIA is recommended in more sectors. The LCA analysis in this study was based on data collected from field visits and the literature, which requires professionals such as process engineers, supervisors, technicians, and operators to present production record books and forms from manufacturing. This approach may cause practical difficulties such as resource allocation, data accuracy reliability and uncertainty, and comparisons between different studies or sites. Therefore, the use of systematic literature reviews may be useful to enhance the accuracy of the LCA evaluation in policy EIA.

Following the application of LCA to policy EIA, which quantified potential environmental impacts, correspondingly, policy implications were proposed as follows.

(1) Advance planning of local waste disposal capacity and processing facilities.

Limited by solar PV module technology, the life span of solar PV cells is around 25 years, which may generate difficulties in future waste processing facilities and disposal capabilities in the region. To ensure the effective treatment of waste materials, suggestions have been made to increase the capacity and capability of processing and disposal of solid and hazardous waste materials. Similarly, it was suggested to formulate a mandatory recycling mechanism from the aspects of recovery, treatment, and disposal.

(2) Integrate clean energy planning with legal ecological environment protection schemes.

The land occupation of solar PV power may have potential conflicts with regional ecological protection systems. In China, the Ministry of Ecology and Environment has enacted ecological space zoning control schemes and set up ecological protection red lines in different regions. Currently, the CEAP development does not consider such ecological space zoning constraints. To mitigate terrestrial ecosystem disturbance, it is suggested to strictly adhere to ecological environment zoning control schemes during construction site planning and the selection of solar PV power stations.

(3) Rational planning of upstream and downstream solar PV industries.

The process of high-purity polysilicon extraction has been found to account for more than half of the energy consumption, pollutants, and CO_2 emissions, followed by the production of industrial silicon and polycrystalline cells. It is, therefore, recommended to rationally distribute upstream industries spatially and in time of operation, considering the regional atmospheric environment carrying capacity as a prerequisite to determine the production scale, location, and timing.

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