Contribution of cross-border renewable energy technology transfer on global carbon mitigation: A case study of solar photovoltaic and biogas projects in China and Ethiopia

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Abstract: Renewable energy technology transfer in developing countries is vital in addressing the global challenges of climate change and energy crises. However, the environmental impact, especially the carbon emission and mitigation properties during technology transfer, has not been explored. In this study, six renewable energy technology transfer projects (four solar photovoltaic and two biogas projects) from China to Ethiopia have been studied using a life cycle assessment to identify the carbon footprint and comparative emission reduction potential between these projects. Results indicated: 1) Solar photovoltaic and biogas technologies exhibit significant differences in greenhouse gas emissions and reduction potential characteristics. 2) Solar photovoltaic technology demonstrates a more competitive effect in terms of carbon emission reduction and efficiency. 3) Biogas technology exhibits a more favorable transfer effect on global mitigation benefits and costs. This study demonstrates that the renewable energy technology transfer project maintains a better low-carbon characteristic and substantially contributes to low-carbon energy transformation and climate change mitigation.

Keywords: renewable energy, carbon footprint, technology transfer, life cycle assessment, global carbon mitigation
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1 Introduction

In 2024, the world added nearly 600 gigawatts (GW) of renewable power capacity, with a total of 1.3 trillion USD of global investment, especially dominated by the onshore wind and photovoltaic technologies[1,2]. Renewable energy (RE) has emerged as a predominant force in addressing multifaceted challenges encompassing the environment, economy, and energy in developing nations, facilitating the transition toward low-carbon economies. Therefore, countries are increasingly collaborating for international technology transfer to satisfy the pressing demand for renewable energy[3-5].

Based on the traditional technology transfer framework proposed by the United Nations Framework Convention on Climate Change (UNFCCC), the renewable energy technology transfer (RETT) program has been developed and rapidly applied by governments and business entities[6,7]. After the Paris Agreement (2015) and the associated wave of climate change concerns sweeping the globe, more and more researchers have also shifted their focus from the applications and implementation process of RETT to low-carbon-transition-related topics. A considerable number of studies has explored the impact of renewable energy technologies (RETs) on climate and environment. Some scholars have assessed the carbon emissions and reduction potential from different types of RETs or stages of their life cycle[8-13]. Additionally, researchers have demonstrated the negative correlation between RETs and environment from a macro-empirical perspective[14-16]. Some literature has paid particular attention to the impacts of RETs on carbon emissions in Belt and Road countries and in low-income countries[17,18]. However, one study also argued that only the investment in wind energy can reduce carbon emissions, while solar and bioenergy will cause an increase in carbon emissions, based on data analysis from 13 countries[19]. All these studies affirm that the roles of RETs and relative trade and business cooperation have received significantly increasing attention in the low-carbon transition.

Although the renewable energy technology transfer through South-South cooperation is rising rapidly, the body of literature is still in its infancy[20]. Less attention has been given to exploring the

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contribution of cross-border renewable energy technology transfer on carbon emissions reduction – including the specific impact on greenhouse gases (GHG) emissions and reduction potential in technology-importing countries and whether the low-carbon nature is maintained throughout the technology transfer process. Moreover, the existing research has mainly been carried out at global or national levels by statistical data. The conclusions of different scholars have also varied. In contrast, this study adopts a more micro-level perspective, incorporating a case study with data from specific engineering projects.

This study is based on a trilateral cooperation initiated by the United Nations Development Programme and the governments of China and Ethiopia in 2019, to implement renewable energy technology transfer and support developing nations in enhancing their capacity to address climate change and collectively achieve the Sustainable Development Goals. In this context, an excellent opportunity was provided to discuss the cross-border carbon footprint and emission reduction potential based on four solar photovoltaic (solar PV) and two biogas demonstration plants established by technology transfer in Ethiopia.

2 Materials and methods

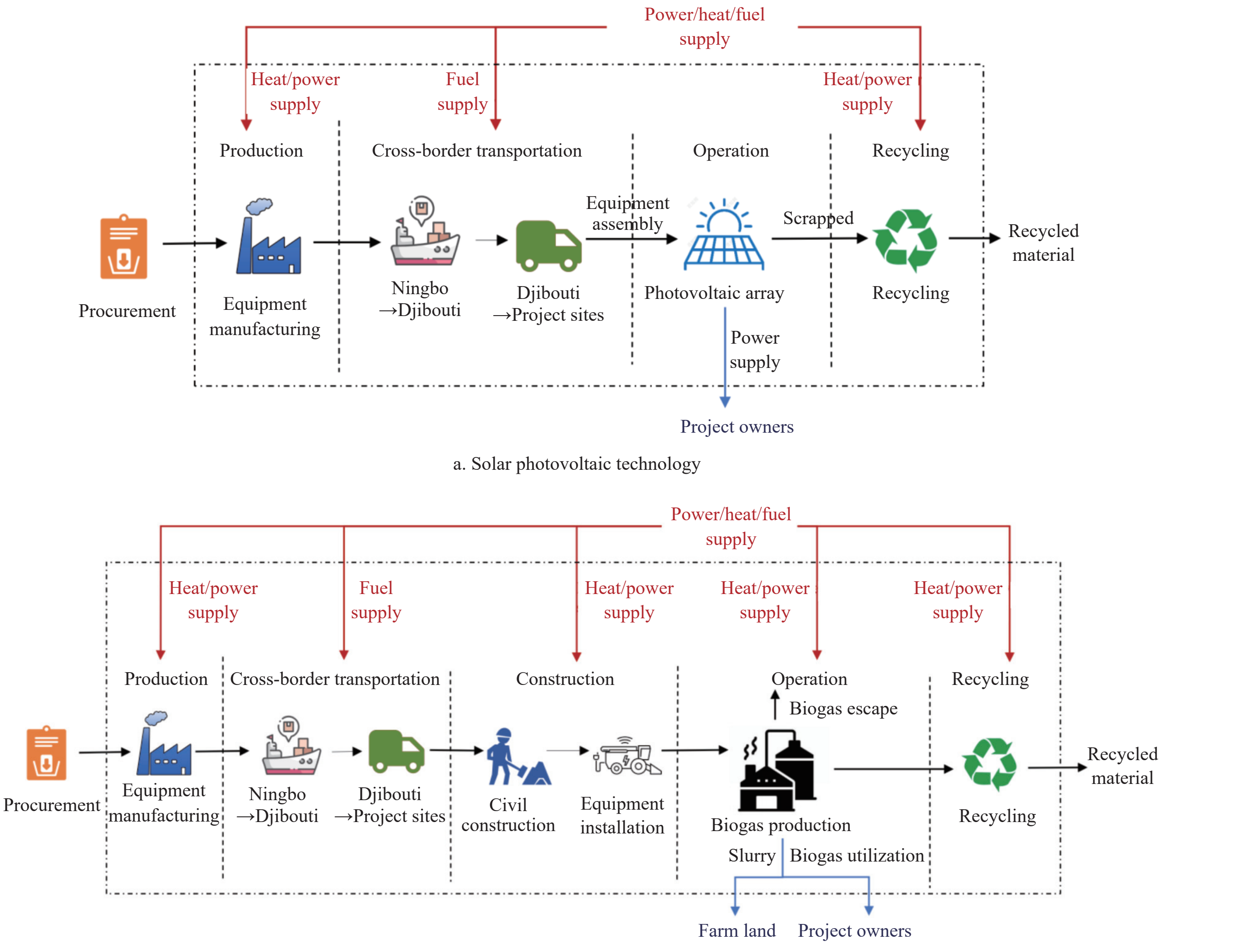
2.1 Case description and boundary of LCA on RETT

The basic information of six RETT projects is listed in Table 1. The six sites are all experiencing varying degrees of electricity shortage. The generated biogas from cow manure and kitchen waste is harnessed for electricity generation, whereas the slurry and residue derived from this process are effectively employed as organic fertilizers. The solar PV and biogas project life spans are 25 and 20 years, respectively.

Table 1 Basic information of four solar photovoltaic and two biogas projects

Solar PV technology projects					
Sites	Location	Annual equivalent utilization hours/h	Rated power capacity/kW	Annual power generation/ $kW·h·a^{-1}$	-
A	Wolaita	2150	6.7-9.1	2738-3720	-
B	Harari	2260	6.7-9.1	2878-3910	-
C	Harari	2260	6.7-9.1	2878-3910	-
D	Amhara	2230	107.9-146.5	45 746-62 110	-
Biogas technology projects					
Sites	Location	Feedstock/ $t·d^{-1}$	Biogas generation/ $m^3·d^{-1}$	Power generation/ $kW·h·a^{-1}$	Biogas slurry and residue/ $t·d^{-1}$
W	SNNP	Cow manure: 2.376 Food waste: 2.19	150	108 290	8.97
S	Oromia	Cow manure: 1.983	65	47 090	4.97

The carbon footprint (CF) of cross-border transferred renewable energy technology was evaluated using Life Cycle Assessment (LCA) to identify the key determinants of GHG emissions and assess the potential for emission reductions within these projects.



a. Solar photovoltaic technology

b. Biogas technology

Figure 1 Boundary of life cycle assessment on renewable energy technology transfer project

Figure 1 shows the different life cycles of the solar PV and biogas projects. The GHG emissions are generated from the five stages of production, cross-border transportation, construction, operation, and recycling of the whole project. However, the emissions from the assembly and construction stages of the solar PV project were considered negligible due to the slight energy and material consumption[21].

2.2 Carbon footprint accounting for RETT projects

The carbon footprint of one project is the sum of the GHG emissions in all stages of its life cycle, referring to the International Standard on the carbon footprint of products[22] and on LCA[23,24]. The carbon footprint (CF) of the solar or biogas project can be calculated as follows:

$$CF_i = E_{ma,i} + E_{tr,i} + E_{co,i} + E_{op,i} + E_{re,i} \quad (1)$$

where, CF_i is carbon footprint, representing GHG emissions throughout the project's life cycle; i is the i^{th} solar PV or biogas project, tCO_2e; $E_{ma,i}$ is GHG emissions from equipment manufacture in China, from cradle to gate, tCO_2e; $E_{tr,i}$ is GHG emissions from cross-border transportation, including sea and land transportation, tCO_2e; $E_{co,i}$ is GHG emissions from engineering construction in Ethiopia, tCO_2e; $E_{op,i}$ is GHG emissions during operation in Ethiopia, tCO_2e; $E_{re,i}$ is GHG emissions from the recycling stage, tCO_2e.

The GHG emission calculation was based on the relevant information from the 2006 and 2019 refinement of Guidelines for National Greenhouse Gas Inventories from the Intergovernmental Panel on Climate Change (IPCC):

$$E_{k,i} = \sum_j (AD_{k,j} \times EF_{k,j}) \quad (2)$$

where, $E_{k,i}$ is emissions total for specific source k, (e.g. manufacture, transportation, construction), i^{th} project; $AD_{k,j}$ is activity j^{th} data applicable to source k; $EF_{k,j}$ is emission factor for specific activity j.

2.2.1 Production and manufacturing

During the first production stage, emissions are calculated by assessing GHG emissions from cradle to gate associated with the standard production process.

1) Photovoltaic module production

The GHG emission of the solar PV project during the production stage can be calculated by Equation (3a):

$$E_{ma,S,i} = WP_i \times EF_{PV} \quad (3a)$$

where, $E_{ma,S,i}$ is GHG emission of the production stage of the i^{th} solar PV project, tCO_2e; WP_i is rated power capacity of the i^{th} solar PV project, kW; EF_{PV} is emissions per unit of mono-crystalline silicon (adopted in this project) photovoltaic module products, 0.29 tCO_2e/kW[25].

2) Biogas equipment production

The emission generated from the production of biogas equipment can be calculated by Equation (3b):

$$E_{ma,B,i} = \sum_j N_{i,j} \times EF_{ma,j} \quad (3b)$$

where, $N_{i,j}$ is mass of the j^{th} major equipment of the i^{th} biogas project, t; $EF_{ma,j}$ is emission factor of the j^{th} major equipment product.

Six types of equipment, including AD reactors, power generators, desulphurization tanks, feeding pumps, heating devices, and waste pulverizers, accounted for over 80% of the total weight required for the process. As the biogas equipment was mostly customized, the GHG emission of equipment was simplified to the production of corresponding raw materials, specifically carbon steel and PVC.

2.2.2 Cross-border transportation

The cross-border transportation process of both solar and biogas projects comprises sea and land transportation. This study assumes that sea transportation commences from Ningbo Port in Zhejiang Province, China, to Djibouti Port near Ethiopia, while the subsequent land transportation is carried out from Djibouti Port to the local demonstration sites in Ethiopia.

The total distance for sea routes calculated based on Shipxy Maritime Service[26] was 5878.4 nautical miles (10 886.79 km). Container ships (200TEU) are employed to transport the equipment. The land transportation distances for the six demonstration sites were estimated using Google Earth. Gasoline trucks are utilized in Ethiopia, considering the local conditions.

2.2.3 Construction

The GHG emissions during the construction stage result from the consumption of construction materials and energy used during construction operations. The building materials and energy consumption are minimal in the photovoltaic installation process, making its contribution to carbon emissions negligible in terms of carbon footprint[27,28], but the carbon emissions associated with the construction and installation of biogas projects should be evaluated. Moreover, the energy consumption during the construction and equipment installation stage is relatively low (<1%). This study omitted GHG emissions from energy consumption in the calculations, and primarily focused on the emissions of building materials, including steel, cement, and bricks[29,30].

2.2.4 Operation

Previous studies[21,31] have suggested that heat and power supply are not required once a photovoltaic array is operational, except during occasional fault maintenance. Studies[28,32,33] have also reported that the GHG emissions during maintenance activities are negligible compared to the project's overall carbon footprint and have thus been excluded from this study. In comparison, GHG emissions during biogas system operation differ greatly from photovoltaic projects. The external heat was required for the anaerobic digestion (AD) process provided by electricity, which caused a considerable amount of GHG emissions. Meanwhile, methane leakage during operation should also be accounted for. Notably, emissions resulting from the transportation of biogas feedstock are not considered due to the location's proximity to the anaerobic digester.

$$E_{op,i} = (E_{power,i} \times EF_E + E_{CH4,i}) \times T_i \quad (4)$$

where, $E_{power,i}$ is annual power consumption of the i^{th} biogas operation, kW·h; EF_E is emission factor for power generation by small coal-fired generating units, with an average value of 0.93 $tCO_2/MW \cdot h$[34]; $E_{CH4,i}$ is annual emission equivalent produced by methane escape of the i^{th} biogas engineering, tCO_2e; T_i is life cycle of the i^{th} biogas engineering, 20 a.

2.2.5 Recycling

The main recycling materials are photovoltaic panels and carbon steel from biogas equipment. According to the literature[33,35], the weight of recycled photovoltaic modules is approximately 70.5 t/MW, with 0.462 tCO_2e/t emissions. This means that recycling each MW photovoltaic module results in 32.571 tCO_2e emissions. The GHG emissions of the four photovoltaic projects from the recycling process can be determined based on the power output.

For biogas projects, the GHG emissions based on the reproduction of recycled steel from equipment can be calculated as the total mass of all carbon steel equipment, neglecting emissions from transportation in recycling. The emission factor of recycling carbon steel was used here.

2.3 GHG emission reduction potential of RETT projects

2.3.1 GHG emission sources and baseline scenario

As revealed by GHG emission reduction accounting, all projects reduce emissions by utilizing renewable energy derived from photovoltaic and biogas engineering, effectively substituting coal-fired power generation and consequently mitigating carbon emissions. Therefore, coal-fired power generation is considered the baseline scenario for this project. Additionally, material recycling is a viable alternative to energy-intensive production using similar raw materials. Therefore, GHG emissions offset by recycling activities are also incorporated into the baseline scenario.

Given that biogas projects produce methane, which has a strong greenhouse effect, the baseline scenario for emission reduction effects encompasses replacing coal-fired power generation with biogas power generation and reducing methane emissions by utilizing livestock and poultry manure and organic solid waste. By contrast, the by-products of biogas projects, namely biogas slurry and biogas residue, can be used to substitute for chemical fertilizers in agricultural fields and enhance soil fertility. Therefore, the baseline must also include GHG emissions associated with chemical fertilizer production.

2.3.2 Calculation of GHG emission reduction potential

The method for calculating the GHG emission reduction potential of RETT projects is based on the Certified Emissions Reductions (CERs) of IPCC and Clean Development Mechanism (CDM) projects, outlined in Equations (5) and (6).

Solar PV technology can be calculated by Equation (5):

$$ER_{S,i} = E_{basic,S,i} - CF_{S,i} \tag{5a}$$

$$E_{basic,S,i} = E_{energy,S,i} + E_{ryd,S,i} \tag{5b}$$

where, $ER_{S,i}$ is emission reductions for the i^{th} solar PV project, tCO_2e; $E_{basic,S,i}$ is total emissions of the baseline scenario of the i^{th} solar PV project, tCO_2e; $CF_{S,i}$ is the life cycle cross-border carbon footprint of the i^{th} solar PV project, tCO_2e; $E_{energy,S,i}$ is emission from coal-fired power generation replaced by the i^{th} solar PV project, which also means the GHG emission reduction by energy substitution, tCO_2e; $E_{ryd,S,i}$ is emissions from the production of photovoltaic panel replaced by recycling material, tCO_2e.

Biogas technology can be calculated by Equation (6):

$$ER_{B,i} = E_{basic,B,i} - CF_{B,i} \tag{6a}$$

$$E_{basic,B,i} = E_{energy,B,i} + E_{manure,\mathrm{CH4},i} + E_{food,\mathrm{CH4},W} + E_{fertilizer,i} + E_{ryd,B,i} \tag{6b}$$

where, $ER_{B,i}$ is emission reductions for the i^{th} biogas project, tCO_2e; $E_{basic,B,i}$ is total emissions of the baseline scenario of the i^{th} biogas project, tCO_2e; $CF_{B,i}$ is the life cycle cross-border carbon footprint of the i^{th} biogas project, tCO_2e; $E_{energy,B,i}$ is emission from coal-fired power generation replaced by the i^{th} biogas project, tCO_2e; $E_{manure,\mathrm{CH4},i}$ is methane emission from manure management, the i^{th} biogas projects, tCO_2e; $E_{food,\mathrm{CH4},W}$ is methane emission from food waste disposal, only for W biogas project, tCO_2e; $E_{fertilizer,i}$ is emissions from fertilizer production replaced by the i^{th} biogas slurry and residue, tCO_2e; $E_{ryd,B,i}$ is emissions from carbon steel production replaced by recycling material, tCO_2e.

1) Emissions from coal-fired power generation (energy substitution)

The six demonstration projects in this study are primarily employed for electricity generation, replacing the coal-fired power system. The paper calculated the theoretical life cycle capacity for power generation and emissions reduction achieved by replacing coal-fired power generation. However, the actual power output and conversion efficiency of photovoltaic modules may vary, leading to fluctuations in power generation. The highest level of power generation corresponds to the rated power and maximum conversion efficiency, achievable when operating at full capacity. This configuration exhibits the maximum potential for emission reduction. Conversely, the power generation is the lowest when operating at the lowest power and conversion efficiency, yielding the minimum potential for emission reduction. The mean value of emission reduction potential was used for further discussion.

2) Methane emissions from livestock and poultry manure

Methane emissions from livestock and poultry manure in the baseline scenario depend on livestock species, numbers, and the type of manure management system. Most livestock manure in Africa is managed as solid storage on pastures. In the project scenario, the former manure treatment of demonstration sites W and S is both carried out through solid management. The baseline emissions are based on Chapter 10.4: Emissions from Livestock and Manure Management, of Volume 4: Agriculture, Forestry and Other Land Use, 2019 IPCC Guidelines for National Greenhouse Gas Inventories[36].

3) Food waste methane emissions

In addition to livestock manure, the raw materials for the W biogas project also include considerable food waste. These materials are mixed and introduced into the reactor for fermentation. Therefore, the baseline scenario for the W biogas project must account for methane emissions resulting from the natural degradation of food waste. Methane emissions from the natural degradation of food waste are calculated according to Chapter 3.1: Solid Waste Disposal, of Volume 5: Waste, 2019 IPCC Guidelines for National Greenhouse Gas Inventories[37].

4) GHG emissions from fertilizer production

As per project requirements, the by-products, biogas slurry, and biogas residue will be returned to nearby fields for utilization. These materials contain N/P/K elements, which serve as a substitute for certain chemical fertilizers, reducing the amount needed. Neglecting potential losses of N/P/K elements during biogas production and storage, the N/P/K contents available for collection and utilization in biogas slurry and residue can replace the same quantity of chemical fertilizer production.

5) GHG emissions from recycling

Assuming a 10% depreciation rate for recycling losses during photovoltaic and carbon steel recycling production, the emission of the basic scenario amounts to 90% of the same output normally manufactured.

3 Results

The carbon footprint and the emission reduction potential of solar PV and biogas technologies are discussed subsequently.

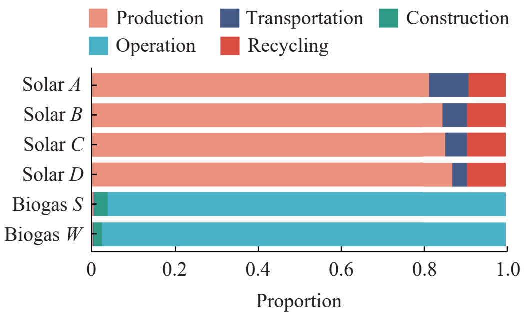
3.1 Cross-border carbon footprint characteristics

The carbon footprints of the six projects are listed in Table 2. Overall, the carbon footprint of biogas technology was relatively higher, and was also related to the scale of the project. As both solar PV and biogas technology were aimed at energy supply, the carbon footprint per unit energy production (CFU) is discussed to assess the emission performance. The CFU of solar PV projects ranged from 0.03-0.04 $tCO_2e/MW \cdot h$ due to the fluctuations in the amount of power generated by photovoltaic systems. The mean CFUs of solar PV projects was about 0.036 $tCO_2e/MW·h$, while both biogas projects recorded emissions exceeding 0.3 $tCO_2e/MW·h$. The CFU of biogas technology was nearly 10 times higher than that of PV technology.

Figure 2 presents the life cycle carbon footprint characteristics for the six projects, which exhibit obviously different proportions of carbon footprint between solar PV and biogas technologies. For solar PV technology, the production process in China was the key contributing factor (from the cradle to the gate), accounting for more than 80% of the carbon footprint. By contrast, biogas technology's carbon footprint primarily occurred within Ethiopia (from gate to grave). Its operation process accounted for more than 90%. Meanwhile, the notable similarity between both technologies was the remarkably low proportion of transportation-related carbon emissions compared to the overall carbon footprint, with a percentage of 3% for solar PV and a mere 0.2% for biogas. The long-distance transportation associated with technology transfer exerted a minimal emission impact.

Table 2 Carbon footprint of renewable energy technology transfer projects

Projects	*A*	*B*	*C*	*D*	*W*	*S*
Production and manufacturing/tCO_2e	2.60	2.60	2.60	42.50	20.10	11.60
Cross-border transportation/tCO_2e	0.30	0.18	0.16	1.70	2.20	0.90
Construction/tCO_2e	-	-	-	-	86.80	56.50
Operation/tCO_2e	-	-	-	-	568.90	214.50
Recycling/tCO_2e	0.30	0.30	0.30	4.80	7.50	4.10
Carbon footprint/tCO_2e	3.20	3.08	3.06	49.00	685.50	287.60
CF in China/tCO_2e	2.60	2.60	2.60	42.50	20.10	11.60
CF in Ethiopia/tCO_2e	0.30	0.30	0.30	4.80	663.20	275.10
CF per unit energy production CFU/$tCO_2e·(MW·h)^{-1}$	0.034-0.047	0.032-0.043	0.031-0.043	0.032-0.043	0.316	0.305
Mean *CFU*/$tCO_2e·(MW·h)^{-1}$	0.0396	0.0363	0.0361	0.0363	-	-



Note: The share of five processes in the carbon footprint is shown by colors; total carbon footprint is 1.0. The emission from the operation of solar PV was negligible; the proportion included only three processes. The proportions of production and recycling in biogas were minimal and not shown clearly.

Figure 2 Proportions of carbon footprint of renewable energy technology transfer projects

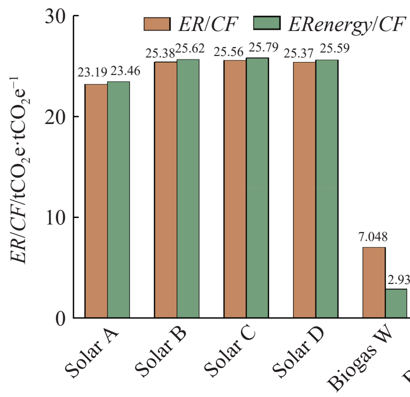
3.2 Emission reduction effects

Table 3 illustrates the life-long cumulative emission reduction potential and per unit power generation (ERU) of solar and biogas projects, which varied between two technologies. The ERU of solar PV technology trended to 0.92 $tCO_2e/MW·h$, while biogas technology was about 2.23-2.57 $tCO_2e/MW·h$. Bio-energy had greater advantages in emission reduction potential. As shown above, low-carbon technologies have both carbon emission and carbon reduction properties. Photovoltaic technology results in a lower carbon footprint, but biogas technology has a greater potential to reduce emissions. Therefore, it was necessary to evaluate the emission reduction efficiency to determine the carbon mitigation impact of the different technologies.

Figure 3 illustrates the emission reduction efficiency of all projects. The ratios of GHG emission reduction potential to carbon footprint (*ER*/*CF*) and the ratios of emission reduction potential from energy substitute to carbon footprint (ER_{energy}/CF) were used to characterize the emission reduction efficiency of technology transfer. The *ER*/*CF* showed the TOTAL emission reduction efficiency, and ER_{energy}/CF focused especially on ENERGY emission reduction efficiency. These two indicators provide a better comparison of the net carbon mitigation impacts of the two technologies. For photovoltaic technology, the mean of *ER*/*CF* was in the range of 23.19-25.56 tCO_2e/tCO_2e, and the mean of ER_{energy}/CF falls within the range of 23.46-25.79 tCO_2e/tCO_2e, aligning with its total emission reduction efficiency. Moreover, the ER_{energy}/CF is a bit higher than *ER*/*CF*. The actual ER is smaller than the theoretical calculation due to the solar PV projects' own emissions. The *ER*/*CF* of biogas technology records an efficiency of 7.05-8.43 tCO_2e/tCO_2e, while ER_{energy}/CF is only 2.94-3.05 tCO_2e/tCO_2e. Solar PV technology is much superior in terms of emission reduction efficiency.

Table 3 Emission reduction potential of six projects

Projects	*A*	*B*	*C*	*D*	*W*	*S*
Baseline emission/ tCO_2e	66.01-88.82	69.27-93.25	69.27-93.25	1101.83-1482.32	5517.09	2711.24
ER potential/tCO_2e	62.81-85.62	66.19-90.17	66.21-90.19	1052.83-1433.32	4831.59	2423.64
Mean total *ER*/tCO_2e	74.22	78.18	78.20	1243.08	-	-
ERU/$tCO_2e·(MW·h)^{-1}$	0.9193	0.9213	0.9215	0.9220	2.2300	2.5700

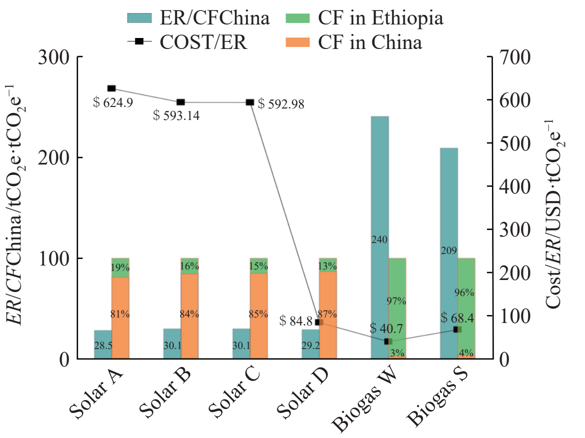


Note: *ER*/*CF* indicates the quantity of emission reduction potential per unit of carbon emission produced by projects; ER_{energy}/CF indicates emission reduction potential resulting from renewable energy generation per unit carbon footprint. Larger numbers indicate greater potential for emission reductions, which means higher efficiency of emission reduction.

Figure 3 Emission reduction efficiency of solar photovoltaic and biogas technologies

3.3 Global emission reduction benefits and costs of RETT

In addition to comparing GHG emission characteristics and effects between solar PV and biogas technologies in the preceding section, this study made an intriguing discovery. Figure 4 presents the "global mitigation benefit of technology transfer (ER/CF_{China})". The metric illustrates the carbon mitigation benefits that the technology-exporting country contributes to the technology-importing country with each 1-ton increase in GHG emissions. It can be shown that the ER/CF_{China} of solar PV technology was in the range of about 30 tCO_2e/tCO_2e, while the ER/CF_{China} of biogas technology was above 200 tCO_2e/tCO_2e. This means that the global mitigation benefit of biogas technology transfer is more pronounced. Meanwhile, comparing the proportion of carbon footprint generated in China and Ethiopia of the two technologies also indicates that the carbon footprint of biogas projects is primarily concentrated in the technology-imported regions. Therefore, if the biogas technological advancements during operation stage are implemented, leading to lower carbon emission intensity, then the biogas technology will hold greater global transfer advantages.



Note: ER/CF_{China} represents the emission reduction potential in the technology-importing country divided by the GHG emissions in the technology-exporting country for each 1-ton unit increase in GHG emissions. CF in Ethiopia and China means the proportion of CF generated in technology-export and import countries. The economic cost of per 1-ton emission reduction is shown with the black points.

Figure 4 The effect and cost of six case projects contributing to global emission reduction

Apart from benefits, the economic cost of technology transfer is another critical consideration. According to the total cost of the six technology transfer projects, we can determine the economic cost per 1-ton CO_2 emission reduction for both solar PV and biogas technologies. Biogas technology exhibits unit mitigation costs of 40.7 and 68.4 USD/tCO_2e, much lower than those of solar technology. However, it's worth noting that the unit mitigation cost of PV technology at a large scale (84.8 USD/tCO_2e) is significantly less than that of small-scale PV projects (592.98-624.9 USD/tCO_2e), due to the economic scale effect.

4 Discussion

The different proportions of carbon footprint between solar PV and biogas technologies will have different impacts on national GHG emission inventories, resulting in embodied carbon transfer. The global GHG emission responsibility calculation is still dominated by the producer principle, considering GHG emissions within the jurisdiction. Consequently, most GHG emissions from photovoltaic technology transfer projects are attributed to the technology-exporting country. Another research study[38] also found that most of the carbon impact of ICT networks in Peru was generated in China by manufacturing electronic components. However, the biogas transfer projects account for emissions mainly in the technology-importing country, as GHG emissions are mainly generated during the operation process.

On the other side, maritime transport is the biggest difference between technology transfer projects and domestic projects, but there is not much difference in the impact on GHG emissions. As can be seen in Figure 3, the emissions from transport account for a small percentage of the total carbon footprint of both technologies. Moreover, the CFU of the solar PV technological transfer is almost the same as domestic applications (0.033-0.05 $tCO_2e/MW \cdot h$[39]). Both of these points indicate that the green low-carbon technology still maintains its low-carbon characteristics during cross-border transportation.

According to indicators of CFU and ERU, biogas technology demonstrates a more pronounced climate effect with higher CFU and ERU, compared to solar PV technology. Meanwhile, solar PV technology is superior to biogas technology in terms of emission reduction efficiency based on the indicators of ER/CF and ER_{energy}/CF. The ER/CF of biogas S project is about 30% of the mean value of solar PV, while its ER_{energy}/CF is only 10% of solar. This suggests that biogas technology's energy emission reduction effect is less significant. On the other side, taking biogas W as an example, the ER_{energy}/CF of W accounts for about 40% of the total efficiency ER/CF. However, the ER_{energy}/CF of solar projects is a bit higher than their total efficiency. This observation also implies that biogas technology is comparatively less efficient than solar technology in power generation. Unlike solar energy, which provides a single renewable energy source, biogas technology contributes to reducing non-CO_2 GHG emissions and significantly curbs methane emissions from agricultural and solid waste sources.

Besides, this study also found that solar PV technology shows consistency in both carbon emission and reduction potential. This stability arises from the standardization of PV products, from manufacturing to application, and the consistent light conditions at technology transfer sites. The influence of projects' location and transportation is minimal, resulting in a more stable provision of low-carbon energy. In contrast, biogas engineering technology is heavily influenced by technology scale and project site conditions due to its customized production. This leads to substantial variations in CFU and ERU. Moreover, project W, with larger power generation, records higher CFU but lower ERU than those of Project S. This also highlights that the emission reduction from energy is not the main function of biogas technology, but the direct reduction of CH_4 emission.

Both solar PV and biogas technologies exhibit positive figures on "global mitigation benefit of technology transfer (ER/CF_{China} >1)", which suggests that both technologies are highly suitable for technology transfer collaborations with developing countries. The biogas technology transfer is more beneficial, nearly 10 times more than that of solar PV technology. Through the analysis of unit cost of emission reduction, biogas technology performs better. While large-scale solar D (84.8USD/tCO_2e) exhibits a relatively low cost, approaching small-scale biogas S (68.4USD/tCO_2e), biogas technology indicates superior advantages in technology transfer regarding both benefits and cost of emission reduction. Moreover, the cost of Solar A is a little bit higher due to the long-distance logistic fees. Therefore, when considering the cost factor of technology transfer, the scale of PV technology must be considered, in order to minimize unit mitigation costs.

5 Conclusions

This study employed the "China-Ethiopia Trilateral Cooperation Project on Biogas and Solar Energy" as a case study to assess the cross-border carbon footprints and emission reduction potentials of two distinct renewable energy technology transfers: solar PV and biogas technology. The key findings are as follows: 1) The distribution of carbon footprints differs significantly between solar PV and biogas technology. Approximately 80% of solar PV's carbon footprint occurs in production, while 90% GHGs emissions from biogas technology occur in operation. 2) Biogas technology demonstrates a more pronounced climate effect with higher per unit energy production of carbon footprint as well as emission reduction. 3) Solar PV technology outperforms in emission reduction efficiency (ER/CF and ER_{energy}/CF). 4) Biogas technology exhibits a more favorable transfer effect on global mitigation benefits and costs per unit of emission reduction through technology transfer. These findings underscore that each renewable energy technology possesses unique emission and mitigation characteristics. It also indicates that the "technology transfer" approach in developing countries is a feasible and effective path for achieving low-carbon transformations and sustainable development goals.

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