Priority change and driving factors in the voluntary carbon offset market

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Abstract

Voluntary carbon offset markets play an important role in climate change mitigation by deploying technologies in order of lowest abatement cost. The objective of this study is to identify the key drivers of changes in the volume of carbon credits issued in voluntary registry offset markets from 2006 to 2020 using a decomposition analysis framework. The results show that the volume of issued carbon credits related to forestry and land use increased from 2006 to 2015 due to priority increases and scale expansions in REDD+ projects. In addition, the reasons for the priority changes in carbon credits issued varied according to the scale of carbon offset programs in each region. The comparison of scale effect and carbon offset program priority is a useful tool for understanding changes in carbon credits issued according to project technology and region. The very rapid increase in forestry carbon credits issued does however pose important policy implications given it has been accompanied by widespread indications of poor governance and questionable outcomes in terms of CO_2 reduction. In light of the IPCC's reliance on carbon credits the need for thoroughgoing policy reform is underlined.

Keywords: voluntary registry offset market, carbon credit, decomposition analysis

1. Introduction

Greenhouse gas emissions must be reduced to mitigate the effects of climate change (IPCC, 2021). Economically efficient climate change mitigation is made possible by carbon pricing schemes, in particular emissions trading schemes and carbon credit schemes (certification of CO_2 emission reductions for trading), which share the roles of CO_2 emission reducers and cost bearers (Lovcha et al., 2022). In response to this growing demand, carbon credits are increasingly being issued through voluntary registry carbon offset markets (Andre and Valenciano-Salazar, 2022; Xu et al., 2023). However, the technical difficulty associated with implementing the carbon offset program differs between regions and project technology (OECD, 2021). This is because the required equipment, capital and labor for implementing carbon offset programs vary between project technology and target area (IPCC, 2022).

What drives the differences in trends in the issuance of carbon credits by region and project technology? Naturally, the cost of project implementation and uncertainty in the amount of CO_2 absorption are important factors for project managers in selecting target area and technology (Pan et al., 2022). However, it is difficult to accurately forecast the cost and efficiency of each carbon offset program, given the reasons for changes in their issuance trends are unclear. Therefore, this study proposes an analytical application that reveals the relative priority by project technology from the public information used for registration in the carbon offset program. The relative priority changes among project technology provides useful information when formulating an effective policy that encourages carbon offset programs.

The objective of this study is to clarify the determining factors contributing to carbon credits issued, as it relates to carbon offset project technology, using a dataset of voluntary registries for carbon offsets. This study is the first to use a decomposition framework to clarify the determinants of carbon credits issued. The contribution of this research is to clarify the reasons behind priority changes in carbon offset credit projects using LMDI analysis. Many previous studies (e.g., Gupta and Rakshit 2023; Velvizhi et al. 2023) have focused only on the number of carbon credits issued. It is important to understand carbon credits issued separately in terms of macro factors (i.e., scale of carbon credit markets) and priority given to each technology. This study attempts to derive a specific measure of the priority given to the carbon offset project by controlling for the scale effect. In doing so this is the first study to apply a decomposition framework to the analysis of the issuance of carbon credits.

2. Background and literature review

2.1. Background

There are several ways to reduce GHG emissions, with the amount of reduction possible and the cost varying by technology. According to the IPCC (2022), plant carbon sequestration and the protection of natural ecosystems in the agricultural and forestry sectors can reduce CO_2 emissions by one ton for less than $20, which is inexpensive compared to the cost of carbon reduction in the industrial sector. From an economic perspective then, it is desirable to adopt technologies in the order of lowest abatement cost, as this minimizes the abatement cost to society (The World Bank, 2022a).

It should be noted that the effects of CO_2 emission reduction are the same regardless of the reduction technology used to promote climate change action. In other words, the contribution to climate change mitigation is the same for the same amount of CO_2 reduced using either expensive or inexpensive technology. Thus, priority should be given to the use of technologies that can reduce CO_2 at a lower cost (The World Bank, 2022a). What is important in balancing economic efficiency and climate change mitigation is to prioritize the use of low-cost abatement technologies by utilizing market mechanisms, rather than forcing the introduction of expensive abatement technologies (IPCC, 2022). This is because the burden of high reduction costs puts pressure on corporate profits, which in turn discourages salary increases, capital investment and R&D investment directed to gaining market competitiveness (OECD, 2017). Allowing companies to also use validated emissions trading and carbon credits to achieve their emission reduction targets is expected to reduce CO_2 emissions without unduly sacrificing economic efficiency (Jiang et al. 2023).

Many companies have sought to accelerate their carbon neutrality efforts through voluntary initiatives following the signing of the COP 21 Paris Agreement in 2015 (World Economic Forum, 2022).

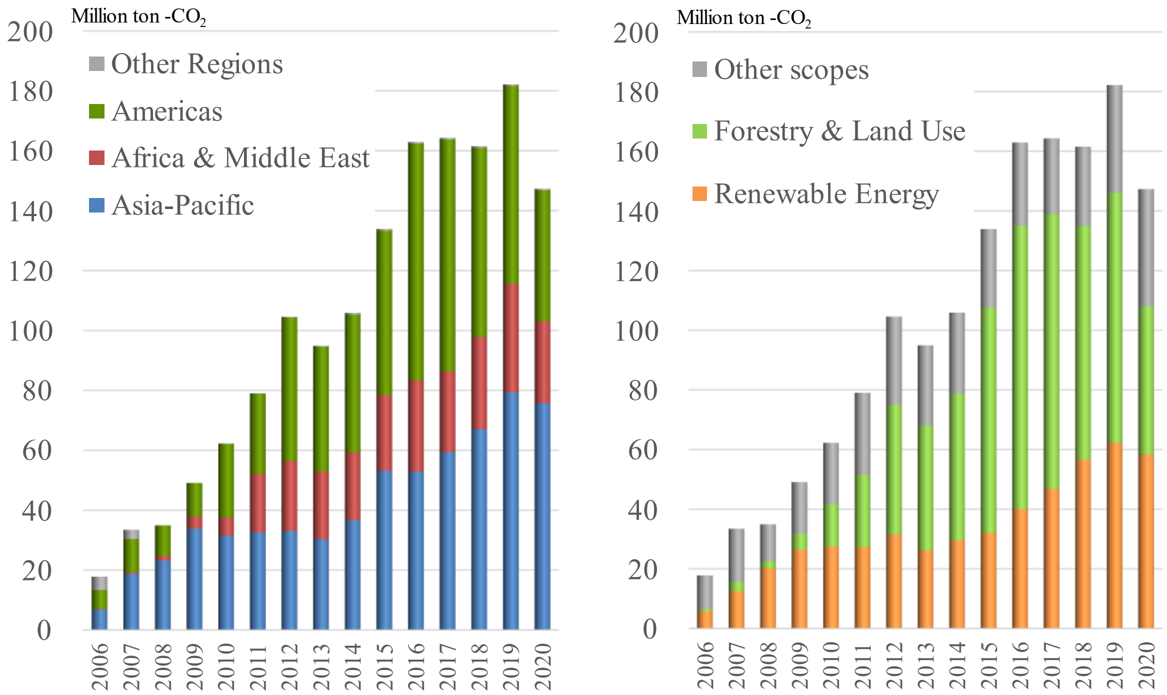
Such companies have promoted carbon neutrality by obtaining carbon credits from the voluntary carbon credit market as a voluntary initiative (ITU and WBA, 2022). For example, major energy companies such as Shell sell carbon neutral LNG using carbon credits issued in the voluntary credit market (Blanton and Mosis, 2021). The International Civil Aviation Authority (ICAO) has also decided to use carbon credits issued in the voluntary carbon credit market to provide carbon neutrality for air transportation (ICAO, 2019).

Figures 1 summarize the carbon credits issued in four voluntary carbon markets from 2006 to 2020.[1] We observe a constant global increase in the amount of carbon credits issued. Using the Voluntary Registry Offsets Database version 6, we grouped carbon credits issued by project technology[2] by region (see Appendix 1 and 2 for grouping methods).

Figure 1(a) shows that the volume of carbon credits issued in voluntary carbon market increased rapidly in the Americas, Africa & Middle East and the Asia-Pacific region. In particular, the Americas and Africa & Middle East regions dramatically increased the volume of carbon credits from 2009 to 2015, with similarly large increases coming from the Asia-Pacific region from 2006 to 2009, and 2015 to 2019. This difference in the timing suggests that the cost, demand and difficulty of implementing carbon credit projects vary among regions. Figure 1(b) shows that the volume of carbon credits issued related to renewable energy and forestry & land use increased the most over the considered time period. Thus, it is shown that the trend of carbon credits issuance differs significantly among regions and project technology.

[1] According to the voluntary Registry Offsets Database version 6 "The Voluntary Registry Offsets Database contains all carbon offset projects listed globally by four major voluntary offset project registries: American Carbon Registry (ACR), Climate Action Reserve (CAR), Gold Standard, and Verra (VCS). These four registries generate almost all the world's voluntary market offsets and include projects eligible for use under the California / Quebec linked cap-and-trade programs as well as UN Clean Development Mechanism projects that transitioned into one of the voluntary registries.". In light of this explanation, we use carbon credits issued in four major voluntary offset project registries in this study.

[2] The Voluntary Registry Offsets Database version 6 categorizes carbon offset projects in two ways. The first is the project scope, which represents the major technological categories of projects. Project scopes are divided into 9 categories. The second is the project type, which represents the detailed technological type of project in each scope. The types are divided into 72 categories. The correspondence between each scope and type is described in Appendices 1 and 2.



(a). Carbon credits issued by project area (b). Carbon credits issued by project technology

Figure 1. Trend of issued carbon credits by vintage year

Source: Voluntary Registry Offsets Database version 6 (So et al., 2022)

2.2. Literature review

A number of previous studies on carbon credits have mainly evaluated the potential amount of carbon credits which can be derived from individual technologies. Ebissa et al. (2023) compares the financial outcomes of plantation forests for carbon credits, logs and timber, concluding that timber production is the most financially beneficial for community-based organizations and individuals. They recommend informed decisions based on a thorough understanding of the associated benefits and risks. Susilowati et al. (2023) suggest that in Indonesia, a hybrid solar and biomass power plant in Nusa Penida, Bali, can economically empower remote areas with renewable energy, reducing CO_2 emissions by over 22,000 tons and generating USD 447,426 annually, with the return enhanced by carbon credits and biochar sales electricity tariff reductions. Kuwae et al. (2022) evaluate Japan's pioneering blue carbon offset credit projects for seagrass meadows, macroalgal beds and macroalgae farming. Highlighted are their unique characteristics in the context of global efforts to mitigate climate change by conserving and expanding blue carbon sinks, and their calls for an acceleration of such initiatives.

In addition to these carbon credit assessments, previous studies have been conducted on carbon credit market transactions. Woo et al. (2021) indicates that the building industry's efforts to reduce its carbon footprint have been hindered by complex and unreliable systems for measuring and reporting carbon emissions, but suggest that adopting blockchain technology could provide a transparent, accurate and affordable solution, potentially allowing the sector to engage effectively in carbon credit markets.

On the other hand, there is no study which has analyzed the voluntary carbon market from a macro perspective and analyed trend changes by region and technology. The predominance of carbon credit projects varies depending on the technology applied and the region where it is implemented (IPCC, 2022). This is because the cost of the project and the amount of credits vary depending on the technology, as well as the regulatory and geopolitical risks in the location where the project is implemented (Worldbank, 2022a). Therefore, it is clear that incentives to implement carbon credit projects vary depending on the type of technology and regions. To clarify: the key driving factors of changes in the nature of carbon credits issued are important for the development of effective policies designed to encourage the growth of the voluntary carbon market. To this end, the present study focuses on the characteristics of carbon credit projects, especially technology and regions.

Figure 2 represents the research framework of this study. The new application of the decomposition method to carbon credits issued is used to clarify the main factors promoting carbon offset program implementation and to what extent they are the cause of the relative priority change among project technologies (*PPRIORITY*), of the scale change in the offset programs (*SCALE*), of the relative importance in changes between project technology (*IMPORTANCE*) and of the level of activity of voluntary registry carbon offset programs (*ACTIVITY*). This decomposition application is useful for climate mitigation policy makers by providing a better understanding of effective macro and micro policies through which the specific technology of carbon offset program in each region can be assessed.

The idea of the PRIORITY indicator was derived from the previous literature on patent data analysis. Revealed technological advantage, a measure of technological advantage using patent data, uses the percentage of patents granted for individual technologies to evaluate the relative specialization of technologies (Zachmann and Kalcik, 2018). Popp (2002) states that the share of individual technology patents in total patents can reflect the growth in the economy and exogenous changes in patenting behavior. These patent data analyses interpret the proportion of each technology as a relative advantage. This study applies this concept to technology selection in carbon credit projects, defining it as an indicator of relative priority.

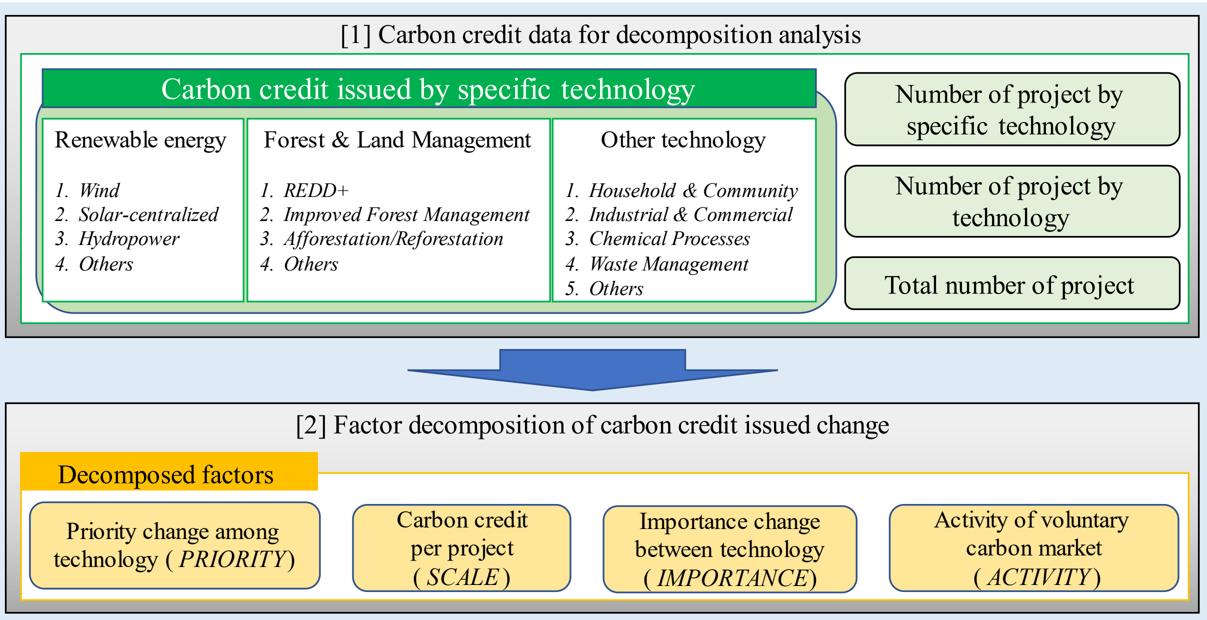


Figure 2. Research framework

The ACTIVITY indicator was derived from the World Bank;s (2022a) analysis,. During economic recessions, CO_2 emissions are expected to decline as corporate activities are also reduced. In this case, the demand for carbon credits in the voluntary carbon offset market may decline because the required CO_2 reductions will be smaller. Lower demand for carbon credits will decrease their price which reduces activity in the voluntary carbon offset market (World Bank 2022a). Conversely, we can also expect demand for carbon credits to increase as climate change policies are strengthened.

The SCALE is derived from the Institute of International Finance's (2021) and UNDP's (2021) definitions. They suggest rapid-supply scale-up action across all offset categories is required to diffuse cost-effective climate change mitigation. They also suggest the scale-up high-integrity supply of carbon credits.

Based on these suggestions, this study employe the SCALE indicator to evaluate the size of carbon credit projects within the decomposition framework.

Finally, this study set the IMPORTANCE as an indicator of relative advantage among technologies. This idea is derived from the World Bank's (2023) study which evaluate the relative importance between project categories by using percentage of total issuance by project technology. By using the above four indicators - PRIORITY and ACTIVITY plus SCALE and IMPORTANCE - it is possible to construct a framework for decomposing the factors of change in carbon credits issued according to technology.

3. Methodology

3-1. Decomposition analysis framework of carbon credits issued

We apply a decomposition analysis framework to clarify the determinant factors associated with the level of change in the issuance of carbon credits. The definitions of each indicator are explained here.

The *PRIORITY* indicator can be defined by the amount of carbon credits issued from a specific technology project divided by the total number of carbon credits issued for other technology projects. Thus, *PRIORITY* represents the share of carbon credits issued by specific technology projects.

SCALE indicator is defined as the total amount of credits issued divided by the number of carbon offset projects. This indicator rises when the amount of carbon credits issued per project increases. In this case, it suggests that the size of the project is increasing. In other words, this study seeks to capture the scale change effect of carbon offset programs using the *SCALE* indicator.

Next, *IMPORTANCE* is defined as the relative importance of carbon offset projects between the various project technologies. This indicator increases if the number of carbon offset projects using specific technologies (e.g., renewable energy) increases more quickly than the total number of carbon offset projects using other technologies. This indicates the way in which project managers are shifting their technological importance preferences for renewable energy in their carbon offset program's strategy.

Finally, the *ACTIVITY* indicator is defined as the total number of carbon offset programs and thus represents the activity level of voluntary registry carbon offset markets. This indicator is affected by macro factors such as climate change policies and economic conditions.

3-2. Decomposition analysis for wind power generation projects

By way of an explanatory example, we introduce a decomposition approach using the carbon credits issued for wind power generation projects ($CREDIT_{WIND}$) which are decomposed using the priority for wind power generation (*PRIORITY*), scale of the carbon offset project (*SCALE*), importance of the renewable energy project (*IMPORTANCE*) and level of activity of the voluntary carbon offset market (ACTIVITY), as shown in equation (1). Here, $CREDIT_{RENEWABLE}$ is the amount of carbon credits issued by the renewable energy project, $PROJECT_{RENEWABLE}$ is the number of carbon offset projects found among the renewable energy projects and $PROJECT_{ALL}$ is the total number of carbon offset projects.

$$\begin{aligned}\mathrm{CREDIT}_{WIND} &= \frac{\mathrm{CREDIT}_{WIND}}{\mathrm{CREDIT}_{RENEWABLE}} \times \frac{\mathrm{CREDIT}_{RENEWABLE}}{\mathrm{PROJECT}_{RENEWABLE}} \times \frac{\mathrm{PROJECT}_{RENEWABLE}}{\mathrm{PROJECT}_{ALL}} \times \mathrm{PROJECT}_{ALL} \\ &= \mathrm{PRIORITY} \times \mathrm{SCALE} \times \mathrm{IMPORTANCE} \times \mathrm{ACTIVITY}\end{aligned} \tag{1}$$

We consider the change in the amount of carbon credits issued for wind power generation from year t ($\mathrm{CREDIT}_{WIND}^{t}$) to year t+1 ($\mathrm{CREDIT}_{WIND}^{t+1}$). Using equation (1), the change in the amount of carbon credits issued by wind power generation projects can be represented as follows.

$$\frac{\mathrm{CREDIT}_{WIND}^{t+1}}{\mathrm{CREDIT}_{WIND}^{t}} = \frac{\mathrm{PRIORITY}^{\mathrm{t+1}}}{\mathrm{PRIORITY}^{\mathrm{t}}} \times \frac{\mathrm{SCALE}^{\mathrm{t+1}}}{\mathrm{SCALE}^{\mathrm{t}}} \times \frac{\mathrm{IMPORTANCE}^{\mathrm{t+1}}}{\mathrm{IMPORTANCE}^{\mathrm{t}}} \times \frac{\mathrm{ACTIVITY}^{\mathrm{t+1}}}{\mathrm{ACTIVITY}^{\mathrm{t}}} \tag{2}$$

We can transform equation (2) into a natural logarithmic function and thus obtain equation (3).[3]

$$\ln(\mathrm{CREDIT}_{WIND}^{t+1}) - \ln(\mathrm{CREDIT}_{WIND}^{t})$$

[3] Zero values in the dataset cause problems in the formulation of the decomposition because of the properties of logarithmic functions. To solve this problem, the literature on LMDI suggests replacing zero values with a small positive number (Ang and Liu, 2007).

$$= \ln\left(\frac{\text{PRIORITY}^{t+1}}{\text{PRIORITY}^{t}}\right) + \ln\left(\frac{\text{SCALE}^{t+1}}{\text{SCALE}^{t}}\right) + \ln\left(\frac{\text{IMPORTANCE}^{t+1}}{\text{IMPORTANCE}^{t}}\right) + \ln\left(\frac{\text{ACTIVITY}^{t+1}}{\text{ACTIVITY}^{t}}\right) \quad (3)$$

Multiplying both sides of equation (3) by $\omega_t^{t+1} = (\text{CREDIT}_{WIND}^{t+1} - \text{CREDIT}_{WIND}^{t}) / \{\ln(\text{CREDIT}_{WIND}^{t+1}) - \ln(\text{CREDIT}_{WIND}^{t})\}$ yields equation (4) as follows. [4]

$$\text{CREDIT}_{WIND}^{t+1} - \text{CREDIT}_{WIND}^{t} = \varDelta\text{CREDIT}_{WIND}^{t,t+1}$$
$$= \omega_t^{t+1}\ln\left(\frac{\text{PRIORITY}^{t+1}}{\text{PRIORITY}^{t}}\right) + \omega_t^{t+1}\ln\left(\frac{\text{SCALE}^{t+1}}{\text{SCALE}^{t}}\right) \quad (4)$$
$$+ \omega_t^{t+1}\ln\left(\frac{\text{IMPORTANCE}^{t+1}}{\text{IMPORTANCE}^{t}}\right) + \omega_t^{t+1}\ln\left(\frac{\text{ACTIVITY}^{t+1}}{\text{ACTIVITY}^{t}}\right)$$

Therefore, the change in the amount of carbon credits issued by wind power generation projects from year t to year t+1 ($\varDelta\text{CREDIT}_{WIND}^{t,t+1}$) is decomposed based on changes in *PRIORITY* (first term), *SCALE* (second term), *IMPORTANCE* (third term) and *ACTIVITY* (fourth term). The term ω_t^{t+1} operates as an additive weight to estimate the amount of carbon credits issued for wind power generation.

This decomposition technique was developed by Ang et al. (1998) and is termed the logarithmic mean Divisia index (LMDI). Ang (2004) noted that LMDI is the preferred method for decomposition analysis because of its theoretical foundation, adaptability, ease of use and result interpretation and lack of the residual terms generated by Laspeyres-type methodologies. Ang (2015) noted that the LMDI is the preferred method of decomposition analysis because of its theoretical foundations, adaptability, ease of use, ease of interpretation and absence of residual terms. The LMDI approach is widely applied in social science research fields to investigate the main driving factors affecting changes to data such as climate change (de Freitas and Kaneko, 2011) and toxic chemical management (Fujii and Managi, 2013).

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[4] Multiplying the left side of equation (3) by $(\text{CREDIT}_{WIND}^{t+1} - \text{CREDIT}_{WIND}^{t}) / \{\ln(\text{CREDIT}_{WIND}^{t+1}) - \ln(\text{CREDIT}_{WIND}^{t})\}$ gives the left side of equation (4). By multiplying each term on the right side of equation (3) by ω_t^{t+1}, the right side of equation (4) is obtained.

4. Data

We used the Voluntary Registry Offsets Database version 6 developed by the Berkeley Carbon Trading Project (So et al., 2022). It covers all carbon offset projects listed globally by four major voluntary offset project registries: American Carbon Registry, Climate Action Reserve, Gold Standard and Verified Carbon Standard. We specified the three groups based on the project technology classification scheme defined by So et al. (2022).

The Voluntary Registry Offsets Database version 6 provides two sets of information on carbon credit data: vintage year (the year in which the reduction or removal occurred) and issuance year (the year the registry issued the credit). In this study, the decomposition analysis is conducted using the carbon credits issued by vintage year. The reason for this is that the vintage year reflects the timing of the implementation of the carbon offset project, making it possible to consider changes in the priority and importance of the project manager. On the other hand, the issuance year reflects the year in which the carbon credit was certified after the carbon offset program was completed and reviewed by a third-party organization. In this case, it is difficult to identify why the amount of carbon credits issued changed in each issuance year because the review period varies by project technology and implementing country. Based on the above, this study applies a factor decomposition analysis using the carbon credits issued by vintage year.

This study focuses on three carbon offset groups: (1) renewable energy (RENEWABLE), (2) forestry & land use (FORESTRY) and (3) other carbon offset technologies (OTHER). Appendix 1 shows the list of projects technologies. Additionally, this study divides the four regional groups (Americas. Asia-Pacific, Africa & Middle East and others) to compare the main driving factors affecting changes in the issuance of carbon credits (see Appendix 2).

Table 1 shows the amount of carbon credits issued from 2006 to 2020 by region and group. Notably, the amount of carbon credits issued varies according to project technology and region. In the Americas, a large volume of carbon credits was issued by the forestry & land use group, especially for improved forest management and REDD+[5]. On the other hand, in the Asia-Pacific the renewable energy group is a major issuer of carbon credits.

The volume of carbon credits issued in Africa & Middle East regions tends to be lower than in other regions. It is also found that the amount of carbon credits issued from household & community (in the 'other' group) is higher than in other regions. In Africa & Middle East regions, many carbon credits have been issued through the carbon offset projects related to cookstoves. An interpretation of this trend relates to the lack of adequate electricity and gas supply in the rural areas in African regions and where cookstoves made from biomass are used for cooking. Several projects are being implemented to improve the performance of these cookstoves. (Mekonnen et al., 2022).

Table 1. Amount of carbon credits issued from 2006 to 2020 by region and group (million ton-CO_2)

Technology		Americas	Asia-Pacific	Africa & Middle East	Other Regions	Total
Renewable energy	Total	50.8	366.8	82.5	3.1	503.3
	Solar - centralized	0.4	59.5	1.6	0.0	61.5
	wind	19.1	167.5	39.5	2.1	228.3
	Hydropower	17.9	108.6	40.1	0.5	167.1
	Others	13.4	31.1	1.3	0.5	46.3
Forestry & land use	Total	388.1	142.8	127.9	0.0	658.8
	Afforestation/reforestation	32.4	13.8	6.9	0.0	53.2
	Improved forest management	175.6	7.9	0.0	0.0	183.5
	REDD+	172.2	117.8	117.3	0.0	407.3
	Others	7.9	3.3	3.7	0.0	14.9
Others	Total	170.7	124.6	67.5	9.1	371.9
	Chemical processes	67.9	6.5	2.1	0.0	76.5
	Household & community	7.2	34.4	47.2	0.0	88.8
	Industrial & commercial	14.1	61.9	0.7	7.5	84.2
	waste management	58.7	17.8	17.0	0.5	94.1
	Others	22.8	4.0	0.5	1.1	28.4

Source: Voluntary Registry Offsets Database version 6 (So et al., 2022)

[5] REDD+ is a regulatory framework created by the UNFCCC Conference of the Parties (COP) to guide activities in the forest sector with the aim of reducing emissions from deforestation and forest degradation, sustainable management of forests and the conservation and enhancement of forest carbon stocks in developing countries. (UN-REDD, 2015)

5. Results

Figures 3 to 5 show the changes in the amount of carbon credits issued. This study divides the 15-year period of analysis (2006-2020) into three periods: 2006-2010 (Period 1), 2011-2015 (Period 2), 2016-2020 (Period 3) and analyzes changes in carbon credits during each period. In Figures 3, 4, and 5, changes from period 1 to period 2 are shown on the left and changes from period 2 to period 3 are shown on the right.

The value of the red point on the vertical axis is the variation in the amount of carbon credits issued in each period. The negative value of the red point indicates that the number of carbon credits issued was lower than in the base period. The bar chart shows the cumulative effects of each decomposed factor on the volume of carbon credits. The sum of the bars is equivalent to the red point. Table 2 to Table 4 represent the results of the decomposition analysis in three regions.

5.1. Forestry & land use

Figure 3 and Table 2 show the results of carbon credit decomposition analysis for each of the four project types in the forestry & land use technologies. Figure 3(a) shows that the increase in carbon credits issued is larger for REDD+ projects. The increase for carbon credits issued in REDD+ is due to the four factors. The increase in these factors can be attributed to the fact that the period of international recognition of REDD+ and the increase in the number of projects was from 2009 to 2015. Prior to this period REDD+ was taken up as a joint proposal by Papua New Guinea and Costa Rica at COP11 in 2005 and REDD+ was widely recognized internationally at COP14 in 2008 (Nhem et al., 2017). The Copenhagen Accord at COP15 in 2009 included the early creation of a framework for REDD+, including funding from developed countries. Indeed, there is evidence to indicate that the relative priority of REDD+ projects has increased as a result of the importance of REDD+ projects. Evidence for this, comes from Kenya's REDD+ project which became the first in the world to receive Verified Carbon Standard VCS certification (Nhem et al., 2017).

However, since 2016, the relative priority of REDD+ has decreased while the priority of forest management has increased (see Figure 3(b)). This suggests that the priority mechanism adopted by carbon offset projects for forestry & land use is shifting from REDD+ to forest management, especially in the

Americas region (see PRIORITY indicator in Table 2). This is due to the expansion of nature-based solution activities targeting forests in developed countries (Seddon et al., 2021). In this respect REDD+ is an initiative to reduce greenhouse gas emissions or increase absorption through the control of deforestation and forest degradation and sustainable forest management with a focus on developing countries. On the other hand, nature-based solutions by improving forest management are efforts to increase the effectiveness of CO_2 absorption and storage through appropriate management of natural capital, which includes developed countries in the target area. As such, they are being actively pursued not only by high-tech companies such as Microsoft, Amazon and Apple (ITU and WBA, 2022), but also by companies that use fossil fuels such as Shell, Unilever and Delta airlines (Seddon et al., 2021).

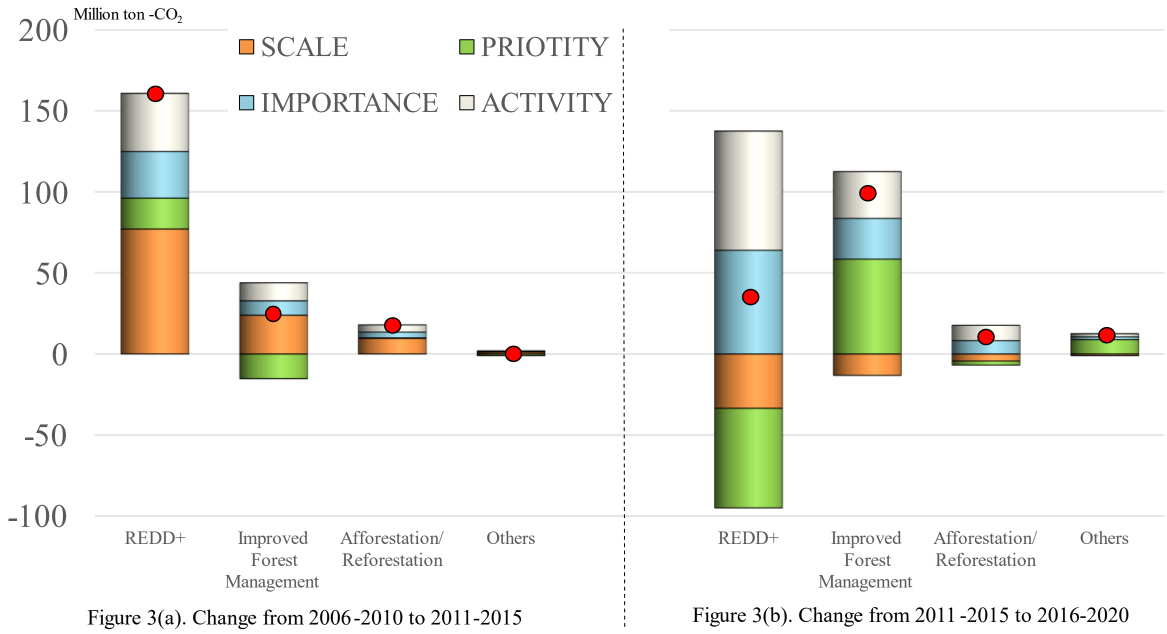

Figure 3. Result of decomposition analysis in the forestry & land use group

Note: The left hand graph shows the results for the period 2011 to 2015, using the period from 2006 to 2010 as the baseline. The right hand graph shows the results for the period 2016 to 20120, using the period from 2011 to 2015 as the baseline.

The following reasons provide background for these efforts. Since climate change and biodiversity loss are inextricably linked, the importance of addressing both crises simultaneously are emphasized (Pörtner et al., 2021). Nature-based climate solutions are rapidly gaining attention as an effective approach to the twin challenges of climate change and biodiversity loss (Seddon et al., 2021). Institutional design is also underway for a framework for biodiversity-related information disclosure. The draft framework of the Task Force on Nature-related Financial Disclosures (TNFD), which provides a disclosure framework for biodiversity and natural capital, was released in March 2022 (TNFD, 2022). The TNFD is expected to serve as a framework for directing the flow of funds to contribute to "nature positivity". Already, Apple Inc. and other corporations have established a $200 million reforestation fund and are working to help solve climate change issues through the power of nature (Apple, 2022).

Table 2. The results of decomposition analysis in forestry & land use by region (million ton-CO_2)

Region		2006-2010 to 2011-2015				2011-2015 to 2016-2020			
		REDD+	Improved forest management	Afforestation/ reforestation	Others	REDD+	Improved forest management	Afforestation/ reforestation	Others
Asia-pacific	Change	42.90	2.31	1.44	0.20	21.82	1.08	10.80	2.90
	SCALE	14.65	1.45	0.38	0.01	-16.81	-1.06	-1.52	-0.32
	PRIOTITY	1.82	-1.75	0.36	0.18	-8.73	-0.85	8.03	2.33
	IMPORTANCE	20.74	2.05	0.54	0.01	29.08	1.83	2.63	0.55
	ACTIVITY	5.68	0.56	0.15	0.00	18.29	1.15	1.66	0.34
Americas	Change	71.70	26.40	14.58	0.61	5.89	98.29	-2.16	5.29
	SCALE	34.22	20.44	7.41	0.80	-15.22	-13.51	-2.83	-0.55
	PRIOTITY	10.95	-9.88	1.42	-0.81	-43.22	54.70	-11.29	3.52
	IMPORTANCE	10.24	6.11	2.22	0.24	47.77	42.40	8.88	1.72
	ACTIVITY	16.29	9.73	3.53	0.38	16.56	14.69	3.08	0.60
Africa& Middle East	Change	46.18	0.00	1.93	0.16	14.91	0.00	2.25	3.41
	SCALE	22.10	0.00	1.17	0.01	19.52	0.00	1.10	0.38
	PRIOTITY	0.48	0.00	-0.48	0.14	-4.01	0.00	1.19	3.04
	IMPORTANCE	-2.49	0.00	-0.13	-0.00	-40.45	0.00	-2.27	-0.78
	ACTIVITY	26.09	0.00	1.38	0.01	39.85	0.00	2.24	0.77

5.2. Renewable energy

Figure 4 and Table 3 show the results of carbon credit decomposition analysis for each of the four project types of the renewable energy technologies. Figure 4(a) shows that the increase in carbon credits issued for hydro and wind projects is substantial from the 2006-2010 period to the 2010-2015 period. While the amount of credits issued by hydro power has been on an increasing trend due to the expansion of activity, the negative importance indicates that the share of renewable energy projects in the total carbon offset projects has been on a declining trend. The same results can be observed for wind power, except that the priority indicator is also significant and positive.

In the 2016-2020 period, carbon credit issuance by solar and wind power projects rose significantly, while hydropower credit issuance declined (see Figure 4(b)). The scale factor for wind and the priority factor for solar are the main drivers of the increase in the period 2016-2020. Table 3 shows that this trend can be particularly observed in the Asian-Pacific region. One reason for the scale expansion of wind power carbon offset projects is that large-scale wind power development projects have been implemented in India and China in response to growing social pressure as a result of electricity shortages and air pollution (IRENA, 2017; The World Bank, 2022b). Most of the carbon credits issued in the voluntary carbon offset market are for projects in China and India, which together account for 70% of the carbon credits derived from wind power projects from 2006 to 2020 (So et al., 2022).

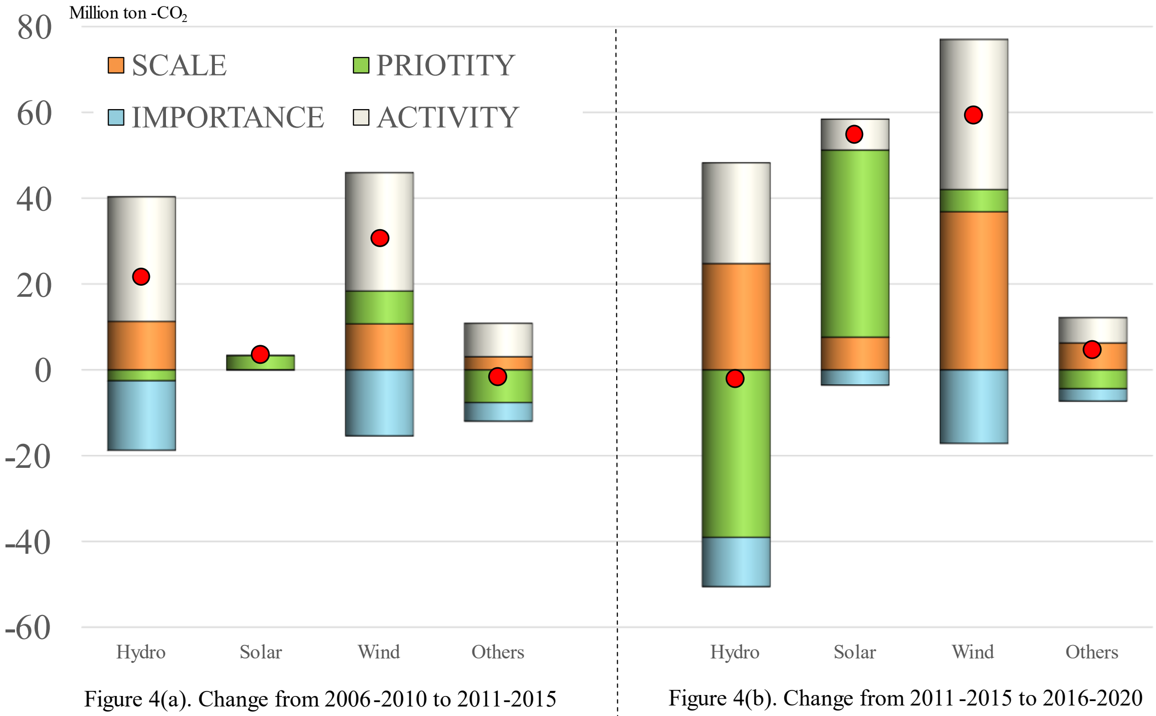

Figure 4. Result of decomposition analysis in renewable energy groups

Note: The left hand graph shows the results for the period 2011 to 2015, using the period from 2006 to 2010 as the baseline.
The right hand graph shows the results for the period 2016 to 20120, using the period from 2011 to 2015 as the baseline.

Figure 4(b) shows a significant increase of credits derived from solar power projects - a result of an increase in priority in the 2016 to 2020 period. Priority indicators were lower for hydropower, suggesting that a priority shift from hydropower to solar has occurred. One interpretation of this trend is that while the cost of solar power has decreased significantly, the cost of installing hydropower has not decreased sufficiently. The installed cost of photovoltaic power generation has decreased from 600$/MWh in 2000 to about 50$/MWh in 2020, which is comparable to the cost of wind power generation (IPCC, 2022). The lower cost of renewable energy generation has led to greater incentives to install new renewable energy projects, especially in developing countries (IRENA, 2017; The World Bank, 2022b).

Table 3. The results of decomposition analysis in renewable energy by region (million ton-CO_2)

Region		2006-2010 to 2011-2015				2011-2015 to 2016-2020			
		Hydropower	Solar - Centralized	Wind	others	Hydropower	Solar - Centralized	Wind	others
Asia-pacific	Change	-3.31	3.26	11.83	-1.50	4.25	53.02	48.58	5.73
	SCALE	3.21	0.01	3.40	0.79	20.75	10.79	37.64	6.13
	PRIOTITY	-7.67	3.25	7.22	-2.57	-24.93	37.85	-4.34	-2.90
	IMPORTANCE	-11.07	-0.03	-11.72	-2.73	-3.15	-1.64	-5.72	-0.93
	ACTIVITY	12.22	0.03	12.93	3.01	11.58	6.02	21.00	3.42
Americas	Change	8.13	0.03	8.00	0.05	-8.84	0.35	0.13	-0.85
	SCALE	5.07	0.00	2.73	3.54	-0.16	-0.00	-0.23	-0.11
	PRIOTITY	1.26	0.03	4.30	-4.75	-6.05	0.42	4.21	1.09
	IMPORTANCE	-1.80	-0.00	-0.97	-1.26	-3.87	-0.09	-5.67	-2.70
	ACTIVITY	3.60	0.00	1.94	2.52	1.25	0.03	1.83	0.87
Africa& Middle East	Change	16.82	0.04	9.91	0.12	1.91	1.51	10.77	-0.10
	SCALE	4.15	0.00	4.16	0.28	0.28	0.01	0.26	0.01
	PRIOTITY	4.19	0.04	-2.76	-0.72	-5.16	1.35	4.26	-0.27
	IMPORTANCE	-1.78	-0.00	-1.79	-0.12	-6.77	-0.15	-6.22	-0.16
	ACTIVITY	10.26	0.00	10.29	0.68	13.56	0.30	12.47	0.33

5.3. Other technology

Figure 5 and Table 4 shows the results of carbon credit decomposition analysis for each of the five project types in terms or other carbon offset technologies. Figure 5(a) shows that the change in carbon credits issued is large for the household & community group and the waste management group from 2006-2010 to

2011-2015. When the changes in household & community carbon credit issuance are examined (Figure 5(a), (b)), the priority indicator for the household & community group is shown to have increased significantly.

The underlying reason is the increase in the number of carbon offset projects for cookstoves in the Asia-Pacific and Africa & Middle East regions (see Table 4). From Voluntary Registry Offsets Database version 6 (So et al., 2022), the number of cookstoves projects targeting South Asia (e.g., India, Bangladesh) and Sub-Saharan Africa (e.g., Rwanda, Uganda) region has increased significantly. The carbon offset program for the building improved cookstoves is a project that not only reduces CO_2 emissions, but also improves people's convenience and health[6]. The improvement of cooking equipment facilities in households has the effect of decreasing the SCALE indicator because the amount of carbon offset per project is small. But the increase in the number of projects contributes to the increase in carbon credits issued (Chan et al., 2015).

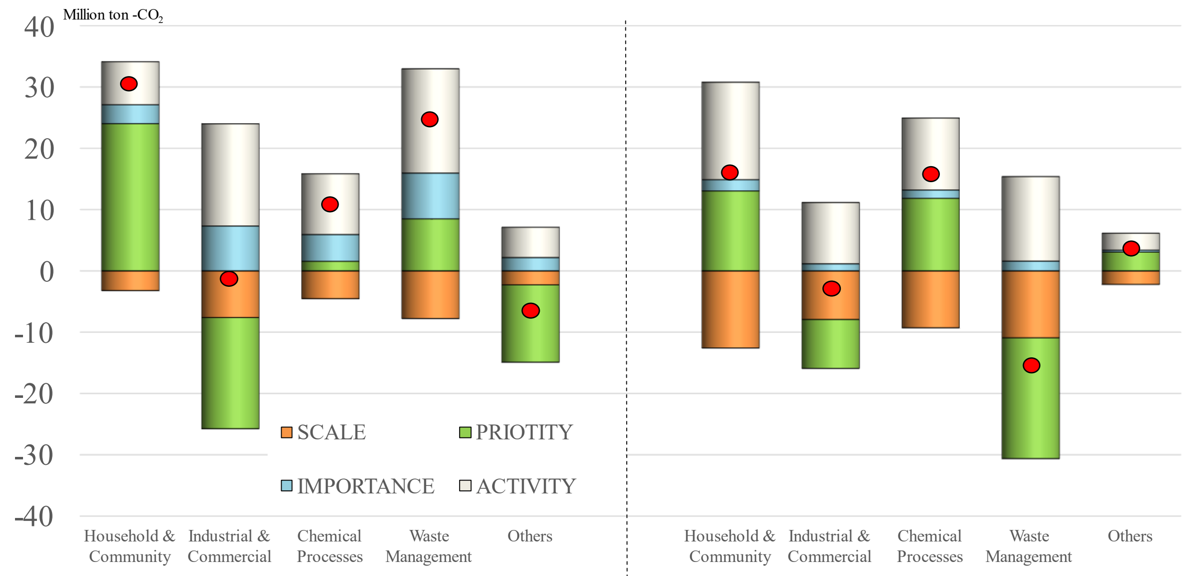

Figure 5(a). Change from 2006-2010 to 2011-2015

Figure 5(b). Change from 2011 -2015 to 2016-2020

Figure 5. Result of decomposition analysis in other carbon offset groups

Note: The left hand graph shows the results for the period 2011 to 2015, using the period from 2006 to 2010 as the baseline. The right hand graph shows the results for the period 2016 to 20120, using the period from 2011 to 2015 as the baseline.

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[6] The carbon offset program relating to "Cookstoves" relates to building improved cookstoves to replace or minimize the use of dung or firewood for cooking. Carbon benefits are realized in the form of reduced emissions from burning biomass as well as reducing deforestation. Stoves generally lessen smoke during cooking, leading to additional health benefits. Replacement cookstoves include residential solar-powered cooking systems, which are not grid-connected (So et al., 2022).

Carbon credit issuance by chemical process projects rose significantly in the 2016 to 2020 periods (see Figure 5(b)). One interpretation of this results is that refrigerant-related project types in the U.S., such as HFC refrigerant reclamation and HFC replacement in foam production, in Ohio, Texas, and Virginia in 2019 and 2020. The results of these efforts are reflected in the increase in the priority index for chemical processing in the Americas region in Table 4.

Table 4. Results of decomposition analysis of other technologies by region (million ton-CO_2)

		2006-2010 to 2011-2015					2011-2015 to 2016-2020				
Region		HH&C	I&C	Chemi	Waste	Other	HH&C	I&C	Chemi	Waste	Other
Asia-pacific	Change	12.14	3.81	-4.70	3.18	-0.16	5.08	-8.00	-0.89	1.62	2.86
	SCALE	-3.94	-15.52	-1.76	-3.22	-0.28	-6.06	-7.59	-0.01	-2.71	-0.47
	PRIOTITY	10.01	-4.57	-5.65	1.45	-0.31	4.84	-8.29	-0.90	1.52	2.85
	IMPORTANCE	4.08	16.07	1.82	3.33	0.29	1.04	1.31	0.00	0.47	0.08
	ACTIVITY	1.99	7.83	0.89	1.62	0.14	5.25	6.58	0.01	2.35	0.41
Americas	Change	2.79	1.86	16.20	12.03	-8.49	1.39	2.91	17.01	-8.76	1.77
	SCALE	0.01	0.05	0.20	0.32	0.12	0.78	1.26	6.69	4.86	1.11
	PRIOTITY	2.39	0.13	9.67	1.71	-12.45	0.64	1.70	10.60	-13.42	0.71
	IMPORTANCE	-0.02	-0.10	-0.37	-0.59	-0.23	-0.74	-1.19	-6.33	-4.60	-1.05
	ACTIVITY	0.41	1.77	6.69	10.59	4.07	0.71	1.14	6.05	4.40	1.01
Africa& Middle East	Change	16.00	0.07	-0.16	9.91	0.24	11.74	0.37	-0.44	-8.38	-0.00
	SCALE	0.76	0.01	0.11	0.69	0.01	-20.47	-0.25	-0.49	-6.10	-0.23
	PRIOTITY	4.06	-0.10	-1.91	-0.85	0.07	9.40	0.35	-0.50	-9.07	-0.03
	IMPORTANCE	2.14	0.03	0.31	1.93	0.03	6.97	0.08	0.17	2.08	0.08
	ACTIVITY	9.04	0.13	1.32	8.14	0.13	15.84	0.19	0.38	4.72	0.18

Note: HH&C is household and community, I&C is industrial and commercial, Chemi is chemical process, Waste is waste management.

6. Conclusions and policy implications

This study has examined the determinant factors contributing to carbon credits issued in voluntary carbon offset markets from 2006 to 2020 using a decomposition analysis framework. We have focused on three carbon offset technologies: forestry & land use, renewable energy, and other carbon offsets. The key results are summarized as follows.

First, the amount of carbon credits issued related to forestry & land use increased from 2006-2010 to 2011-2015 due to scale expansion in the REDD+ project. Meanwhile, priority was shifted from REDD+ to improve forest management in the 2016 to 2020 period. The reason for this shift is that climate change mitigation that utilizes natural capital, such as nature-based solutions, have been promoted mainly in the United States.

Second, carbon credits issued related to renewable energy increased from 2006-2010 to 2011-2015 due to growth of the voluntary carbon offset market. Meanwhile, carbon credits issued increased in the 2016 to 2020 period due to scale expansion of wind power technology and priority gain in solar power technology. This is because the cost of solar and wind power decreased significantly in late 2010's, which provided a strong incentive for project developers to implement carbon offset projects using these technologies.

Finally, we observed that the priority changes in carbon credit issued were diverse among carbon offset projects in each region. This is because 'incentive' and 'difficulty for carbon offset program implementation' vary according to project types and regions. Project developers have different motivations to implement different types of carbon offset program in different regions. Additionally, the determining factors behind the project development of carbon offset programs vary according to technology. The comparison of the scale effect and prioritization of the carbon offset program is therefore a useful tool for understanding changes in carbon credits issued by project technology and region.

This is the first study to investigate the change of carbon credit issued using decomposition analysis and numerical data. The application of a decomposition method to carbon credits issued by technology and region can clarify the trend and priority change for carbon offset project implementation in more detail. This information is helpful for policy makers and carbon offset project developers in creating more effective carbon offset protocols and management ideas. This is particularly important given the growing criticism of the effectiveness of REDD and forestry management carbon credit schemes and where it is claimed a majority of projects are significantly underestimating levels and sustainability of CO_2 reduction. This relates to a range of issues relating to the lack of a robust criteria for establishing credible deforestation baselines, problems in reliably monitoring and verifying change in forest cover; poor governance of illegal logging, lack of financial compensation to forest inhabitants and what is termed 'international leakage' which relates to whether forest conservation in one country drives deforestation in another.

But given the IPCC's pathways to carbon neutrality critically depend on the use of carbon offsets reform rather than abandonment is clearly essential. The extent of the increase in forestry related offsets which this article tracks therefore indicates that it is this category of offsets – which is by far the hardest to monitor and measure in terms of efficacy – needs priority attention to reform. Given carbon credits are traded internationally, such reform would involve internationally agreed and far stricter regulation. While the needed wide scope of such reforms may reduce the scope for creating these types of credits, this may be an advantage in encouraging the uptake of more reliable alternatives – especially those relating to renewable energy. One innovative way of improving the efficacy and attractiveness of forestry related carbon offsets is the issuance of combined carbon and biodiversity credits in which the returns are jointly maximized (Webb, et al., 2023). However, this would also require both reform of the carbon credit scheme and additionally a creative regime of co- regulation.

For future research, it will be important to consider the legal and energy market factors that affect the carbon credit market[7]. By applying an econometric model using these factors, it is possible to analyze the impact of different legal status and energy market prices on carbon credits issued in voluntary markets.

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Declarations of interest

The authors declare no competing interests.

[7] Figures A1 to A6 in the Appendix show the results of factor decomposition analysis for countries that have introduced carbon taxes, emissions trading schemes and carbon credits, as well as for countries that have not. The analysis results are consistent with the discussion of the analysis explained in Chapter 5.

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Appendix 1. List of project technology groups, scope and type in Voluntary Registry Offsets Database

Technology group	Technology scope	Technology type
Forestry & Land Use	Forestry & Land Use	Afforestation/Reforestation
Forestry & Land Use	Forestry & Land Use	Avoided Forest Conversion
Forestry & Land Use	Forestry & Land Use	Avoided Grassland Conversion
Forestry & Land Use	Forestry & Land Use	Improved Forest Management
Forestry & Land Use	Forestry & Land Use	REDD+
Forestry & Land Use	Forestry & Land Use	Sustainable Grassland Management
Forestry & Land Use	Forestry & Land Use	Wetland Restoration
Renewable Energy	Renewable Energy	Biomass
Renewable Energy	Renewable Energy	Geothermal
Renewable Energy	Renewable Energy	Hydropower
Renewable Energy	Renewable Energy	RE Bundled
Renewable Energy	Renewable Energy	Solar – Centralized
Renewable Energy	Renewable Energy	Solar – Distributed
Renewable Energy	Renewable Energy	Solar Lighting
Renewable Energy	Renewable Energy	Solar Water Heaters
Renewable Energy	Renewable Energy	Wind
Others	Transportation	Bicycles
Others	Transportation	Electric Vehicles & Charging
Others	Transportation	Fleet Efficiency
Others	Transportation	Fuel Transport
Others	Transportation	Mass Transit
Others	Transportation	Shipping
Others	Transportation	Truck Stop Electrification
Others	Waste Management	Composting
Others	Waste Management	Landfill Methane
Others	Waste Management	Methane Recovery in Wastewater
Others	Waste Management	Waste Diversion
Others	Waste Management	Waste Incineration
Others	Waste Management	Waste Recycling
Others	Household & Community	Biodigesters
Others	Household & Community	Bundled Energy Efficiency
Others	Household & Community	Clean Water
Others	Household & Community	Community Boreholes
Others	Household & Community	Cookstoves
Others	Household & Community	Lighting
Others	Household & Community	Weatherization

Source: Voluntary Registry Offsets Database version 6 (So et al., 2022)

Appendix 1 (cont.). List of project technology group, scope and type in Voluntary Registry Offsets Database

Technology group	Technology scope	Technology type
Others	Industrial & Commercial	Aluminum Smelters Emission Reductions
Others	Industrial & Commercial	Brick Manufacturing Emission Reductions
Others	Industrial & Commercial	Energy Efficiency
Others	Industrial & Commercial	Fuel Switching
Others	Industrial & Commercial	Grid Expansion & Mini-Grids
Others	Industrial & Commercial	Leak Detection & Repair in Gas Systems
Others	Industrial & Commercial	Mine Methane Capture
Others	Industrial & Commercial	Mineralization
Others	Industrial & Commercial	Natural Gas Electricity Generation
Others	Industrial & Commercial	Oil Recycling
Others	Industrial & Commercial	Pneumatic Retrofit
Others	Industrial & Commercial	University Campus Emission Reductions
Others	Industrial & Commercial	Waste Gas Recovery
Others	Industrial & Commercial	Waste Heat Recovery
Others	Chemical Processes	Advanced Refrigerants
Others	Chemical Processes	HFC Refrigerant Reclamation
Others	Chemical Processes	HFC Replacement in Foam Production
Others	Chemical Processes	HFC23 Destruction
Others	Chemical Processes	N2O Destruction in Adipic Acid Production
Others	Chemical Processes	N2O Destruction in Nitric Acid Production
Others	Chemical Processes	Ozone Depleting Substances Recovery & Destruction
Others	Chemical Processes	Propylene Oxide Production
Others	Chemical Processes	Refrigerant Leak Detection
Others	Chemical Processes	SF6 Replacement
Others	Agriculture	Bundled Compost Production and Soil Application
Others	Agriculture	Compost Addition to Rangeland
Others	Agriculture	Feed Additives
Others	Agriculture	Improved Irrigation Management
Others	Agriculture	Manure Methane Digester
Others	Agriculture	Nitrogen Management
Others	Agriculture	Rice Emission Reductions
Others	Agriculture	Solid Waste Separation
Others	Agriculture	Sustainable Agriculture
Others	Carbon Capture & Storage	Carbon Capture & Enhanced Oil Recovery
Others	Carbon Capture & Storage	Carbon Capture in Cement
Others	Carbon Capture & Storage	Carbon Capture in Plastic

Source: Voluntary Registry Offsets Database version 6 (So et al., 2022)

Appendix 2. List of region group and countries

Asia-pacific	Americas	Africa & Middle East		Other regions
Australia*	Argentina*	Angola	Madagascar	Albania
Bangladesh	Aruba	Bahrain	Malawi	Austria*
Cambodia	Belize	Benin	Mali	Bulgaria*
China*	Bolivia	Botswana	Mauritania	Germany*
Fiji	Brazil	Burkina Faso	Mauritius	Greece*
India	Canada*	Burundi	Mayotte	Italy*
Indonesia*	Chile*	Cameroon	Morocco	Kosovo
Kazakhstan*	Colombia*	Central African Republic	Mozambique	Latvia*
Laos	Costa Rica	Chad	Namibia	Netherlands*
Malaysia	Dominican Republic	Comoros	Niger	North Macedonia
Mongolia	Ecuador	Côte d'Ivoire	Nigeria	Romania*
Myanmar	El Salvador	Cyprus	Oman	Serbia
Nepal	Guatemala	Djibouti	Republic of Congo	Spain*
New Caledonia	Haiti	DRC	Rwanda	Switzerland*
New Zealand*	Honduras	Egypt	Saudi Arabia	United Kingdom*
Pakistan	Mexico*	Eritrea	Senegal	
Papua New Guinea	Nicaragua	Ethiopia	Sierra Leone	
Philippines	Panama	Gambia	Somalia	
Russia*	Paraguay	Georgia	South Africa*	
Singapore*	Peru	Ghana	Sudan	
South Korea	Suriname	Guinea	Syria	
Sri Lanka*	United States*	Guinea-Bissau	Tanzania	
Taiwan	Uruguay*	Iraq	Togo	
Tajikistan		Israel	Tunisia	
Thailand*		Jordan	Turkey	
Timor-Leste		Kenya	Uganda	
Turkmenistan		Lesotho	United Arab Emirates	
Uzbekistan		Liberia	Zambia	
Vietnam			Zimbabwe	

Source: Voluntary Registry Offsets Database version 6 (So et al., 2022)

Note: * represents the country which implemented a carbon tax, carbon emission trading systems, and carbon credit mechanisms. (Countries are identified by the Carbon Pricing Dashboard provided by World Bank). This grouping method is applied in Figure A1 to A6.

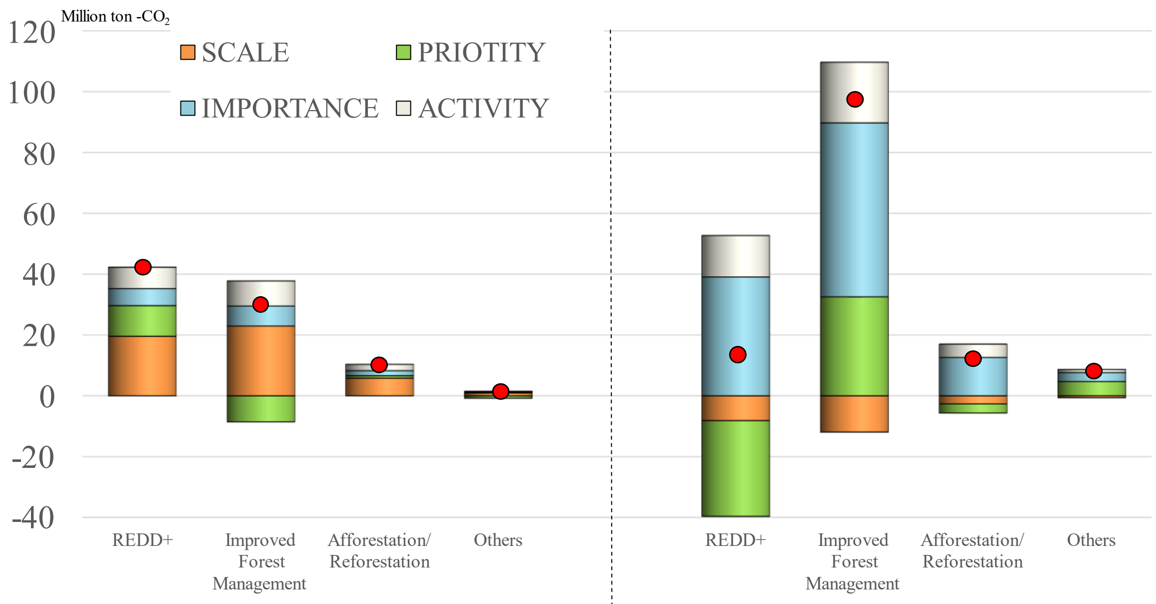

Figure A1(a). Change from 2006-2010 to 2011-2015

Figure A1(b). Change from 2011-2015 to 2016-2020

Figure A1. Decomposition analysis results of forest and land use in countries which implemented carbon taxes, emission trading systems and carbon credit mechanisms.

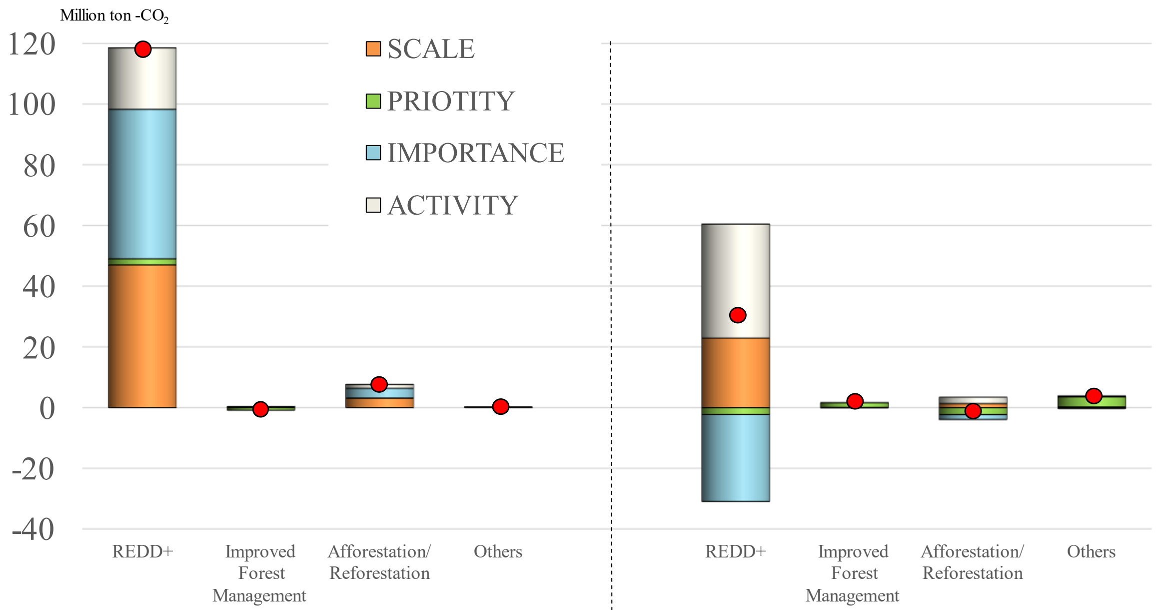

Figure A2(a). Change from 2006-2010 to 2011-2015

Figure A2(b). Change from 2011-2015 to 2016-2020

Figure A2. Decomposition analysis results of forest and land use in countries which do not implement carbon taxes, emission trading systems and carbon credit mechanisms.

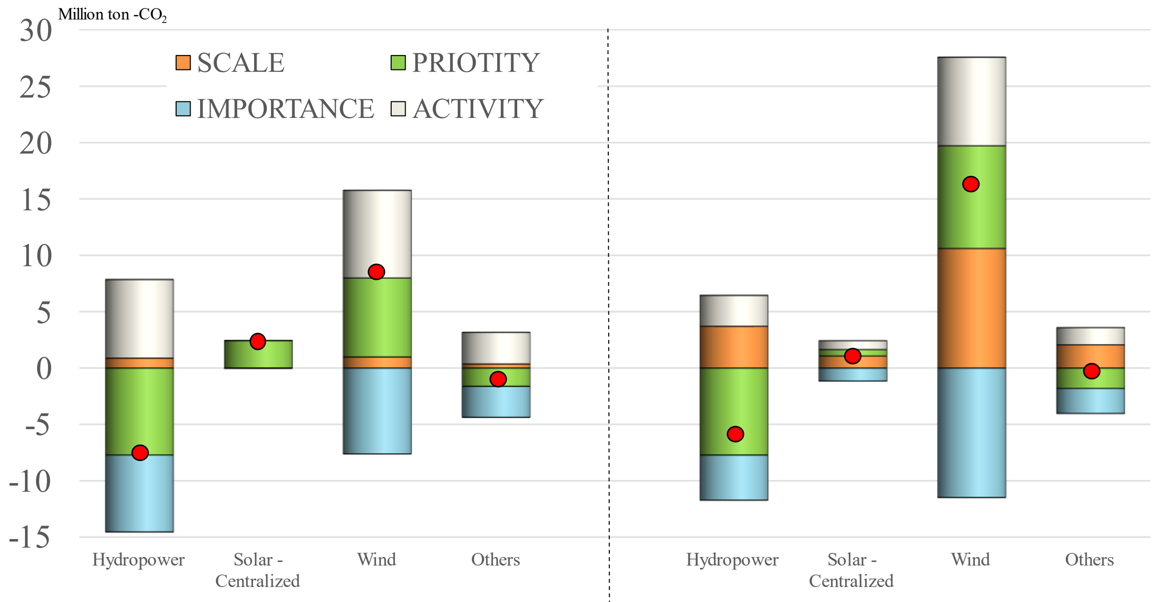

Figure A3(a). Change from 2006-2010 to 2011-2015

Figure A3(b). Change from 2011-2015 to 2016-2020

Figure A3. Decomposition analysis results of renewable energy in countries which implemented carbon taxes, emission trading systems and carbon credit mechanisms.

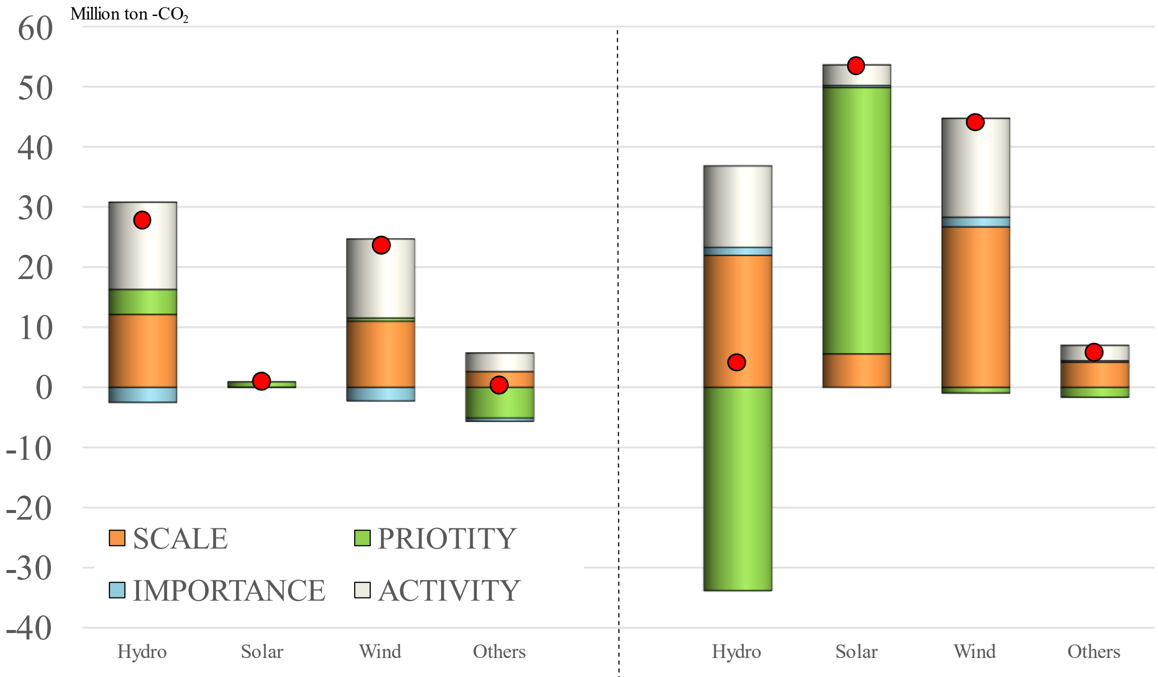

Figure A4(a). Change from 2006-2010 to 2011-2015

Figure A4(b). Change from 2011-2015 to 2016-2020

Figure A4. Decomposition analysis results of renewable energy in countries which do not implement carbon taxes, emission trading systems, and carbon credit mechanisms.

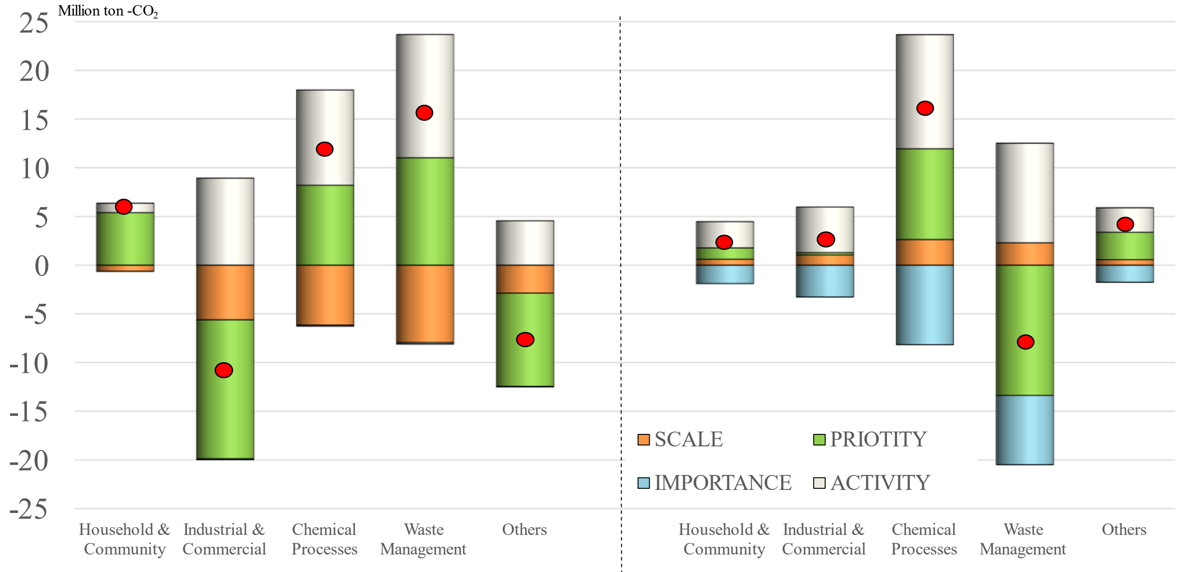

Figure A5(a). Change from 2006-2010 to 2011-2015 Figure A5(b). Change from 2011-2015 to 2016-2020

Figure A5. Decomposition analysis results of other technologies in countries which implemented carbon taxes, emission trading systems, and carbon credit mechanisms.

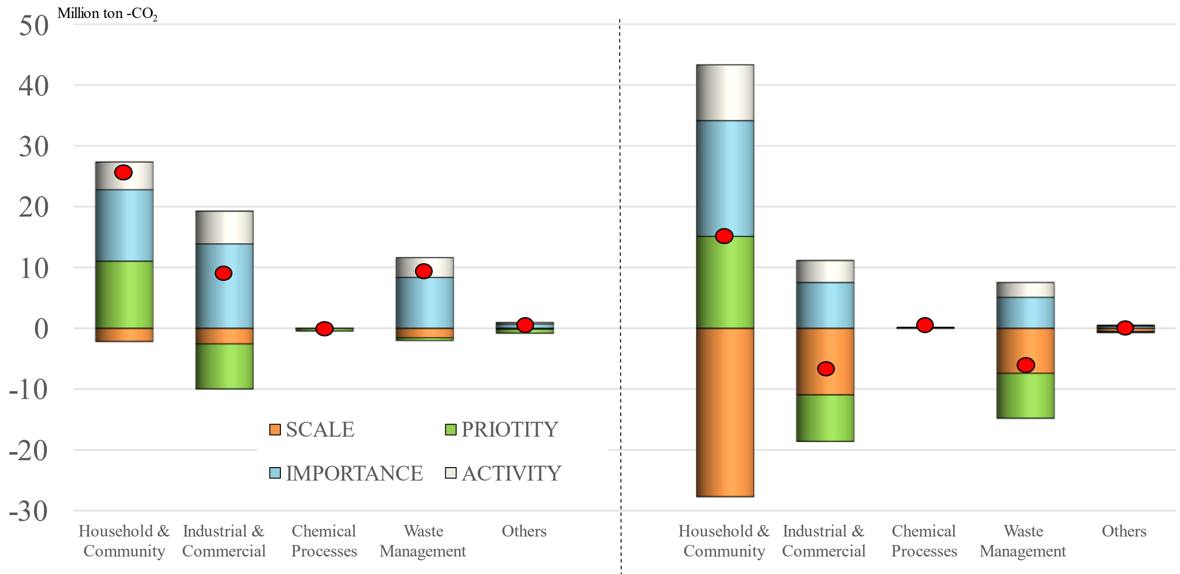

Figure A6(a). Change from 2006-2010 to 2011-2015 Figure A6(b). Change from 2011-2015 to 2016-2020

Figure A6. Decomposition analysis results of other technologies in countries which do not implement carbon taxes, emission trading systems, and carbon credit mechanisms.