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Net CO2 Emissions from Global Photovoltaic Development

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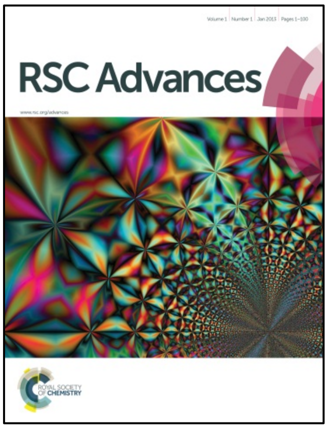

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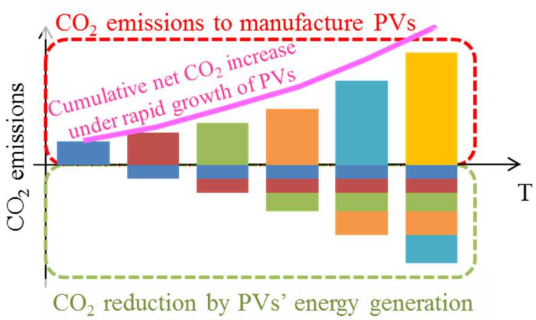

The net CO_2 emissions by PV deployment in the world were estimated in the past and future.

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Net CO_2 Emissions from Global Photovoltaic Development

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We examine cumulative net energy use and cumulative net CO_2 emissions associated with the development of photovoltaics (PVs) on a global scale. The analysis is focused on the performance of five countries with the largest installed PV capacities —Italy, Japan, Germany, Spain, and the United States— and on the aggregate values for the world (23 countries). The historical record shows that, during the past 19 years of development, the installed base has grown to 64 GW, with an average annual growth rate of almost 40%. During that period the manufacturing and use of photovoltaics has led to a cumulative net consumption of approximately 286 PJ of energy, and cumulative net emissions of 34 Mt of CO_2 as a result of a considerable payback time. While energy/CO_2 payback time is not unique to PV systems, it plays a larger role in the development of new energy systems than other low-carbon systems. PV energy/CO_2 payback time decreases with the following measures: installation of PVs in locations with a large PV potential and high CO_2 emissions of the electricity replaced, manufacturing PVs at locations with low CO_2 emissions of kWh of electricity used in the production, recycling PVs, and increasing PV conversion efficiency. The analysis is therefore extended into the future for three scenarios with different maximum capacities of photovoltaics (20%, 50%, and 100% of total electricity production). In these scenarios, cumulative net CO_2 emissions can be reduced by 4%, 9%, and 18%, respectively, over the long term (by the year 2050). Short-term CO_2 increases during growth versus long-term CO_2 reduction present a trade-off in developmental growth strategies.

1. Introduction

Gutowski, Gershwin, and Buonassisi (2010) developed a mathematical model of the effects of the growth rate of renewable energy generation capacity in a region[1]. They showed that, if the growth rate exceeds a critical value, the energy consumption of building new systems exceeds the energy delivered by those systems to that region. In this paper, we use the historical data to validate this result. In particular, we identify countries whose growth rate of renewable energy capacity exceeds the critical value, and some where it does not. In addition, we clarify the future environmental impact of the growth of renewable energies from a long-term perspective.

Many consider photovoltaics (PVs) to be one of the more promising options to produce renewable energy and also to reduce greenhouse gas emissions. PVs have the highest potential among all of the other renewable energies[2]. The efficiency of commercial PVs has been improved at a rate of nearly 2% annually[3]. PV efficiency in laboratories now exceeds 40%, which is nearly double that in 1975[4]. The cost of a PV system in 2010 was less than half of that in 1990, and it is expected that the crossover point for the conventional utility price and the PV electricity price will occur in the near future if we stay on the current learning curve[5]. In fact, the capacity of PVs has been increasing at a rate of about 40% annually throughout the world over the past 19 years[6].

These facts lead us to have a very optimistic view of our future environment. However, recently some researchers have questioned such an optimistic view. Pearce (2008) suggested the existence of a 'cannibalisation effect', which implies that the replacement of conventional power plants with new power plants causes an additional environmental burden[7]. The concern regarding the cannibalisation effect originated from Chapman's work (1975), which warned of an energy deficit due to the time gap between construction and energy production during the rapid deployment of nuclear power plants[8]. Some other studies have shown that the rapid growth of renewable energies could lead to a net energy shortage[9-10]. For example, Matsuhashi and Ishitani (2001) discussed a diffuse strategy for PVs in Japan using dynamic analysis[11]. Gutowski, Gershwin, and Buonassisi (2010) developed an analytical framework to capture the dynamic nature of energy replacement[1]. They found that the net energy production in our society can become negative in the short term if the growth rate exceeds a critical value. This is because, during PV capacity growth, the energy production from deployed PVs could be cancelled or surpassed by the energy consumption needed to manufacture new PVs.

Recently, Dale and Benson (2013) warned of the possibility that the PV industry could be an energy sink in terms of electricity use during its growth in the years 2000–2010 from a global perspective[12]. However, there are still some issues that need to be discussed before any conclusions can be drawn about whether PV deployment actually increases energy consumption in the world or not. First, they calculated the energy balance using PV electricity generation not in primary energy terms, whereas they employed primary energy consumption to produce PVs. Most PVs have been connected to the energy grid, and they have worked to replace the energy produced by conventional power plants. Therefore, it seems reasonable to calculate the energy production in primary energy terms, as recommended by the International Energy Agency (IEA) guidelines[13]. Secondly, they calculated the net energy production using a global average data. As shown in our study, the energy payback time varies drastically when considering the global supply chain[14]. The capacity of PVs is different for each country[6], and the supply chain of PVs has changed due to the growing shares of developing countries[15-16]. Therefore, it seems meaningful to investigate the net energy produced by PVs throughout the world by considering those factors. In addition, there has been no study verifying the cumulative net CO_2 reduction by PVs from a global perspective.

The research objective of this study is to focus on the following two points. (i) To examine whether cumulative net primary energy consumption and cumulative net CO_2 emissions have increased due to the deployment of PVs in each country from a lifecycle point of view using actual data from 1992 to 2011. (ii) To estimate the future impact of such rapid growth of PV deployment using a scenario analysis. Based on the obtained results, we provide some practical suggestions for future energy policy.

2. Method

2.1. Assumptions for cumulative net primary energy consumption and cumulative net CO_2 emissions by PVs from 1992 to 2011

We developed the analytical framework of the study by considering the change of embodied energy consumption and CO_2 emissions of PVs[1], where the embodied energy/CO_2 means the total energy requirement or CO_2 emissions throughout all processes required to produce a product, including extraction, manufacturing, and transportation in terms of primary energy consumption or CO_2 emissions. The annual net primary energy consumption E_N [MJ] and annual net CO_2 emissions C_N [kg] in year t are estimated with the following equations, with the newly manufactured PV capacity N [kW], the cumulative PV deployment T [kW], the primary energy of PV E_m [MJ/kW], the CO_2 emissions of PV C_m [kg/kW], primary energy consumption per kWh of electricity E_e [MJ/kWh], CO_2 emissions per kWh of electricity C_e [kg/kWh], and annual PV energy generation per kW PV (PV potential) e [kWh/kW] at the operating conditions:

$$E_{Nt} = T_t e E_e - E_{mt} N_t \qquad (1)$$

$$C_{Nt} = T_t e C_e - C_{mt} N_t \qquad (2)$$

The cumulative net primary energy consumption E_C and cumulative net CO_2 emissions C_C in year t can be estimated by the sum of equations (1) and (2), respectively.

The cumulative PV deployments T and newly deployed PV N in the countries from 1992 to 2011 are obtained from the statistical data[6] as shown in Figure 1. Here, the top five countries—Germany, Spain, Japan, Italy, and United States—with the largest shares of cumulated PVs in the 23 countries are selected for the case studies. At present, these five countries account for nearly 80% of the 64 GW total PVs in the world. As shown in the figure, their annual PV growth rates are large: 61% for Germany, 34% for Japan, 47% for Italy, and 27% for the United States from 1992 to 2011, and 63% for Spain from 1994 to 2011. In total, the installed PVs in the world grow by 40% annually.

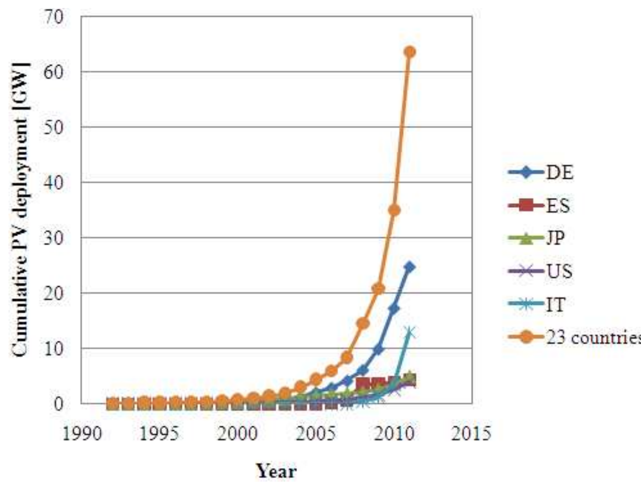

Figure 1. Cumulative PV deployment in the countries

The values of the assumptions for each country are shown in Table 1. The average PV potential e in each country is obtained using the analytical framework in our latest study[17]. The primary energy consumption per kWh of electricity E_e and CO_2 emissions per kWh of electricity E_c are estimated using the data of AIST-LCA ver.5[18] and the country grid data[19-20].

Table 1. Assumptions for each country

	DE	ES	JP	US	IT	23 countries in 2009	Reference
e [kWh/kW]	812	1251	1060	1156	1167	998	17
E_e [MJ/kWh]	9.6	7.5	10.1	9.3	8.0	9.2	18-20
E_c [kg/kWh]	0.49	0.32	0.45	0.53	0.41	0.45	18-20

The embodied energy per kW PV E_m and the CO_2 emissions per kW PV C_m are estimated with the following assumptions. We assume that all photovoltaics installed in the countries are mono- or multi- crystalline silicon photovoltaic because nearly 80% of the PV market is shared by them so far[21]. Even if we consider brand new PVs such as thin-Si PVs or CdTe PVs, their shares are less than 20% in total, and hence the effect of neglecting them in the present market is limited in this study. In our latest study, we estimated the embodied energy and CO_2 emissions using the primary energy consumption per kWh of electricity and CO_2 emissions per kWh of electricity at the each location of the production stages[14]. Then, first we estimated the averages of the primary energy consumption per kWh of electricity and that of CO_2 emissions per kWh of electricity weighted by the market share of each country at each manufacturing stage from 1992 to 2011 using the market data[15-16], and primary energy consumption per kWh of electricity and that of CO_2 emissions per kWh of electricity in each country, which are obtained by LCA software[18] and country grid data[19-20]; the market data at each stage covers data from 2005 to 2011, hence we assume that the market shares before 2005 are fixed at the same level as in 2005. Secondly, we estimated the embodied energy and CO_2 emissions of mono- and multi-Si PVs using the obtained primary energy per kWh of electricity and CO_2 emissions per kWh of electricity from 1992 to 2011 using the analytical framework of our latest study[14]. Here, the embodied energy and CO_2 emissions of an inverter and a mounting stage are assumed to be constant. Thirdly, we estimated the averages of embodied energy and CO_2 emissions weighted by the market share of mono- and multi-Si PVs from 1992 to 2011[21]. Finally, we estimated the embodied energy and CO_2 emissions of PVs from 1992 to 2011 by multiplying the factor of technological development, where we assumed that the annual reduction rate of embodied energy and CO_2 emissions is in the range between 5% and 10% based upon the foregoing studies[22-24].

The embodied energy and CO_2 emissions of PVs from 1992 to 2011 are shown in Figure 2; the annual reduction rate of embodied energy and CO_2 emissions is 8%. While the values of embodied energy shown in this figure are relatively larger than those from Dale and Benson (2013), they correspond well to the results of Gorig and Breyer (2012).

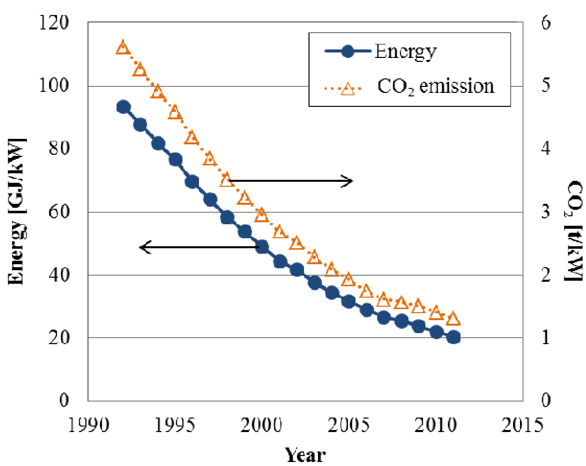

Figure 2. Embodied energy and CO_2 emissions of PVs from 1992 to 2011

2.2. Assumptions for CO_2 emissions in the future

Here, the following case studies are conducted: a business-as-usual (BAU) case, in which the growth rates of CO_2 emissions and electricity consumption in the future are estimated to meet those values of the IEA baseline scenario in 2030 and 2050[25]; case 1, in which the capacity limit of PVs in the world is 20% of the total electricity consumption; case 2, in which the capacity limit of PVs is 50% and the total PV energy generation over the 20% of total electricity is supplied through storage[26]; and case 3, in which the capacity limit is 100% and the storage is used for energy generation over the 20% of total electricity.

The other assumptions for this estimation are shown as follows. The lifetime of PVs is 25 years. We assume the growth rate of PVs is 40%, which is estimated using the statistical data from 1992 to 2011[6]. The PV potential and CO_2 emissions per kWh of electricity in the world are 1000 kWh/kW and 0.45 kg/kWh, respectively, which are estimated by taking the average of 23 countries weighted by their market share in the past[6, 14, 18-21]. The PV efficiency improved from 2% to 10% in 1990[3] up to 30% at the Shockley–Queisser limit[27], whereas the maximum champion data of multi-junction PV cell efficiency in the lab reaches 40% at present[4]. Improvements in PV manufacturing after 2011 are assumed to reduce CO_2 emissions by 6% per year, based on an annual reduction in embodied energy of 8%[22-23] and an increase in PV efficiency of 2%[3]. The reduction of embodied CO_2 emissions continues until it reaches 1/20 of that in 2008, which is estimated by the material consumption and the chemical thermodynamic limit of those materials[28-29]. CO_2 emissions to storage kWh of electricity are calculated from the average value for the NaS battery for PVs[30]. The key parameters mentioned above are summarised in Table 2.

Table 2. Assumptions for the scenario analysis in the future

		BAU	Case 1	Case 2	Case 3	Reference
CO_2 increase [%]	from 2010 to 2030	1				25
	from 2030 to 2050	1.8				
Maximum limit of PV in total electricity consumption [%]			20	50	100	
Lifetime of PV [year]			25			
Growth rate [%/year]			40			6
Annual PV energy generation [kWh/kW]			1000			14
CO_2 emissions per kWh of electricity [kg/kWh]			0.45			18-21
Improvement of conversion efficiency from 12% in 2008 to 30% [%/year]			2			3, 27
Reduction rate of embodied CO_2 emissions [%/year]			8			22-23
Capacity of PV energy without storage [%]			20			26
CO_2 emissions of storage [kg/kWh]			0.06			30
Efficiency of storage [%]			80			30

3. Results and discussion

3.1. Case studies in the past

Gutowski, Gershwin, and Buonassisi (2010) clarified that cumulative net energy consumption and cumulative net CO_2 emissions increase when the growth rate of PVs is larger than the critical growth rate, which is the reciprocal of payback time[1]. Therefore, if we assume that the energy and CO_2 paybacks of PVs are three years[14], we can roughly estimate that Germany, Italy, and Spain could increase their cumulative net primary energy consumption and cumulative net CO_2 emissions. However, the energy and CO_2 paybacks of PVs could be changed by many factors. Therefore, we examine whether they have actually increased their primary energy consumption and CO_2 emissions. Here, the embodied energy and CO_2 emissions of PVs from 1992 to 2011 are estimated, taking into account the historical changes of supply chain, market shares of each type of photovoltaic, and technology development. The energy generation by 1 kW PV and CO_2 emissions per kWh of electricity in each country are estimated using the country's average data[18-20]. In this analysis, we assume that half of all newly deployed PVs in each year generate energy in the same year.

Figure 3 shows the cumulative net primary energy consumptions in the countries. In this figure, the ranges of vertical lines on each plot indicate the uncertainties of the results, where the plots show the most conservative case in which the reduction of embodied energy is 8% annually[22-23] and an average PV potential in each country is assumed. Ranges are between the most pessimistic case, in which the reduction rate of embodied energy is 5% annually and PVs have been installed in the location with the smallest PV potential in the country, and the most optimistic case, in which the reduction rate of embodied energy is 10% annually and PVs have been installed in the location with the largest PV potential in the country. Since it is natural to assume that the PVs have been installed in locations with a large PV potential in each country, the actual values could be biased toward the optimistic. The uncertainty becomes large when the PV potential changes drastically, and in countries that have seen rapid growth in PVs in recent years, such as Germany and Italy.

As shown in Figure 3, the manufacturing and use of photovoltaics has led to a cumulative net consumption of approximately 286 PJ of energy for the 23 countries in the conservative case. However, the results are sensitive to the assumptions of the optimistic or pessimistic case, particularly for Spain and the United States. Those two countries have decreased energy consumption except for the case with the pessimistic assumptions. On the other hand, it is certain that Japan has decreased its energy consumption because of its moderate PV growth rate after stopping its rapid growth in 2006, whereas Germany and Italy have increased their energy consumption even taking into account their uncertainties because of their rapid PV growth recently. Therefore, from the viewpoint of global primary energy consumption, it could be concluded that the hypothesis of the ensemble effect is true.

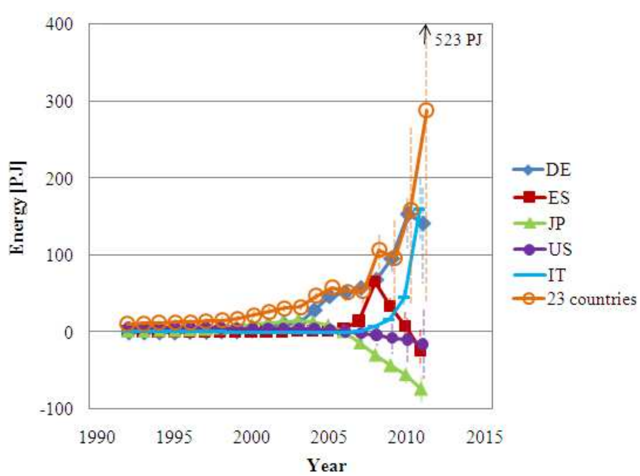

Figure 3. Cumulative net primary energy consumption in the countries

Figure 4 shows the cumulative net CO_2 emissions in the countries. The critical growth rates for CO_2 emissions are relatively smaller than those for primary energy consumption because the carbon payback time (CPT) is relatively longer than the energy payback time (EPT)[14]. This implies that the risk of the ensemble effect increases. As a result, the cumulative net emissions are 34 Mt of CO_2 for the 23 countries in the conservative case. As shown in the figure, Germany and Italy have clearly increased their CO_2 emissions and Spain has slightly increased their CO_2 emissions, even taking into account their uncertainty; Japan has decreased CO_2 emissions. Although they are likely biased toward CO_2 reduction, the results could be changed for the United States. As a result, it could be concluded that the cumulative net CO_2 emissions in the world have increased during the past 19 years.

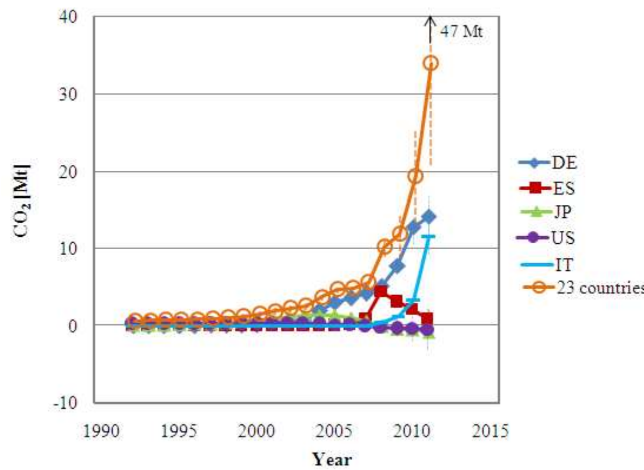

Figure 4. Cumulative net CO_2 emissions in the countries

Figures 5 and 6 show the cumulative net energy consumption and cumulative net CO_2 emissions per cumulative PV deployment versus the production weighted average annual growth rate ratio (AGR) in each country and the total of 23 countries, where the AGR is the average of the ratio of the annual actual growth rate to the annual critical growth rate weighted by the annual production of PVs from 1992 to 2011. If a country has an AGR more than 1, it means that its cumulative net energy consumption and cumulative net CO_2 emissions may increase. In these graphs, we removed the plot for Belgium because their PV data are only available for 2011.

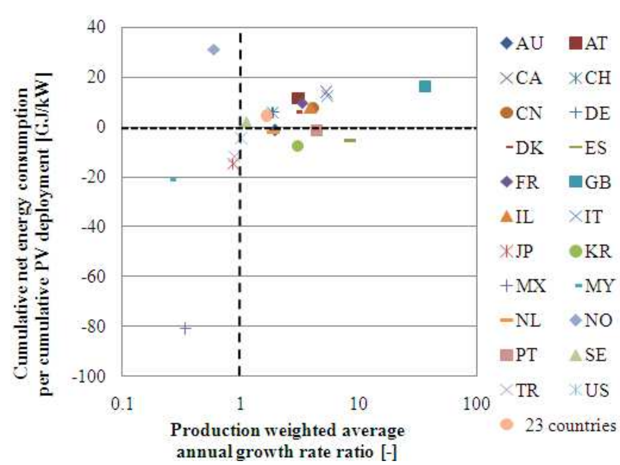

Figure 5. Cumulative net energy consumption per cumulative PV deployment versus production weighted average annual growth rate ratio

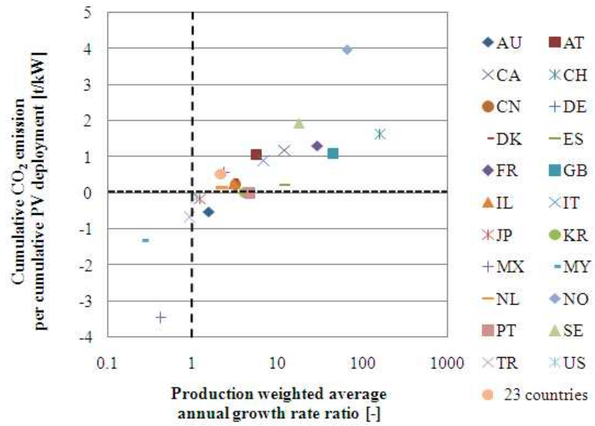

Figure 6. Cumulative net CO_2 emissions per cumulative PV deployment versus production weighted average annual growth rate ratio

As shown in the figures, the cumulative net energy consumption and cumulative net CO_2 emissions per PV increase with increasing AGR and become positive when the AGR is more than 1, except for Norway (see Figure 5). Norway deployed a large amount of PVs before 1992, and their growth rate after 1992 has been small. Our calculation of AGR reflects the data after 1992. Therefore, while the plot in Figure 6 looks like it is on the line, the relationship between the cumulative net energy consumption/CO_2 emissions and AGR is weak. Therefore, except for the error of Norway, the critical growth rate model seems to work well to verify whether both cumulative net energy consumption and cumulative net CO_2 emissions have increased.

The discussion of the critical growth rate implies the dilemma between rapid PV deployment and environmental burden during growth[1]. The solution to this dilemma is to increase the critical growth rate. By increasing the critical growth rate more than the actual growth rate, CO_2 emissions can be reduced even with rapid PV growth. To increase the critical growth rate, we should reduce the carbon payback time. The strategies to reduce the carbon payback time are roughly divided into two approaches: increasing the CO_2 reduction at the usage stage or decreasing the CO_2 emissions at the manufacturing stages.

First, there are two more specific strategies to increasing CO_2 reduction at the usage stage. The first is to install PVs into a suitable location with a large PV potential. The global PV potential map is very useful when seeking a suitable location[17]. The second is to install PVs in a location with the large CO_2 emissions per kWh of electricity in their grid. If the PV is substituted for the carbon-intensive electrical grid, then a large carbon savings can be achieved. In our latest study, we identified Mongolia and Botswana as having the largest potential of CO_2 reduction in the world because of their large CO_2 emissions per kWh of electricity and their large PV potential[14].

Secondly, there are also specific strategies to reduce CO_2 emissions at the manufacturing stages. For example, optimising the locations of the manufacturing stages could be a useful option. As previously stated, the CO_2 emissions per kWh of electricity are different for the countries. Therefore, we can reduce CO_2 emissions at the manufacturing stages by manufacturing PVs and their materials in countries with small CO_2 emissions per kWh of electricity. In our latest study, it is clarified that CO_2 emissions at the manufacturing stage can be drastically reduced by optimising the locations of the PV's lifecycle[14]. Also, we can reduce CO_2 emissions by introducing brand new PVs with low embodied CO_2 emissions. For example, it is pointed out that the embodied CO_2 emissions of thin-Si PVs, CdTe PVs, and CIS PVs are smaller than those of mono- or multicrystalline Si PVs[14, 31-32]. Recycling has the potential to reduce CO_2 emissions during manufacture by 6–20% [24]. Finally, improving the efficiency of each manufacturing process and PV efficiency will reduce the embodied CO_2 emissions per unit PV. It is well known that the process efficiency and PV efficiency have been improved along the learning curve[3]. These two efficiencies could be improved as PV capacity increases over time.

3.2. CO_2 reductions after growth

In our previous results, we showed that cumulative net primary energy consumption and cumulative net CO_2 emissions from PVs have increased throughout the world. However, it seems obvious that as growth slows or stops, this situation could be reversed. Based on our estimation, if the five countries had stopped their PV growth in 2011, their cumulative net CO_2 emissions would decrease rapidly and all of their cumulative net CO_2 emissions would become negative in two years.

Figure 7 shows the historical recovery time in each year from 1992 to 2011 for each country. In this figure, the negative recovery time means that the cumulative net CO_2 emissions are already negative when the growth stops. While the recovery time is highly fluctuating due to the change of growth in some countries, the recovery time decreases with decreasing carbon payback time because of the rapid technology development. For the case studies in Figure 7, the recovery times are never more than 3 years after 2005 and less than 2 years in 2011 for all of the cases. The results agree with our estimation.

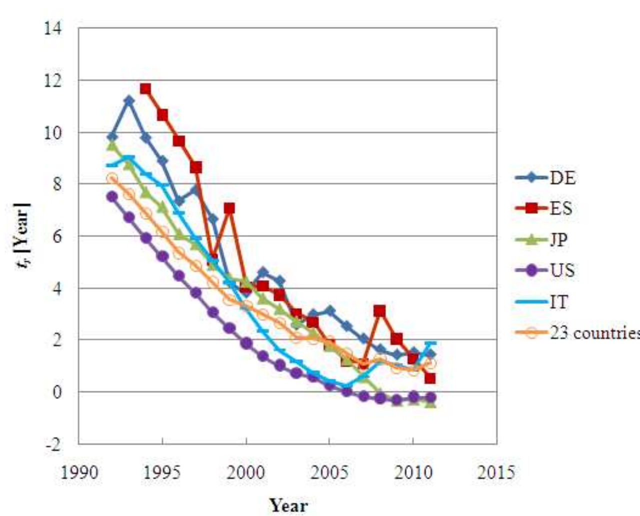

Figure 7. Recovery time in each country

3.3. CO_2 emissions in the future from a global perspective

Electricity consumption will continue to grow[25]. If PV deployment grows at the present rate, future CO_2 emissions will be a matter of concern. Therefore, in this section, we discuss future energy consumption and CO_2 emissions.

As stated in section 2.2, we assume that the future electricity demand will continue to grow at nearly 1% per year as BAU. PV grows at 40% per year until it reaches its capacity limit (20%, 50%, or 100% of electricity supply for cases 1, 2, and 3, respectively). As a result, the annual CO_2 emissions of 7%, 17%, and 36% would be reduced by PV deployment in the year 2050 as compared to the present-day BAU scenario. The resulting cumulative reductions for CO_2 in the atmosphere from BAU would be 4%, 9%, and 18% for the three cases, respectively. The amount of CO_2 increase from the growth of PVs is much smaller than the CO_2 decrease from PVs. A detailed discussion is presented as follows.

Figure 8 shows the annual net CO_2 emissions in the world for each case study. CO_2 emissions increase until nearly 2015 without a large difference from BAU for all the cases. Then, the CO_2 emissions during growth are quite small compared with the CO_2 reduction from BAU from a long-term point of view. After 2015, CO_2 emissions gradually drop from that in BAU because the capacity of PVs becomes large and the embodied CO_2 emissions become small due to the improvement of conversion efficiency and manufacturing processes. The CO_2 reductions from the BAU stop when the PV reaches its capacity limit. The years when the PVs reach their capacity limits are around 2025, 2028, and 2029, respectively. The effect of CO_2 reduction becomes suddenly prominent when PVs reach their capacity limit because nearly 80% of all PVs have been installed in the past five years, with a growth rate of 40%. Then, while CO_2 reduction from BAU increases with increasing capacity, the timing of the maximum effect is delayed with increasing the maximum capacity.

The annual net CO_2 reductions from BAU in 2050 for cases 1, 2, and 3 are by 7%, 17%, and 36%, respectively. These values look small considering the large deployment of PVs in the world. However, since the CO_2 emissions coming from the electricity and heat sector made up 41% of all emissions in the world in 2010[33], the estimated values could be reasonable. Then, we can roughly estimate the future CO_2 reduction from that in BAU by using the capacity limit of PVs and the share of CO_2 emissions from the power industry. These results do not change so much, even if we change the other assumptions in the long run.

The CO_2 emissions from the other sectors are 22% from transport, 20% from industry, 6% from residential, and 10% from other[33]. Therefore, if we can replace fossil fuel consumption for the energy use in the other sectors, we can reduce CO_2 emissions more. Without doing that, even a 50% reduction in CO_2 emissions is unachievable, even if all conventional power stations are replaced by PV generation.

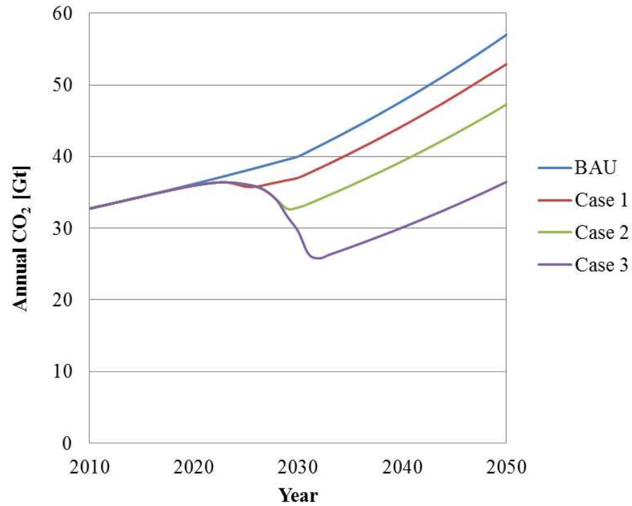

Figure 8. Annual net CO_2 emissions in each case study

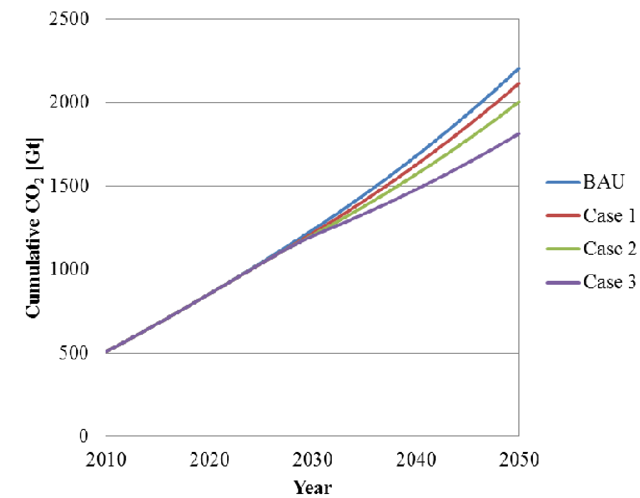

Figure 9. Cumulative net CO_2 emissions in the future

Figure 9 shows the cumulative net CO_2 emissions in the future for each case study. The cumulative net CO_2 reductions from BAU in 2050 for cases 1, 2, and 3 are 4%, 9%, and 18%, respectively. Those values are nearly half of the percentages of annual CO_2 reduction from that of BAU. The reduction from that of BAU becomes prominent around 2030 after the PVs reach their capacity limit.

The most dominant parameter to reduce the cumulative net CO_2 emissions is the maximum capacity of PVs. The effects of other factors relating to the CO_2 intensity of PVs on the cumulative net CO_2 emissions, such as embodied CO_2 emissions of a 1 kW PV system, PV potential, CO_2 emissions per kWh of electricity at the location of PV deployment, energy storage, and so on, are not so large in the future because the CO_2 intensity of PVs is much smaller than that of average conventional power plants in the world already, and hence the amount of CO_2 reduction by replacing conventional power plants with PVs will not be affected even if the other parameters relating to the CO_2 intensity of PVs change in the future. Therefore, the point is not how much we can reduce the CO_2 intensity of PVs, but how much and how fast we can install them in the future.

On the other hand, the reduction of cumulative net CO_2 emissions from that of BAU in each case study becomes prominent after 2030, as shown in Figure 9. This is reasonable because most PVs have been installed in the past few years, as stated before. To shift the timing of large CO_2 reduction earlier, the growth rate must be larger.

To shift the timing earlier with the large capacity limit, the growth rate should be increased further. However, these long-term strategies, such as increasing the capacity limit and the growth rate of PVs, could cause a short-term negative impact because the ensemble effect increases with increasing growth rate, as previously discussed.

Figure 10 shows the peaks of the cumulative net CO_2 increase during the growth and the cumulative net CO_2 decrease in 2050 for each case study. As shown in the figure, while the peak of the cumulative net CO_2 increase during growth increases with increasing growth rate, it is much smaller than the amount of the cumulative net CO_2 decrease in 2050. For example, nearly 500 Gt CO_2 emissions can be reduced in 2050 for case 3 with growth rate of 100% in Figure 10, which illustrates the most aggressive case. The cumulative net CO_2 increase is 3.4 Gt in this case, which is only less than 1% of the CO_2 reduction.

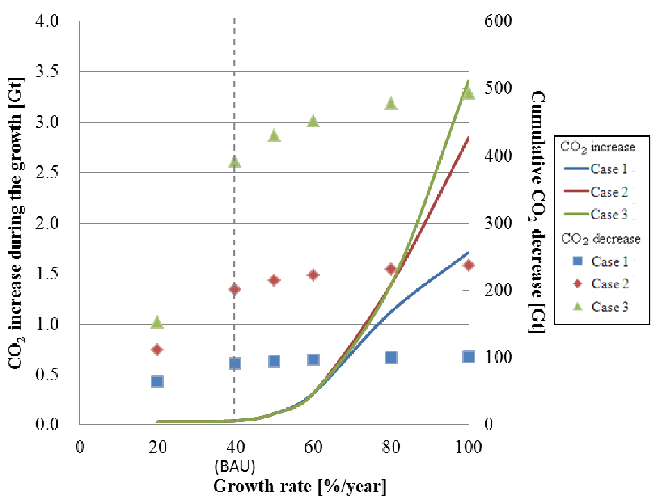

Figure 10. Cumulative net CO_2 increase during the growth and CO_2 decrease in 2050

4. Conclusions

Summarising the discussion in this work, there is a possibility that the cumulative net energy consumption and cumulative net CO_2 emissions have increased worldwide over the past 19 years owing to the rapid growth and deployment of PVs. Furthermore, emissions will continue to increase if the high growth rates of PVs continue. However, the CO_2 increase during growth is much smaller than the CO_2 reduction from a long-term perspective. In addition, the CO_2 increase will be paid back soon after stopping growth. Therefore, it may be reasonable to deploy PVs rapidly as much as possible in the grid to moderate global warming from a long-term point of view, even with the increase in energy consumption and CO_2 emissions during growth. Strategies to decrease payback time could be useful to moderate such negative side effects. However, the more 'inconvenient truth' is that, even if we replace all of the conventional power plants with PVs, it may not be enough to reduce CO_2 emissions drastically by 2050. This implies the need for more positive actions to combat global warming.

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