Energy & Environmental Science

Accepted Manuscript

Dynamic Carbon Mitigation Analysis: The Role of Thin-Film Photovoltaics

C. J. M. Emmott [a,b], N. J. Ekins-Daukes[a] and J. Nelson [a,b],

The introduction of substantial levels of renewable energy technologies will incur greenhouse gas (GHG) emissions during product manufacture. We have developed a model to assess the impact on GHG of a growth of solar photovoltaic (PV) capacity. The model is applied to growth scenarios in India and Germany, locations which differ in their insolation and the carbon intensity of the local grid. The impact of growth is to delay net GHG emission reductions by up around 4 and 9 years in the Indian and German scenarios receptively. This dynamic approach quantifies the benefit of technologies with a lower GHG footprint in achieving rapid GHG emission reductions. In addition, short lifetime PV technologies, with a low GHG footprint, such as organic PV, can show greater emission reductions despite a higher levelised global warming potential (gCO_{2eq}/kWh). Finally, a measure of the dynamic cost of GHG emission reductions is proposed to assess the cost, over the short term, of emission reductions from renewable energy technologies.

INTRODUCTION

The energy and resource demands necessary for a transition to renewables will lead to substantial carbon emissions. If deployment of a low carbon technology grows rapidly then a situation can be reached where the carbon emissions associated with manufacturing future generators outweigh the carbon emissions avoided by existing capacity (figure 1). Just as such developments will require a large financial investment, a *carbon investment* will also be necessary in order to allow for future carbon reductions.

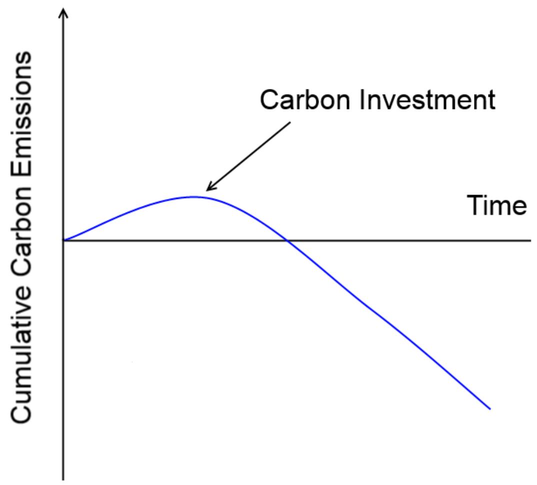

Figure 1. Schematic showing the net rate of carbon emissions resulting from growth in the deployment of low carbon energy capacity, replacing carbon intensive capacity. The area enclosed under the graph represents the carbon investment.

Dynamic Carbon Mitigation Analysis

Integrated-assessment and carbon constrained energy system optimisation models have been designed to explore the transitions to clean energy technologies. However, these models do not explicitly account for emissions associated with the growth of low-carbon technologies and thus lack a true life-cycle perspective. Alternatively, life cycle analysis (LCA) is a commonly used technique for assessing the environmental impacts of energy technologies, often expressed as the Global Warming Potential (a measure of the gCO_{2eq}/kWh averaged over the system lifetime).[1–3] Such techniques have been extended to assess carbon mitigation potential by additionally accounting for avoided carbon emissions.[4–6]

Whereas a steady-state assessment of mitigation potential can determine carbon savings resulting from a single unit [4,7] or a given capacity,[8] dynamic carbon mitigation analysis accounts for capacity growth as well as technical development of the technology and background system. Such analysis thus combines the energy system model and LCA approaches to study the implications of energy transitions.

Prior studies have assessed both the implications for carbon emissions [9–14] and net energy balance [15–23] on the transition to low-carbon technologies. Whilst some have argued that such a dynamic consideration demonstrates a need to limit the growth rate of technology,[11,15,21] the majority have concluded that allowing for a period of increased carbon emissions or energy demand allows long term carbon reductions from renewable energy generation to be maximised. These analyses have also demonstrated that emissions from manufacturing and deploying such technologies have limited impact on long term mitigation, whilst also highlighting the need to understand the implications of such a transition.

Scope of this Study

Dynamic carbon mitigation analysis has yet to be applied to an understanding of how differing properties of specific subsets of technology groups (e.g. specific PV technologies) impact such a scenario analysis. There is a strong drive in R & D of thin-film PV technology, but as yet there is limited understanding of how these technologies could contribute to GHG emission reductions. This work aims to apply dynamic carbon mitigation analysis methods to build an understanding of the mitigation potential of specific PV technologies. In addition, this work attempts to relate such analysis to the cost of carbon abatement and explores the potential for thin-film PV technologies to supply lower costs of carbon mitigation than the dominant crystalline silicon PV technology.

A dynamic carbon mitigation model was developed and applied to the case of a number of PV technologies for two national case-studies: India and Germany. Both countries have seen or are expected to see strong growth in PV deployment but differ in the solar resource; the carbon intensity of displaced fossil fuel generation; the ambition of industry growth; and the stage of development of solar technology, thus allowing varying inputs to the model to be compared.

We use the model to assess three PV technologies with different life cycle emissions per unit of PV capacity, and thus can demonstrate the impact of less carbon intensive technologies. These three technologies are mono-crystalline silicon (referred to from here on as c-Si), the most carbon intensive, but one of the most common technologies; cadmium telluride thin-film (CdTe), a lower carbon technology; and organic photovoltaics (OPV) which represents a possible future technology with the potential for low emissions during manufacture but short lived modules. In contrast to c-Si and CdTe, OPV is a pre-commercial technology but has the potential to become a hugely scalable technology ,[24,25] and thus within this study we aim to illustrate its for carbon mitigation.

METHODS

A dynamic carbon mitigation model was developed in the software VENSIM.[26] A simplified schematic of this model is shown in figure 2. This model calculates the instantaneous net carbon emissions at each discrete time-step, according to equation 1.

$$\begin{aligned} &Net\ Carbon\ Emissions\ (t) \\ &\quad = A_{em}(t) - M_{em}(t) - O_{em}(t) \\ &\qquad [tCO_{2eq}/unit\ time] \quad (1) \end{aligned}$$

Where A_{em} is the avoided emissions due to the installed capacity; O_{em} is the emissions from operation of the installed capacity; and M_{em} is the emissions from the manufacture of the low carbon technology.

At each time interval the emissions from manufacturing (M_{em}) and maintaining a given technology (O_{em}), are calculated from LCA data; while the emissions which will be avoided by the deployment of the technology (A_{em}), are calculated from the displaced fossil fuel generation. By considering the cumulative carbon emissions (calculated from integrating the net carbon balance from t=0 to t), the payback of carbon "invested" during the initial period of growth is accounted for.

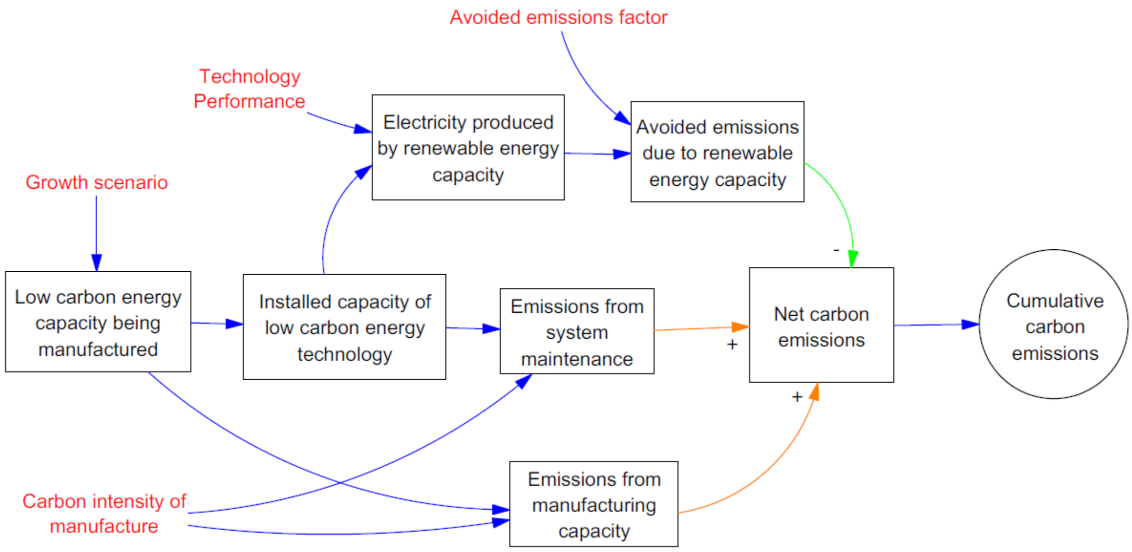

Figure 2. Simplified schematic of the model created within the software VENSIM to determine net carbon emissions due to the deployment of a low carbon energy technology. Arrows indicate dependencies of the output or interim variable. Labels in green represent user defined inputs to the model, which may be time dependent. Values in boxes are recalculated at each time-step.

Model Inputs

Time-Step

Capacity being manufactured at time t will add to the installed capacity at time t + time-step. This gives the delay between emissions from manufacturing the technology and the emissions that are avoided once the technology is generating electricity. Renewable energy technologies such as wind and solar have very short deployment times compared with centralised plants such as nuclear power. Although large solar projects can often require more than nine months planning and construction [27], the majority of emissions result from manufacture of components such as inverters and solar panels. As such, assuming there is limited stockpiling of inventory along the supply chain, the majority of emissions are likely to occur within one six month time period. It is therefore assumed that emissions from installing capacity occur 6 months prior to that capacity inputting electricity into the grid. Sensitivity to this value is discussed in a later section.

LCA Data

Data on the carbon emissions associated with manufacturing PV systems was taken from a variety of process-based LCA studies. LCA data were divided into electricity used during manufacture, and direct emissions including those resulting from the direct use of fossil fuels during manufacture. GHG emissions resulting from electricity use during manufacture were calculated considering the location of manufacture of the PV modules.

Data on these two components were gathered from ecoinvent [28] for c-Si and reference [[3]] for CdTe whilst data for OPV was based on the a very low energy manufacturing process (process H, as described in reference [[29]]) and assuming a module efficiency of 2% which has already been exceeded on large area devices.[30] Emissions resulting from the balance of system components (mounting structure and control electronics) were taken from references [[28]] and [[31]], with the exception of OPV where mounting structures were not included due to the lightweight, flexible nature of the technology which enables minimal mounting structures.

German Scenario. Emissions from electricity use in manufacture were based on the distribution of the global PV manufacturing industry (see figure SI.3.1 in supplementary information) and the average emissions factors of the grid [32] at each location. A scenario in which modules are manufactured in Europe was additionally considered based on the emissions data per square metre provided in reference [[28]], which assumes polysilicon manufacture is based in Norway and hence powered by clean hydro-electricity (figure 3).

Indian Scenario. India has established policies to supply much of its future PV capacity from indigenous manufacturers. Emissions from electricity use were calculated from the projected emissions factor of the Indian grid. A feedback loop was added to the model to account for the changing emissions factor of electricity supplied to these factories, due to increased deployment of PV in the country. See supplementary information for details.

Technology Development. : The evolution of the LCA of the technology (dynamic LCA), resulting from decreasing material use, improved efficiency and evolution of the background power generation mix was also be taken into account. Module efficiency improvements for c-Si were based on extrapolations of historical improvement, from 11% in 2000 to 25% in 2035, in line with projections in the literature.[33] CdTe efficiency was extrapolated from 7% in 2000, peaking at the practical limit for the technology of 17.5% in 2025.[34] Manufacturing resource efficiency improvements for c-Si were based on changes to the ecoinvent database from 2003 to 2010 [28] and linearly extrapolated to 2035. Such manufacturing efficiency improvements in CdTe manufacture were not included due to a lack of data. Values for OPV shown in figure 3b are based on a projection [29] of achievable performance and manufacturing technology and no additional improvements were considered. The resulting GHG emissions per unit capacity used in each case-study are shown in figure 3b.

Maintenance. Operation and maintenance was accounted for by 0.125% of emissions required to install one MW_p of new capacity being added to the emissions balance every 6 months for each MW_p of installed capacity. This is based on emissions from replacing the inverter twice during the system lifetime, resulting in maintenance comprising 6% of the total emissions from manufacturing, installing and maintaining a system over a 25 year lifetime.

Other. Storage is omitted from this model since minimal storage would be required to integrate PV in an electricity system with less than 10% of total annual generation coming from PV,[35] which applies to both the Indian and German scenarios. Recycling of PV systems is also omitted from the model due to uncertainties surrounding the carbon intensity of this. The carbon emissions resulting from the construction of factories to manufacture PV technologies are also neglected as this is assumed to be negligible compared with the manufacture of PV systems themselves.

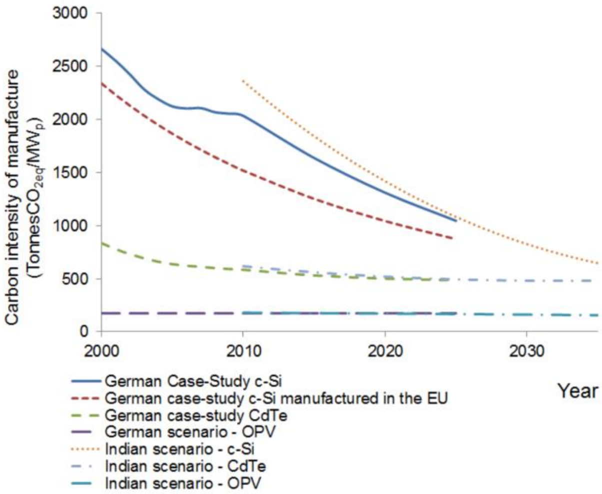

Figure 3. Dynamic LCA of PV capacity based on changes in manufacture location or background grid mix as well as module and manufacturing efficiency. See text for details.

Technology Performance and Lifetime

Electricity output was modelled with a capacity factor (CF). The CF represents the percentage of time for which the rated power is being produced by the system. Electricity output E_{out} is given by equation 2, where C is the installed capacity (in MW_p), and t is the time period (in years) for which the output occurs.

$$E_{out} = CF \times C \times 8766 \times t \qquad \text{[MWh]} \qquad (2)$$

The CF differs between India and Germany due to differing solar resource. For India a CF of 18% was assumed for all technologies, based on the modelling of a c-Si system in Gujarat state using the PVGIS software.[36] For the German case, 11% was assumed based on a PV system located in Leipzig, near the centre of Germany, modelled in PVGIS.

Lifetimes of c-Si and CdTe technology were assumed to be 25 years, in-line with current manufacturer's warranties. OPV technology has a shorter lifetime, assumed to be 5 years, which is considered to be the minimum lifetime for the technology to be economically viable,[37] and is close to previously demonstrated lifetimes.[38] Degradation in system output over its lifetime was not considered in the model.

Growth Scenarios

Growth scenarios were modelled with an S-curve [13,39] and are shown in figure 4. The German scenario considered PV deployment between 2000 to 2025, based on historical capacity and future government targets up to 100 GW_p. For the Indian scenario, growth in PV deployment from 2010 to a requirement to meet 10% of electricity demand by 2035 was analysed (equal to 205 GW_p). In addition different growth scenarios were considered to understand the implications of changing the rate of growth. See the supplementary information for full details.

The model assumes equal installed capacity, independent of PV technology, at a given time. OPV technology is assumed to have a system lifetime of only 5 years compared with 25 years for c-Si and CdTe. Therefore, this technology requires much greater capacity additions in order to account for replacement systems.

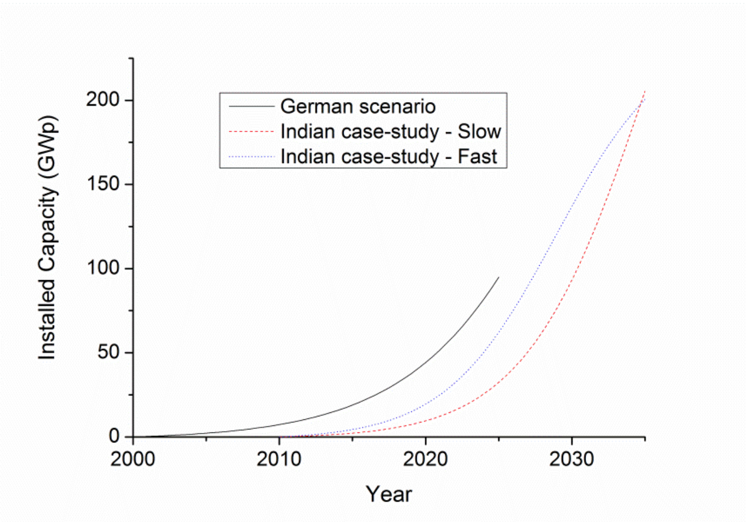

Figure 4. Growth scenarios used for the Indian and German case-studies.

Avoided Emissions

To determine the GHG emissions avoided by the uptake of a low-carbon technology, a time-dependent avoided emissions factor (AEF) is calculated. The AEF accounts for the emissions avoided as the result of two aspects: over the short term, which type of existing generators are reducing their output, and how is this affecting their operational efficiency (known as the operating margin); and in the longer term, what type of generators are not being built, which would have been if low-carbon generators were not present (known as the build margin).[40,41] The AEF will change over time, reflecting changes in the efficiency of new fossil fuel capacity as well as political and economic factors which may influence the uptake of certain technologies for future capacity in a 'baseline' scenario.

Future AEF values are extremely difficult to predict as they are highly dependent on future political, social and economic landscapes of specific countries, which can undergo huge swings as evidenced by the shale gas revolution in the USA and the recent abandonment of nuclear power in Germany. The AEF has been argued by some to decrease temporally (due to more efficient baseline technology),[40,42] however, by others, to increase (since a greater penetration of intermittent sources reduces reliance on carbon-intensive base-load technologies and increases use of potentially lower carbon gas-fired peaker plants);[43] and by further studies, to increase or decrease depending on a carbon price and future gas prices.[6]

The assumed values for the AEF in the Indian and German scenarios are shown in figure 5. In the German case, a linear evolution was assumed starting with an initial AEF of 0.679 $kgCO_{2eq}/kWh$, taken from a dispatch model of the German grid,[44] and a final value of 0.746 $kgCO_{2eq}/kWh$, resulting from the assumption that PV will displace 35% gas and 65% coal, based on the average of scenarios in reference [[6]], and assuming emissions factors for future coal and gas plants in Germany from reference [[32]].The initial AEF in the Indian scenario (0.877 $kgCO_{2eq}/kWh$) was based on the UNFCCC methodology used for calculating carbon credits for renewable energy projects,[45] and the same assumption of 35% gas and 65% coal displacement as before was assumed in the long term, resulting in an AEF of 0.744 $kgCO_{2eq}/kWh$ in 2035 .

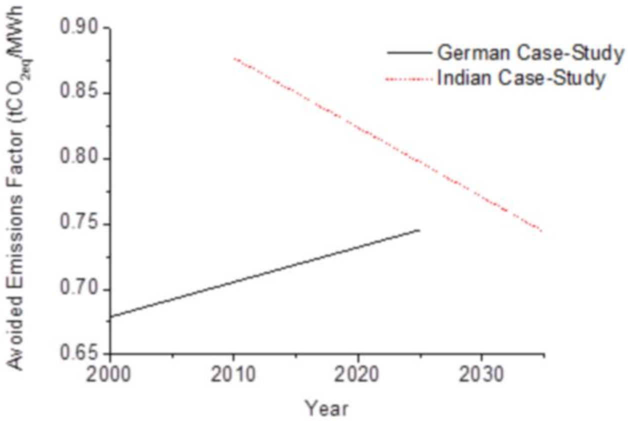

Figure 5. Time dependent avoided emissions factors used in the two case-studies.

RESULTS

The dynamic carbon mitigation model presented above produces a GHG emissions pathway resulting from the growth of a low-carbon energy technology. This allows for a comparison of the cumulative emissions balance after a given point in time. In addition, the time before which the technology pays back the emissions produced during the early stages of growth, or the *industry carbon payback time,*[9] can be calculated from the x-axis intercept of the cumulative emissions plot (figures 6 and 7), values for which are shown in table 1.

Scenario	Industry Carbon Payback Time (years)	Cumulative emissions at end of scenario ($MtCO_{2eq}$)
India (2010-2035)		
Fast growth		
c-Si	4.4	-1680
CdTe	1.4	-1790
OPV	0.5	-1820
Slow growth		
c-Si	4.3	-1140
CdTe	1.4	-1230
OPV	0.5	-1289
Germany (2000-2025)		
c-Si	9.4	-256
EU c-Si	8.0	-280
CdTe	3.0	-334
OPV	1.0	-366

Table 1. Summary of the carbon payback times and cumulative emissions calculated for each scenario as a function of PV technology using the dynamic carbon mitigation model.

German Scenario. The resulting cumulative carbon emission pathway resulting from the growth of various PV technologies from 2000 to 2025, for the German scenario, are shown in figure 4.

This plot shows that greater and more rapid emission reductions are realised by the use of thin-film technology. Similarly, the emissions pathway for the scenario of exclusively using technology manufactured in the EU, which provides a lower carbon grid mix for manufacture, shows that significantly greater and more rapid emission reductions can be realised in comparison to the use of c-Si modules manufactured according to market share.

The x-axis intercept (see inset of figure 6) shows that real emission reductions are realised after more than 9 years in the case of c-Si technology being used. However, through the use of cleaner manufacturing locations or lower carbon PV technology, this can be reduced to as little as one year.

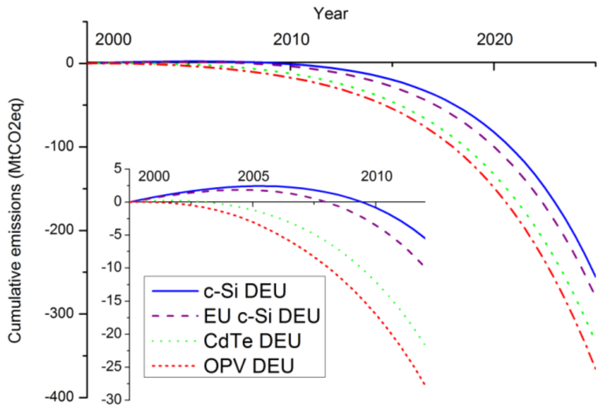

Figure 6. Cumulative GHG emissions resulting from deployment of PV technologies in Germany, and (inset) emissions in the first decade of growth.

Indian Scenario. The results from the Indian Scenario are shown in figure 7. Comparison of the fast and slow growth scenarios shows the limited influence of growth rate on the industry carbon payback time (see inset within figure 7). Although the rate of growth greatly impacts the level of carbon emission mitigation that is realised, with faster growth showing greater reductions in the time period analysed.

Comparing these results to the German scenario shows much more rapid emission reductions in the Indian Scenario, resulting from higher insolation and higher carbon displaced generation. However, figure 7 also shows that there is significantly less differentiation between the technologies, highlighting the reduced impact that the carbon intensity of the PV technology has on the level of carbon mitigation.

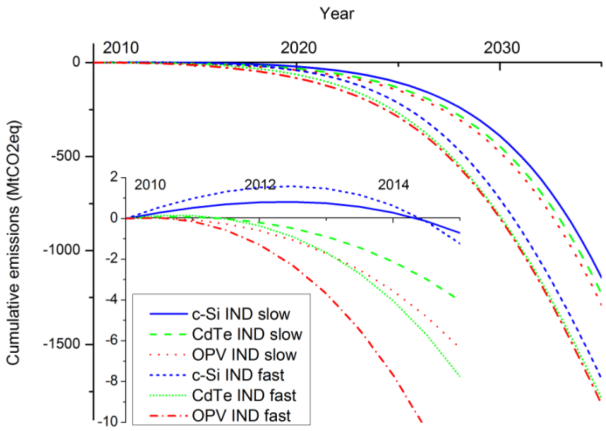

Figure 7. Cumulative GHG emissions resulting from deployment of PV technologies in India, and (inset) emissions in the first decade of growth.

DISCUSSION

Environmental Implications

Dynamic vs. Static Carbon Mitigation Analysis

Static mitigation analysis techniques fail to account for the fact that future capacity is continuously being manufactured, impacting the mitigation resulting from the use of a technology as a whole, whilst also failing to account for changes in the technology and background systems.

Consideration of the growth of a technology results in a dynamic analysis emphasising emissions from technology to a much greater extent. Looking at the German case-study; CdTe technology could realise 30% greater emission reductions by 2025 compared with c-Si. A static mitigation analysis, calculated along the lines of reference [4] results in CdTe providing just 8% greater emission reductions that c-Si.

This dynamic analysis also allows for a better comparison between technologies of differing lifetimes, such as is the case with OPV technology. Using the same LCA assumptions for the German case in 2010 (figure 3b) and considering a static analysis shows that over 25 years, manufacturing OPV modules and their replacements will produce 700 tCO_{2eq}/MW_p compared with 584 tCO_{2eq}/MW_p for a CdTe system, suggesting that OPV has a lower mitigation potential than CdTe technology. However, a dynamic analysis (as seen in figures 6 and 7) shows that due to the low upfront carbon investment of OPV, this technology can, in fact provide greater emission reductions than CdTe as long as PV capacity is growing.

Carbon Investment and the Rate of Growth

The results of the dynamic carbon mitigation model presented above demonstrate that in order to realise significant growth, PV capacity will require a carbon investment. Although the magnitude of this investment is small, as noted in previous studies,[10,13] it is significant in delaying emission reductions. The resulting industry carbon payback time influences the contribution that PV can make to rapid emission reductions.

Figures 6 and 7 show that, for a given scenario, the carbon investment and industry carbon payback time are dependent on a variety of factors. A far smaller carbon investment is seen in the Indian scenario due to the much higher solar resource in addition to the use of more modern, and hence lower carbon, PV technology, as well as to the higher carbon intensity grid power being displaced. However, despite the optimum conditions for carbon mitigation from PV being present in India, a significant carbon investment is still required if c-Si technology is used.

Comparison of the fast and slow growth pathways within the Indian scenario (figure 7) show that, although the carbon investment is increased with faster growth, there is little impact on the industry carbon payback time. This provides a case against previous analysis which has argued that growth rates should be limited in order to avoid any carbon investment.[11] If growth rates remain extremely high, as has been seen in the early stages of the PV industry, then a runaway carbon investment could occur. However, as the industry matures, high growth rates cannot be maintained, and the industry will tend towards a self-financeable growth rate, closer to 15%,[46] preventing a runaway net carbon increase. Thus, provided PV capacity follows an S-shaped growth curve (rather than sustained exponential growth), faster growth will enable much greater emission reductions over similar time frames to a slower growth scenario.

The Case for Thin-Film PV Technologies

As discussed in the previous section; slowing growth will reduce the ability for a technology to provide rapid emission reductions. Instead, technology selection can limit carbon investment and provide much more rapid GHG emission reductions. This dynamic analysis accentuates the importance of the emissions from manufacturing a technology and demonstrates the added benefit of focussing policy on lower-carbon PV technologies, such as thin films, or manufacturing technology in cleaner locations.

Looking at the German scenario (figure 6); if all PV capacity was provided by CdTe technology rather than c-Si (as has historically been the case), 30% more carbon reductions could be realised by 2025. In addition, real emission reductions would have been realised almost one and a half years earlier, and by the end of 2013, emission reductions from PV in Germany would have resulted in GHG emission reductions of 32 $MtCO_{2eq}$ rather than a saving of only 11 $MtCO_{2eq}$.

Such thin film technologies may allow for mitigation targets to be met which would not be possible with more mature c-Si technology, and provide the possibility of equalling emission reductions from early growth in c-Si technology. The results of the Indian scenario show that commencing deployment of OPV technology in 2014 would lead to equal levels of mitigation being achieved as if the same deployment scenario commenced in 2010 but focussed on c-Si technology.

However, focussing on CdTe technology may lead to undesired consequences relating to the availability of Tellurium for their manufacture. Although the availability of Tellurium has been shown to not be a limiting factor for the technology at the scale of deployment discussed in this work, increased use of CdTe may lead to increased costs for this raw material due to the increased demand, impacting the cost reduction ambitions.[47] In addition, increased extraction of Tellurium may require mining of less productive deposits, potentially raising the carbon footprint of this material (a factor which has not been considered in this work).

Looking at the scenario of EU manufactured c-Si technology within the German scenario (figure 6) illustrates that the advantages of thin-film technologies outlined here apply, to a lesser degree, to technologies manufactured in lower-carbon locations, as is the case for European manufactured c-Si.

Temporal Delay between Manufacturing and Installing Capacity

A sensitivity analysis was conducted on the delay between manufacturing and installing PV systems. Figure 8 shows the German scenario assuming a 2 year period between manufacture of the technology and that capacity producing power (all other analyses assume 6 months). This increased delay leads to a short term increase in emissions which is 46% greater in magnitude. In addition, cumulative net emission reductions are not realised until 2012 for the baseline c-Si scenario (2.5 years later than in the 6-month time-step scenario)

This analysis suggests that in order to maximise global carbon emission reductions, policy should be established to discourage inventory stockpiling of PV system components and reduce the time components spend in freight, for example by encouraging manufacture close to the installation location.

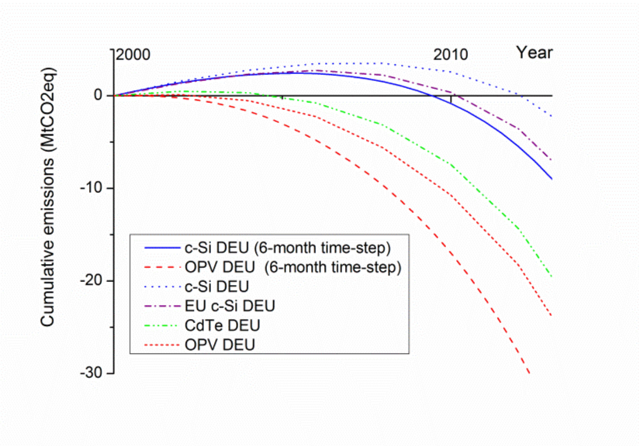

Figure 8. Cumulative GHG emissions resulting from deployment of PV technologies in Germany from 2000 to 2013, assuming 2-year delay between PV manufacture and installation.

Economic Implications

Dynamic Abatement Cost

Dynamic carbon mitigation analysis provides an understanding of carbon mitigation resulting from the use of a technology at a given point of time in the technologies growth. Here we propose a *dynamic abatement cost* to allow an understanding of the financial cost of short term carbon savings. This is analogous to a *marginal abatement cost* (MAC), shown in equation 3.[48]

$$\mathrm{MAC} = \frac{\text{Full cost of low carbon alternative} - \text{Full cost of reference solution}}{\text{GHG Emissions from reference solution} - \text{GHG Emissions from alternative}}$$

[\$/tCO$_{2eq}$] (3)

The dynamic abatement cost (equation 4) follows a similar framing, but instead considers total installed capacity and emission reductions up to a time, t.

$$\text{Dynamic Abatement Cost (t)} = \frac{\text{Cost of all capacity deployed until time ,t} - \text{cost of reference solution}}{\text{Total cumulative emissions balance at time ,t}}$$

$[\$/tCO_{2eq}]$ (4)

Making assumptions for the discounted cost of PV capacity and a reference solution over time (see SI), and assuming all technology to have an equal cost per peak Watt (including OPV, despite the much shorter lifetime, and hence a considerably higher levelised cost); the dynamic abatement cost of the above scenarios was calculated (figures 9 and 10). For comparison, a MAC value was calculated based on equation 3 for the year 2000 and 2010 for the German and Indian Scenarios respectively.

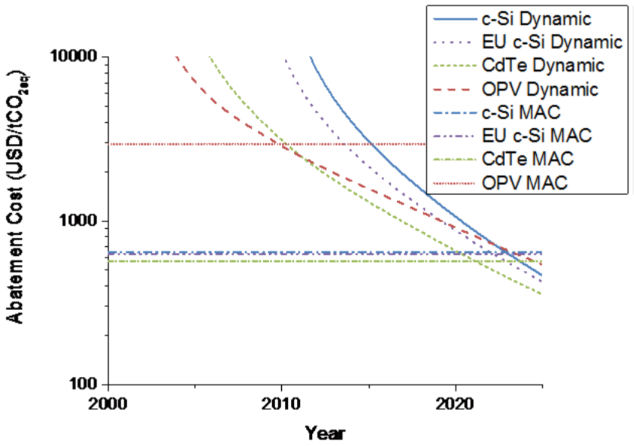

Figure 9. Dynamic and marginal abatement costs for PV technology deployed within the German scenario.

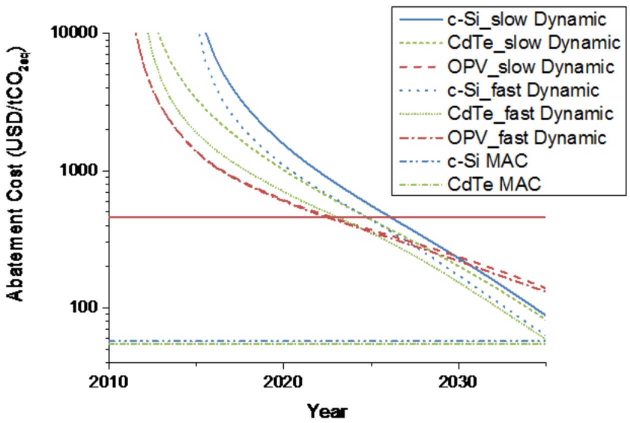

Figure 10. Dynamic and marginal abatement costs for PV technology deployed within the Indian scenario.

This analysis shows that the high capital energy and hence carbon cost of mature PV technology (i.e. c-Si) leads to very high costs of short term carbon reductions, although this can be substantially reduced by the choice of PV technology. The value of short term carbon savings is further discussed in the SI.

Lower Cost Abatement with OPV. Figures 9 and 10 demonstrate the potential for very low carbon technologies such as OPV to deliver rapid, low cost carbon reductions despite very short system lifetimes. Assuming that an OPV and c-Si PV system require equal financial investment per unit capacity but have system lifetimes of 5 years and 25 years respectively, OPV could provide lower cost carbon savings than c-Si for emission reductions realised before 2030 and 2022 for the Indian and German scenarios respectively, despite the inferior lifetime and hence substantially more expensive levelised electricity cost.

Justifying More Expensive Technology. Comparison of the dynamic abatement cost of the various technologies shows the potential for justifying higher costs for lower carbon technologies. Looking at the German scenario (figure 9) EU manufactured PV systems could be 8% more expensive than the global market average and still result in the same cost of reducing carbon emissions by 2025. Similarly, CdTe technology could be 27% more expensive than c-Si and still result in the same cost of emission reductions by 2025. This large differentiation in the cost of abatement will remain as long as the industry is expanding. However, as PV capacity plateaus, the difference in dynamic abatement cost will tend towards that seen in the MAC calculation.

This analysis provides an argument for providing an increased subsidy for technologies with a lower carbon footprint. For example, by focussing on a lower carbon technology such as c-Si manufactured in the EU rather than the Far East, substantially more carbon emissions would be mitigated over the next couple of decades, possibly justifying an increased subsidy for installations using such technology, despite the fact that this may not result in the cheapest PV system costs. However, this could also have unintended consequences such as limiting cost reductions due to preventing a globalized market.

Rate of Growth. Comparison of the dynamic abatement cost resulting from the two Indian growth pathways (figure 10) show that faster, earlier growth in PV capacity results in lower carbon mitigation costs over the next two decades despite faster growth resulting in more expensive, more carbon intensive PV systems being installed. In the long term, as the installed capacity of a technology plateaus, the dynamic abatement cost calculation will show that slower capacity growth is the lower cost pathway; however, this result highlights the added value of rapid growth of a technology in providing rapid and low cost emission reductions.

CONCLUSION

We have used a dynamic model of carbon emissions mitigation in order to understand the implications of choice of technology and deployment growth rate on the carbon budget during the transition to a renewables based energy mix. We consider PV technologies deployed in Germany and India as case studies. We show that, in order for PV to make a substantial contribution to emissions mitigation by displacing more carbon intensive power sources, an initial carbon investment will always be required. This leads to a delay of several years between start of deployment and net savings in carbon emissions. However, use of thin film technologies, which have a lower carbon footprint than crystalline silicon, and manufacture in cleaner locations can shorten this delay and significantly increase reductions over the first two decades of technology growth, relative to the baseline case of crystalline silicon PV manufactured in China. Additionally we show that rapid growth of a technology will increase both the carbon investment of a transition and longer term emission reductions, but have little impact on the industry carbon payback time.

Organic PV modules, manufactured with an energy optimised printing process, reflecting the potential for the technology, can provide the greatest emission reductions of all PV technologies even though they appear to be more carbon intensive than other thin-film technologies such as CdTe when considered on the basis of static LCA. Static LCA techniques provide limited information under conditions of rapid growth, especially when comparing technologies with differing lifetimes, due to the inability to capture the nature of upfront carbon emissions.

By linking this analysis to technology economics, we propose a dynamic abatement cost. This provides a framework to assess the cost of short term mitigation, and allows for a fairer comparison of the mitigation costs associated with of a technology undergoing rapid growth.

ACKNOWLEDGMENTS

CJME would like to acknowledge support from Climate-KIC and the Grantham Institute for Climate Change through a PhD studentship. JN would like to acknowledge support from the Royal Society through an Industrial Fellowship. The authors would also like to thank Chiara Candelise, Ajay Gambhir, Antonio Urbina, and three anonymous reviewers for insightful discussions on this work.

NOTES AND REFERENCES

[a] Department of Physics, Imperial College London, South Kensington, London, SW7 2AZ

[b] Grantham Institute for Climate Change, Imperial College London, South Kensington, London, SW7 2AZ

Electronic Supplementary Information (ESI) available: Full details of the VENSIM model presented in this work can be found in the ESI. Further details of the assumptions used in the economic cost analysis as well as for the growth scenarios and life cycle analysis data can also be found in the ESI. In addition further discussion of the value of short term carbon savings are contained within the ESI. See DOI: 10.1039/b000000x/

1. D. Yue, P. Khatav, F. You, and S. B. Darling, *Energy Environ. Sci.*, 2012, **5**, 9163.

2. V. M. Fthenakis and H. C. Kim, in *IEEE*, 2006, pp. 3–6.

3. International Energy Agency, *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems*, New York, 2011.

4. S. Krauter and R. Ru, *Renew. Energy*, 2004, **29**, 345–355.

5. C. Reich-weiser, D. Dornfeld, and S. Horne, in *15th International CIRP Conference on Life Cycle Engineering*, Sydney, 2008.

6. M. Pehnt, M. Oeser, and D. Swider, *Energy*, 2008, **33**, 747–759.

7. R. E. H. Sims, H. Rogner, and K. Gregory, *Energy Policy*, 2003, **31**, 1315–1326.

8. M. Fischedick, R. Schaeffer, A. Adedoyin, M. Akai, T. Bruckner, L. Clarke, V. Krey, I. Savolainen, S. Teske, D. UrgelVorsatz, and R. Wright, in *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, eds. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, and C. von Stechow, Cambridge University Press, Cambridge, UK, 2011.

9. G. Briner, Imperial College London, 2009.

10. E. Drury, P. Denholm, and R. M. Margolis, *Environ. Res. Lett.*, 2009, **4**, 034010.

11. R. Kenny, C. Law, and J. M. Pearce, *Energy Policy*, 2010, **38**, 1969–1978.

12. M. L. J. Bojić, G. Jovanović, V. Marjanović, S. Jovanović, I. Nikolić, and Z. Djordjević, in *3rd IEEE International Symposium on Exploitation of Renewable Energy Sources*, Subotica, Serbia, 2011, pp. 59–65.

13. N. H. Reich, E. A. Alsema, W. G. J. H. M. van Sark, W. C. Turkenburg, and W. C. Sinke, *Prog. Photovoltaics Res. Appl.*, 2011, **19**, 603–613.

14. A. Arvesen and E. G. Hertwich, *Environ. Res. Lett.*, 2012, **7**, 039501.

15. J. Mathur, N. K. Bansal, and H.-J. Wagner, *Energy Policy*, 2004, **32**, 281–287.

16. A. Black, in *Solar World Congress*, Orlando, Florida, 2005.

17. C. Gonçalves da Silva, *Energy*, 2010, **35**, 1312–1316.

18. C. Gonçalves da Silva, *Energy*, 2010, **35**, 3179–3193.

19. T. G. Gutowski, S. B. Gershwin, and T. Bounassisi, in *International Symposium on Sustainable Systems and Technologies*, Washington DC, 2010.

20. B. Lloyd and A. S. Forest, *Energy Policy*, 2010, **38**, 7378–7394.

21. I. N. Kessides and D. C. Wade, *Energy Policy*, 2011, **39**, 5322–5334.

22. M. Gorig and C. Breyer, in *27th European Photovoltaic Solar Energy Conference and Exhibition*, 2012, pp. 24–28.

23. M. Dale and S. M. Benson, *Environ. Sci. Technol.*, 2013, **47**, 3482–3489.

24. S. B. Darling and F. You, *RSC Adv.*, 2013, **3**, 17633.

25. F. C. Krebs, N. Espinosa, M. Hösel, R. R. Søndergaard, M. Jørgensen, and M. C. Scharber, *Adv. Mater.*, 2013, 29–39.

26. Ventana Systems Inc, 2012.

27. S. Berry, *Solar Century response to 2012 PV RO banding consultation*, 2012.

28. Swiss Centre for Life Cycle Inventories, .

29. N. Espinosa, H. Markus, D. Angmo, and F. C. Krebs, *Energy Environ. Sci.*, 2012, **5**, 5117–5132.

30. M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, *Prog. Photovoltaics Res. Appl.*, 2014, 1–9.

31. M. J. de Wild-Scholten, E. A. Alsema, E. W. Horst, M. Baechler, and V. M. Fthenakis, in *21st European Photovoltaic Solar Energy Conference*, Dresden, Germany, 2006, pp. 4–8.

32. International Energy Agency, *CO2 Emissions from Fuel Combustion*, 2012.

33. European Photovoltaic Technology Platform, *A Strategic Research Agenda for Photovoltaic Solar Energy Technology*, Belgium, 2011.

34. First Solar, *Annual report 2012*, 2012.

35. P. Denholm and R. M. Margolis, *Energy Policy*, 2007, **35**, 4424–4433.

36. European Commission Joint Research Centre, 2013.

37. B. Azzopardi, C. J. M. Emmott, A. Urbina, F. C. Krebs, J. Mutale, and J. Nelson, *Energy Environ. Sci.*, 2011, **4**, 3741.

38. J. a. Hauch, P. Schilinsky, S. a. Choulis, S. Rajoelson, and C. J. Brabec, *Appl. Phys. Lett.*, 2008, **93**, 103306.

39. M. R. Patel, *Wind and Solar Power Systems*, CRC Press, 2005.

40. G. Keith, B. Biewald, A. Sommer, P. Henn, and M. Breceda, *Estimating the Emission Reduction Benefits of Renewable Electricity and Energy Efficiency in North America : Experience and Methods*, Cambridge, MA, 2003.

41. A. D. Hawkes, *Energy Policy*, 2010, **38**, 5977–5987.

42. D. Sivaraman and G. a. Keoleian, *Energy Policy*, 2010, **38**, 5708–5718.

43. P. Denholm, R. M. Margolis, and J. M. Milford, *Environ. Sci. Technol.*, 2009, **43**, 226–32.

44. Federal Ministry for the Environment Nature Conservation and Nuclear Safety, *Renewable Energy Sources in Figures: National and International Development*, 2012.

45. S. Bhawan and R. K. Puram, *CO2 Baseline Database for the Indian Power Sector*, New Delhi, 2012.

46. P. D. Lund, *Renew. Energy*, 2014, **66**, 33–40.

47. C. Candelise, J. F. Speirs, and R. J. K. Gross, *Renew. Sustain. Energy Rev.*, 2012, **15**, 4972–4981.

48. McKinsey & Company, *Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve*, 2009.