Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Supplementary Information

SI.1 THE VENSIM MODEL

A model was developed within the system dynamics software VENSIM, a diagram of which is shown in Fig. SI.1.1.

SI.1.2 Feedback within the Indian Case-study

Indian solar energy policy aims to develop an indigenous manufacturing industry to supply PV projects developed within the country. As such, there is the possibility that much of the PV capacity installed in India will be locally manufactured. In order to reflect this situation, the model shown in Fig. SI.1.1 was adapted to include a feedback loop linking the production of PV electricity to the electricity required to manufacture future capacity. This adapted model is shown in Fig. SI.2.1.

The impact of this feedback look is extremely limited. Future improvements in energy and material use efficiency in the manufacture of PV systems greatly outweighs cleaning of the electricity grid due to increased production of PV electricity, which in the scenarios analysed, represents just 10% of electricity in the Indian grid by 2035. The impact of the feedback loop is further limited by the fact that the grid is assumed to have a decreasing emissions factor despite the use of PV technology, to account for other clean energy generators and improvements in the efficiency of thermal generators. This evolution in the carbon intensity of the grid is shown without the influence of PV and with PV contributing to a cleaner grid in Fig. SI.2.2.

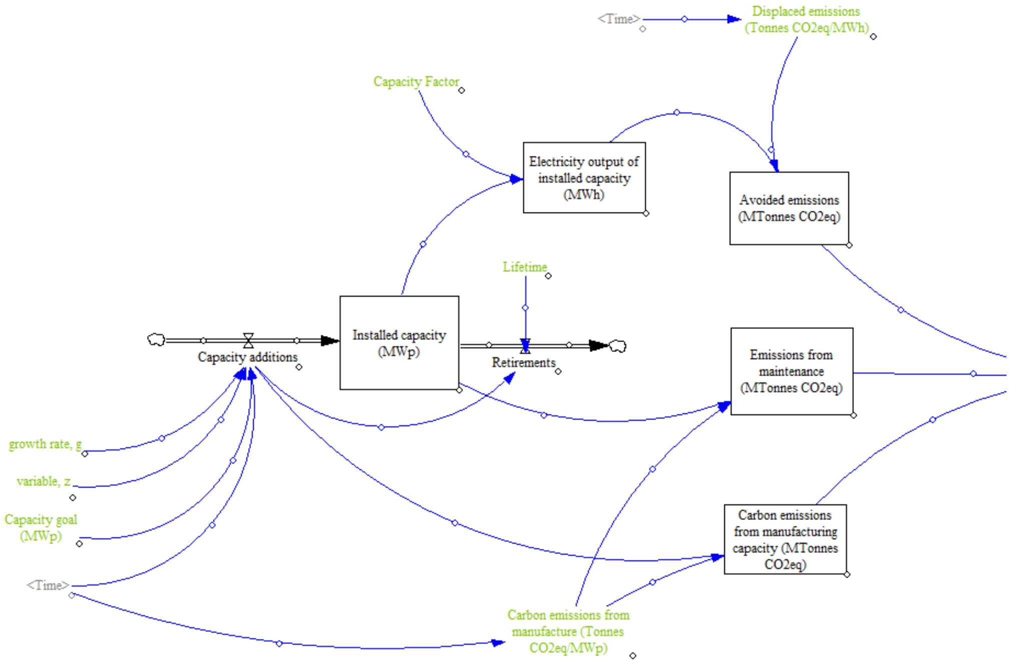

Fig. SI.1.1 – The full model created within the software VENSIM to determine net carbon emissions due to the deployment of a low carbon energy technology. Arrows indicate dependencies of the output. Labels in green represent user defined inputs to the model.

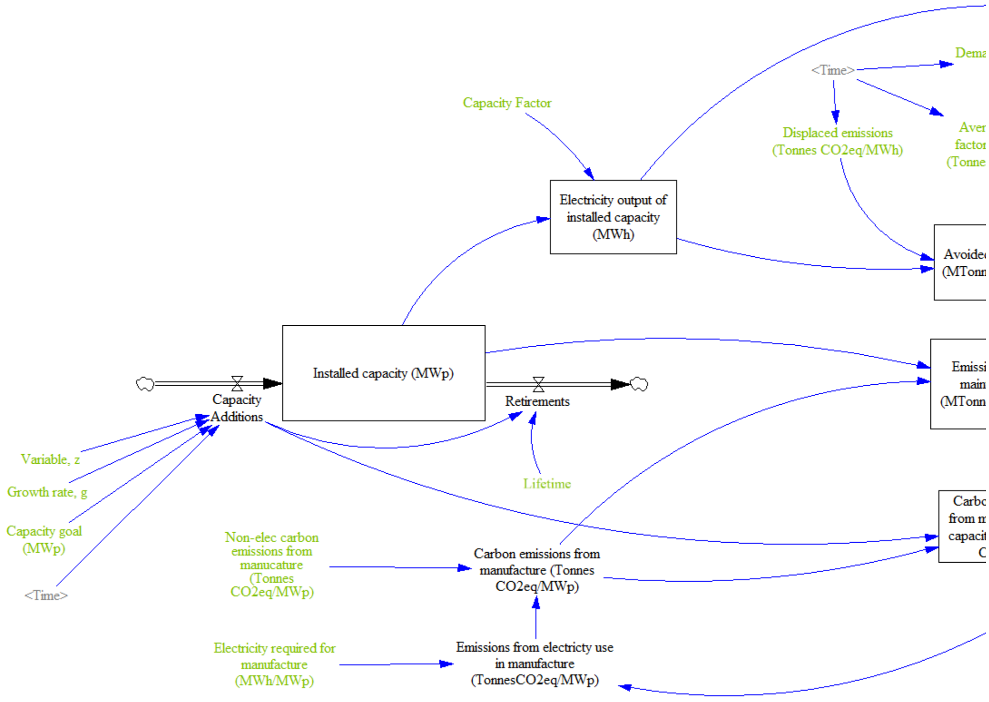

Fig. SI.2.1 – Adaptation of the model shown in Fig. A.1 used for the Indian case-study. Here a feedback loop is included to reflect the scenario of locally manufactured PV systems.

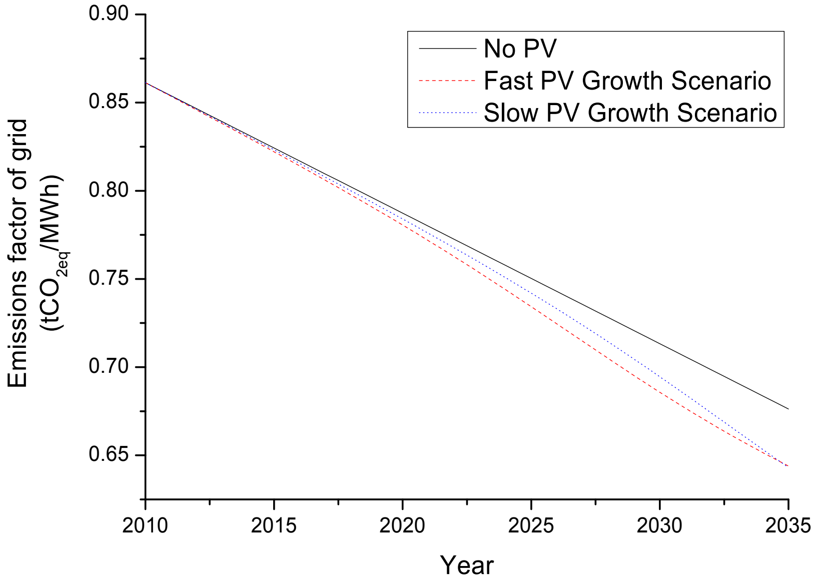

Fig. SI.2.2 – Emissions factor of grid used to determine carbon emissions from PV manufacture, showing influence of feedback loop for both fast and slow growth scenario alongside assumed cleaning of grid due to other renewables and increased efficiency of future power plants.

SI.2 DETAILS OF GROWTH SCENARIOS

Growth in deployment was modelled according to the following equation. Values for the variables defining the nature of growth in each scenario are shown in table SI.2.1.

$$Capacity\ (t) = \int_{0}^{t} \frac{Capacity\ goal * g * e^{z+gt}}{(e^{z+gt} + 1)^2} dt$$

Input	Indian case-study	German case-study
Capacity Factor	18%	11%
Growth Scenario	**OPV:** *Slow growth:* g = 0.1244, z = -6.512 Capacity goal = 825,000 MW$_p$ *Fast growth:* g = 0.121, z = -5.5 Capacity goal = 675,000 MW$_p$ **Other Technologies:** *Slow growth:* g = 0.1212, z = -6.017 Capacity goal = 416,595 MW$_p$ *Fast growth:* g = 0.1319, z = -4.922 Capacity goal = 242,710 MW$_p$	**OPV:** g = 0.0982, z = -5.912, Capacity goal = 650,000 MW$_p$ **Other Technologies:** g = 0.0853, z = -5.748, Capacity goal = 541,781 MW$_p$

Table SI.2.1 – Model inputs used for the two case-studies analysed.

SI.3 FURTHER DETAILS ON LCA ASSUMPTIONS

GHG emissions associated with manufacturing PV systems greatly depend on the carbon intensity of electricity supply to PV module factory. In order to takes this into account, the German scenario takes the global distribution of PV manufacture combined with emissions factors of the grid of the respective locations from [1] (for "other" the world average emissions factor was used).

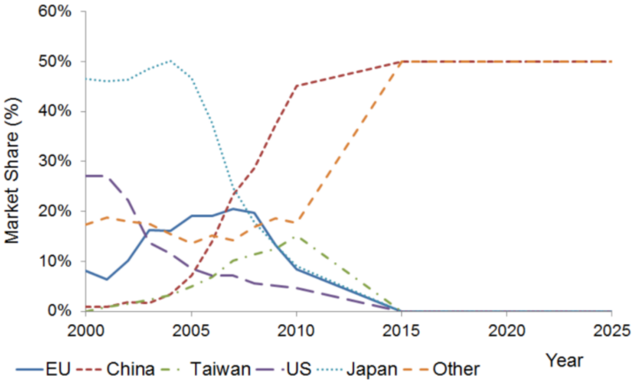

Figure SI.3.1. Global distribution of PV module manufacture (data for 2000 to 2010 from reference [2]) after which 50% assumed in China, with the remaining 50% assumed to be manufactured in a number of unspecified countries.

SI.4 ASSUMPTIONS USED IN ABATEMENT COST CALCULATIONS

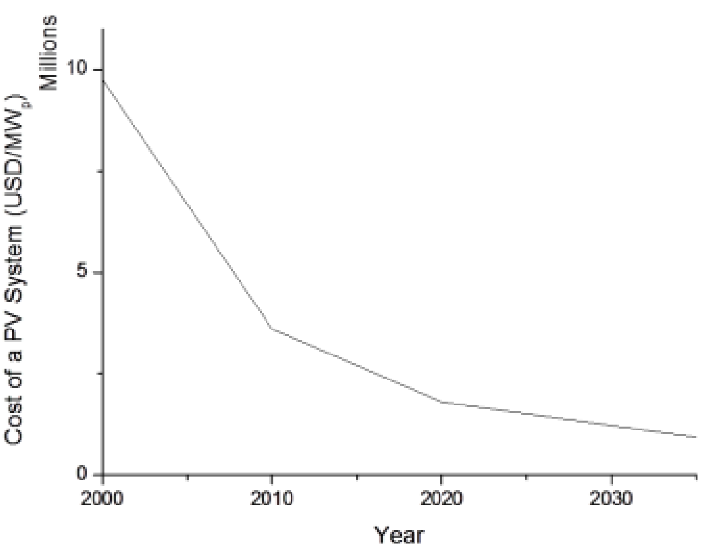

Figure SI.4.1– Evolution in the cost of a PV system over time (not discounted) [3,4].

In order to calculate dynamic and static mitigation costs for the uptake of PV technology, a number of assumptions were made on the cost and evolution in cost of PV technology and a reference solution. Costs per MW$_p$ were assumed to be equal for all PV technology, as is likely to be the case in the long term, and is approximately the current situation for CdTe and c-Si [5]. This assumes OPV to be a currently available technology, competitive on a cost per W$_p$ basis with c-Si, however, to date the technology has not developed this far. As such analysis of OPV provides an example of what could be achievable with a very low carbon and low lifetime technology. Historical costs were based on [3] and future costs on [4], as shown in figure SI.5.1.

Costs for the reference solution were taken as: 64.63 USD/MWh[1] for the Indian case-study; and 55.21 USD/MWh[2] for the German case-study, based on the 2012 average spot price of the relevant exchanges [6,7], and were assumed constant throughout the scenarios. Future costs were additionally discounted at a societal discount rate of 3.5% from the first year of the scenario to account for society's time preference (as suggested by [8]).

SI.5 FUTURE CARBON COSTS

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[1] Assumes an exchange rate of 1 USD = 54.73 INR

[2] Assumes an exchange rate of 1 USD = 0.77 EUR

The value of early carbon savings is influenced by both political and physical factors. Reference [9] shows that delaying mitigation action, even for just a couple of decades, is one of the largest sensitivities in the cost of climate change mitigation. The social cost of carbon is often considered as an indication of the value of emissions savings. The majority of studies have shown that emissions saved earlier provide the greatest reductions in climate change damage and thus are more valuable to society than delayed emission reductions.[10] Moreover, emission reductions realised later will prevent greenhouse gas emissions from being available to be emitted within other sectors (whilst also keeping within an emissions budget) and as such, a delay in emission reductions could be thought to represent a carbon budget opportunity cost.

REFERENCES

1. International Energy Agency, *CO2 Emissions from Fuel Combustion*, Paris 2011.
2. Earth Policy Institute, http://www.earth-policy.org/data_center/C23 (accessed 17th January 2013).
3. C. Candelise, M. Winskel, and R. J. K. Gross, *Renwable Sustain. Energy Rev.*, 2013, **26**, 96-107.
4. S. Teske, G. Masson, M. Antal, G. Concas, E. Despotou, A. El Gammal, D. F. Montoro, M. Latour, P. Llamas, S. Lenoir, G. Masson, P. Vanbuggenhout, S. Rolland, and R. Short, *Solar generation 6: Solar Photovoltaic Electricity Empowering the World*, Brussels, Belgium, 2011.
5. International Renewable Energy Agency, *Solar Photovoltaics*, Abu Dhabi, United Arab Emirates, 2012, vol. 1.
6. India Energy Exchange, http://www.iexindia.com/marketdata/areaprice.aspx (accessed 13th May 2013).
7. EPEXSPOT: European Power Exchange, Press Release: 2012 Volumes on European Power Exchange EPEX Spot Hit New Record, Paris, 2013.
8. F. Kesicki, *Marginal abatement cost curves for policy making – expert-based vs. model-derived curves*, London, 2011.
9. J. Rogelj, D. L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, *Nature*, 2013, **493**, 79–83.
10. R. Clarkson and K. Deyes, *Estimating the Social Cost of Carbon Emissions*, London, UK, 2002.