The solar photovoltaics wedge: pathways for growth and potential carbon mitigation in the US

Easan Drury\(^1,3\), Paul Denholm\(^1\) and Robert M Margolis\(^2\)

\(^1\) National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401, USA
\(^2\) National Renewable Energy Laboratory, 901 D Street SW, Suite 930, Washington, DC 20024, USA

E-mail: easan.drury@nrel.gov

Received 24 July 2009
Accepted for publication 3 September 2009
Published 17 September 2009
Online at stacks.iop.org/ERL/4/034010

Abstract

The challenge of stabilizing global carbon emissions over the next 50 years has been framed in the context of finding seven 1.0 Gton C/year carbon reduction wedges. Solar photovoltaics (PV) could provide at least one carbon wedge, but will require significant growth in PV manufacturing capacity. The actual amount of installed PV capacity required to reach wedge-level carbon reductions will vary greatly depending on the mix of avoided fuels and the additional emissions from manufacturing PV capacity. In this work, we find that the US could reduce its carbon emissions by 0.25 Gton C/year, equal to the fraction of a global carbon wedge proportional to its current domestic electricity use, by installing 792–811 GW of PV capacity. We evaluate a series of PV growth scenarios and find that wedge-level reductions could be met by increasing PV manufacturing capacity and annual installations by 0.95 GW/year/year each year from 2009 to 2050 or by increasing up to 4 GW/year/year for a period of 4–17 years for early and late growth scenarios. This challenge of increasing PV manufacturing capacity and market demand is significant but not out of line with the recent rapid growth in both the global and US PV industry. We find that the rapid growth in PV manufacturing capacity leads to a short term increase in carbon emissions from the US electric sector. However, this increase is small, contributing less than an additional 0.3% to electric sector emissions for less than 4.5 years, alleviating recent concern regarding carbon emissions from rapid PV growth scenarios.

Keywords: photovoltaics, solar, carbon reduction, carbon wedge, PV LCA emissions

1. Introduction

The magnitude of carbon reductions required to stabilize global carbon emissions over the next 50 years has been framed in the context of finding seven\(^4\) 1.0 Gton C/year carbon reduction wedges. The wedge scenario is defined by freezing global carbon emissions at 7 Gton C/year for the 50 years starting in 2004 (Pacala and Socolow 2004) or 2006 (Socolow and Pacala 2006). In the electric sector, one wedge could be met by annually displacing 3800 TWh of coal-generated or 8200 TWh of natural gas generated electricity, assuming emission rates of 0.26 kg C kWh\(^{-1}\) and 0.12 kg C kWh\(^{-1}\) respectively (EIA 2009b), with a carbon-free source over the next 50 years.

Solar photovoltaics (PV) represents one possible energy source that could supply a carbon reduction wedge. Solar energy is the single largest resource for renewable electricity in the US, and grid-connected PV is the fastest growing renewable energy technology (REN21 2008). However, the global PV market would have to grow substantially, from
extrapolate growth rates to 2050 using the 2006–2030 growth
AEO2009 projection extends from 2009 to 2030, and we
evaluate the sensitivity of PV growth targets to the assumptions
in the base case scenario, including the additional PV capacity
and 2060 for the late growth scenario. Additionally, we
reductions.
rapidly increasing PV manufacturing capacity and the time
quantify the short term increase in carbon emissions from
manufacturing emissions in the years they are produced, we
displacement scenarios in section 3.2. By accounting for PV
technology. We evaluate a range of PV growth scenarios in
to evaluate the potential role of PV as a carbon reduction
study uses the carbon wedge concept as a framework
to evaluate a range of PV growth scenarios in the US that reach
carbon reductions on the order of 25% of a wedge, which is approximately equal to the US fraction of
global electricity use, by setting an annual emissions reduction
target of 0.25 Gton C/year by 2050. We define three PV
growth scenarios that reach this emission reduction target,
including a reference case growth scenario with a constant
annual increase in PV manufacturing and installation capacity
(GW/year/year), and two bounding scenarios that represent
possible limits for early and late growth trajectories. These
three scenarios do not follow the linear growth trajectory
exactly as defined in the wedge scenario, instead they are
designed to reach cumulative carbon reductions at the wedge
scale (0.25 × 25 Gton/C) by 2050 for the early growth scenario
and 2060 for the late growth scenario. Additionally, we
evaluate the sensitivity of PV growth targets to the assumptions
in the base case scenario, including the additional PV capacity
required to offset embodied carbon emissions in section 3.1,
and the sensitivity of PV growth targets to multiple fuel
displacement scenarios in section 3.2. By accounting for PV
manufacturing emissions in the years they are produced, we
quantify the short term increase in carbon emissions from
rapidly increasing PV manufacturing capacity and the time
required for PV growth scenarios to achieve net emissions
reductions.

2. PV growth scenarios

2.1. Reference case electricity growth and carbon emissions:
2008–2050

We define the reference case growth of the US electricity
industry using the Annual Energy Outlook 2009 (AEO2009)
report from the US Department of Energy (EIA 2009b). The
AEO2009 projection extends from 2009 to 2030, and we
extrapolate growth rates to 2050 using the 2006–2030 growth
rates. In the AEO2009 reference case, the amount of electricity
generated in the US increases by 24% from 2009 to 2030 and
by 54% from 2009 to 2050, as shown in figure 1. Conventional
coal provides 42% of the growth from 2009 to 2030 and 34%
of the growth from 2030 to 2050, since the AEO2009 does
not include possible constraints on, or costs associated with,
carbon emissions.

In our analysis, we use the AEO2009 to define the
reference case growth in carbon emissions from US electricity
generation. The carbon emission rate for electricity generated
by coal, natural gas and petroleum are given in table 1, where
the carbon intensity of each technology decreases over time
based on projected efficiency gains. The total amount of carbon
emitted by the US electricity sector increases 16% by 2030 and
33% by 2050. The increase in carbon emissions is less than the
increase in US generation capacity, reflecting the decreasing
market share of coal fired generation and increasing market
share of natural gas and renewable technologies.

Figure 2 shows the reference case growth in carbon
emissions from US electricity generation. To reach carbon
reductions on the order of the US fraction of one wedge would
require decreasing electric sector carbon emissions by 29%.

2.2. PV growth scenarios

To calculate the amount of PV capacity required to supply a
carbon reduction wedge in our reference scenario, we make
a series of simplifying assumptions that approximate PV
electricity generation and the fuel displaced by PV electricity.
First, we assume a 20% PV capacity factor based on likely
improvements in inverter efficiencies, the use of tracking
arrays, and preferential deployment in regions with a good solar resource. We assume that 50% of PV is installed on rooftops, building facades or non-tracking arrays located in load centers, and thus avoids the transmission and distribution losses, which are approximately 7% on average in the US (EIA 2009a). We assume PV has a 30 year operation lifetime and degrades at 0.5%/year (Fthenakis et al. 2008).

We assume that the fuel displaced by PV electricity will change over time as PV penetrates the market. At low penetration, PV primarily displaces peaking and intermediate load generators which are typically fueled by natural gas in the US (Denholm et al. 2009). However, at higher penetration PV will begin to offset coal fired generation. In our reference case scenario, we approximate the decrease in natural gas displacement by assuming a linear decrease from 100% to 0% natural gas displacement for PV penetration levels from 0% to 20%. Equations (1)–(3) express the amount of coal and natural gas fired electrical energy displaced by PV electricity.

\[ f_{\text{NatGas,Displaced}}(\% \text{PV}) + f_{\text{Coal,Displaced}}(\% \text{PV}) = 1 \]

\[ f_{\text{NatGas,Displaced}}(\% \text{PV}) = \text{NatGas}(t - 1) + \Delta \text{NatGas}_{\text{BAU}}(t) \]

\[ f_{\text{Coal,Displaced}}(\% \text{PV}) = \text{Coal}(t - 1) + \Delta \text{Coal}_{\text{BAU}}(t) \]

\[ (1 - f_{\text{NatGas,Displaced}}(\% \text{PV})) \times \Delta \text{PV}_{\text{Output}}(t) \]

The fuel displacement scenario represents a simplifying assumption based on Denholm et al. (2009). Calculating the actual mix of displaced generation in the future would require simulating the full US electricity market and making assumptions about the future capacity mix. Given this uncertainty, we explore additional fuel displacement scenarios in section 3.2.

When calculating the potential contribution of PV to a wedge, we consider certain ‘upstream’ components of fuel production and use, as calculated in the life-cycle analysis (LCA) literature. This is primarily associated with the large amount of energy used to transport natural gas, as well as methane leaks, which due to its high global warming potential produces an additional 4.69 g Ce MJ⁻¹ delivered (Spath and Mann 2000), a 25.4% increase to the carbon intensity of delivered natural gas. Transporting coal adds an additional 0.75 g Ce MJ⁻¹ delivered (Spath et al. 1999), a 2.6% increase. As a result, our PV wedge is primarily from avoided fuel combustion in the electric sector, but contributes to reducing greenhouse gas emissions by avoiding methane leaks and reducing fuel combustion in other sectors.

Using these simplifying assumptions, the US share of one carbon wedge can be supplied with 756–774 GW of PV capacity installed by 2050. This level of PV penetration could be reached with a constant annualized growth rate ranging from 17.1 to 17.2%, which is in line with the 17.1% mean annual growth of global nuclear capacity from 1960 to 1996 (BTM 1999). To place this amount of PV capacity in context, 500–700 GW could be installed on commercial and residential rooftops (Denholm and Margolis 2008b), and 2000 GW of PV capacity could be located on 1% of current US cropland (Denholm and Margolis 2008a).

We evaluate three PV penetration scenarios that lead to the US share of annual emission reductions at the wedge level (25% × 1.0 Gton C/year) by 2050, as shown in figure 3. The reference case growth scenario (const. growth) represents adding a fixed amount of PV manufacturing capacity (GW/year/year) each year, equivalent to building one new 0.92 GW/year PV factory each year from 2009 to 2050. In addition to the constant growth scenario, we consider an early adoption scenario which represents policy and technology-driven growth in the near term to reach carbon reduction targets more quickly, and a late adoption scenario which could represent less-than-anticipated PV cost reductions over the next two decades or less aggressive carbon reduction goals. These PV growth trajectories deviate from the idealized linear trajectory defined in the wedge scenario (Pacala and Socolow 2004), and they reach cumulative wedge-level carbon reductions (25% × 25 Gton C) by 2050 for the early growth scenario and 2060 for the late growth scenario.

Figures 4 and 5 provide further details about the growth rates for the three scenarios. Figure 4 shows the growth in annual installed capacity, analogous to building additional PV manufacturing and installation capacity, and figure 5 shows the...
the annual installed capacity. It is important to distinguish between growth in cumulative PV capacity, which is given by annual installed capacity (measured in units of GW/year) and the growth in manufacturing and installation capacity (measured in units of GW/year/year). The traditional metric of growth in the electric sector is the growth in cumulative installed capacity. However, since PV is starting from such a small base, it is also important to consider the growth required in the manufacturing and installation capacity. For example, in 2008 the cumulative installed PV capacity grew by 0.34 GW/year in the US. If this annual installation rate were held fixed from 2009 to 2050, a total of 15.3 GW of PV capacity would be installed by 2050 which would account for approximately 2% of a carbon reduction wedge. In contrast, if the annual growth in PV installation capacity in 2008 is continued through 2050 then a total of 142 GW of PV capacity would be installed by 2050, which is much more significant, but still far below wedge-level reductions. Thus without significant growth in PV manufacturing and installation capacity, cumulative PV installations will fall well short of achieving wedge-level reductions. Table 2 summarizes the recent trends in US cumulative installed capacity (GW), annual installed capacity (GW/year), and the growth in annual installed capacity (GW/year/year).

Figure 4 shows the increase in manufacturing capacity for both the reference case and the early and late growth scenarios. The reference case represents adding 0.92 GW/year/year of PV manufacturing and installation capacity each year from 2009 to 2050. The early and late growth scenarios are bounded by a maximum PV manufacturing and installation increase of 4.0 GW/year/year, which is sustained for 4 years in the early growth scenario and 17 years in the late growth scenario. To place the growth of PV manufacturing in context, the capital expenditure of building a 1.0 GW PV factory ranges from $1–3 billion (2007 US dollars) (Maycock and Bradford 2007). This scale of investment would require $0.9–2.8 billion/year for the reference case, and a maximum of $4.0–12.0 billion/year (2007 US dollars) at peak for the early and late growth rates.

While these scenarios do not represent the entire range of theoretically possible scenarios, they do represent a likely ‘envelope’ for wedge-level growth scenarios. The early and late growth scenarios were bounded by a maximum growth rate of PV manufacturing and installation capacity equal to 4.0 GW/year/year. This results in an annual PV installation rate of approximately 25 GW/year by 2015 in the early growth scenario (equal to approximately 75 times the capacity growth rate of 0.34 GW/year in 2008). The late growth scenario must achieve an annual growth rate of approximately 78 GW/year in 2050, which is three times greater than the maximum annual growth rate projected for the entire electric generation sector from 2008 to 2030 (EIA 2009b).

To provide context for these growth rates, Mehta and Bradford (2009) have projected that global PV manufacturing capacity (including both crystalline silicon and thin film PV) could increase from 3.2 GW/year in 2007 to 23.7 GW/year by 2012 based on existing and planned investments in expanding PV production (Mehta and Bradford 2009). This growth in PV manufacturing capacity is analogous to an annual increase of 4.1 GW/year/year for 5 years. If the US share of global PV growth were 25%, approximately equal to the current US share of global electricity use, this would correspond to a 1.0 GW/year/year increase which is approximately equal to our constant growth in PV manufacturing capacity scenario. A recent survey of US PV market forecasts from industry analysts (Bartlett et al 2009) estimated that US PV demand will increase from 0.4 to 4.4 GW/year from 2008 to 2012, which is also in line with the wedge-level PV growth targets. Thus the engineering and market challenges could be to sustain the growth in PV manufacturing capacity and market demand over time. Additionally, if the global PV growth rate of 4.1 GW/year/year is met and sustained, not only the US but the global PV market could already be on track to reach wedge-level carbon reductions by 2050.

Assuming the cost of installed PV systems is within a range from $2.10–3.40 W−1 (2007 US dollars) by 2015 and

Table 2. Recent growth in US PV capacity. (Note: Source: SEIA 2009.)

| Year | Cumulative US PV capacity (GW) | Annual installed US PV capacity (GW/year) | Growth in PV installation capacity (GW/year/year) |
|------|-------------------------------|------------------------------------------|--------------------------------------------------|
| 2006 | 0.57                          | 0.15                                     | 0.04                                             |
| 2007 | 0.77                          | 0.20                                     | 0.05                                             |
| 2008 | 1.11                          | 0.34                                     | 0.14                                             |

Figure 4. Annual increase in PV manufacturing and installation capacity (GW/year/year) for the three growth scenarios. This corresponds to the increase in annual installed PV capacity each year, not the annual installed PV capacity.

Figure 5. Annual installed PV capacity (GW/year) for the three growth scenarios.
$1.80–2.10 \text{ W}^{-1}$ (2007 US dollars) by 2030\(^9\), the size of the US retail PV market in the reference case scenario will reach $14.8–23.5$ billion in 2015 and $38.3–44.4$ billion in 2030. For the purpose of comparison, the annual investment in the North American electricity sector, including generation, transmission and distribution, has been estimated from $84$ to $126$ billion (2007 US dollars) for capacity expansion from 2007 to 2030 (IEA 2008). In the private sector, US consumers spent $21$ billion on personal computers, $26$ billion on TVs (US Census 2009), and $440$ billion on light duty vehicles in 2007 (BEA 2009).

The cumulative installed PV capacity (figure 3) is calculated from the annual installed PV capacity assuming that PV modules have a 30 year operational lifetime. Cumulative PV capacity levels off after 2039 in the early growth scenario as PV systems older than 30 years are retired. The three PV penetration scenarios lead to 756–774 GW of cumulative installed PV in the US resulting in avoided carbon emissions of 0.25 Gtons C/year by 2050, as shown in figure 6 and summarized in table A.1 in the appendix.

### 3. Sensitivities

The results in section 2 are based on a series of simplifying assumptions that ignore the carbon emissions generated by manufacturing PV and enabling technologies, and use one fuel displacement scenario. In this section, we evaluate the additional PV capacity required to reach carbon reduction goals by considering the embodied carbon emissions and a variable fuel displacement fraction.

#### 3.1. PV carbon emissions

Although PV uses a carbon-free ‘fuel’, manufacturing PV is an energy intensive process which leads to significant carbon emissions released to the atmosphere at the time PV is manufactured. To fabricate crystalline silicon PV modules, quartz must be mined, purified, fabricated into a thin semiconducting wafer, wired together and encased in a protective housing. For thin film PV modules, metal ores must be mined, purified and deposited on a durable substrate and encapsulated in a protective housing.

We calculate the carbon emissions from the PV growth scenarios as the sum of emissions from manufacturing PV systems, building PV factories and manufacturing enabling technologies:

$$\text{Carbon}_{\text{PV}}(t) = \text{PV}_{\text{Module,Frame&BOS}}(t) \times \text{carbon intensity}_{\text{PV}}(t)$$

$$+ \text{factories}(t) \times \text{carbon intensity}_{\text{Factories}}(t)$$

$$+ \text{enabling technologies}(t)$$

$$\times \text{carbon intensity}_{\text{Enabling Tech}}(t).$$

The carbon emissions associated with each component in equation (4) are calculated from the amount of PV, factories or enabling technologies manufactured in a given year times their carbon intensities. We discuss the carbon intensity of each component successively below.

We calculate the carbon intensity of manufacturing PV using LCA emissions based on 2004–2006 PV manufacturing data (Fthenakis et al 2008). The amortized carbon emissions range from 7 g C\(_e\) kWh\(^{-1}\) for thin films (CdTe) to 15 g C\(_e\) kWh\(^{-1}\) for mono-crystalline silicon PV (mono-Si). We received the total manufacturing emission rates (Fthenakis 2009) which can be reproduced by multiplying the variable emission rates by the amount of energy generated by a given amount of PV over its lifetime assumed in Fthenakis et al (2008). We calculate the fraction of PV manufacturing emissions from the use of electricity and fossil fuels using the different assumptions of regional electricity fuel mixes given in Fthenakis et al (2008). These results are summarized in table 3.

The carbon intensity of manufacturing PV, carbon intensity\(_{\text{PV}}(t)\), decreases over time in two ways: first, the carbon intensity of electrical energy decreases as PV displaces coal and natural gas use; second, we assume the energy required to manufacture a given amount of PV decreases over time with improvements in manufacturing processes and technological advances. To characterize these trends, we calculate the carbon intensity of electricity at each time step using the current PV market fraction, and we decrease the energy required to manufacture a given amount of PV capacity by 45% from 2008 to 2020 which could represent an increase in thin film PV market share to 90% or improved Si PV manufacturing techniques that would enable them to stay competitive. We calculate the additional PV capacity required to offset these embodied carbon emissions (table 4), and we evaluate the sensitivity of the additional capacity requirements to the carbon intensity of PV using an upper bound scenario which assumes no decrease in the carbon intensity of PV and a lower bound scenario which assumes a 75% reduction in PV carbon intensity for the entire analysis period (equivalent to thin films achieving 100% market share and thin film carbon intensity decreasing by a factor of two). These results are summarized in table 4.

In addition to PV manufacturing emissions, we also add the emissions associated with tracking arrays and operations and maintenance (O&M) for all PV systems. These emissions are estimated using economic input–output life-cycle assessment (EIO LCA) methods, where the cost of tracking arrays and O&M are multiplied by the carbon

\(^9\) NREL estimate based on discussions with multiple PV manufacturers and financial analysts.
Table 3. Efficiencies and lifetime carbon emissions of PV technologies. (Note: includes carbon emissions for the module, frame and balance of systems. Source: adapted from Fthenakis et al 2008.)

| Technology | Efficiency (%) | \( g \text{ Ce } k\text{W}^{-1} \) | Electricity use (\( g \text{ Ce } k\text{W}^{-1} \)) | Fossil fuel use (\( g \text{ Ce } k\text{W}^{-1} \)) | Total (\( g \text{ Ce } /k\text{W} \)) |
|------------|---------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Mono-Si    | 14.0          | 14.8                            | 332                             | 274                             | 605                             |
| Multi-Si   | 13.2          | 14.2                            | 310                             | 272                             | 581                             |
| Ribbon-Si  | 11.5          | 11.9                            | 278                             | 209                             | 487                             |
| CdTe       | 9.0           | 7.0                             | 143                             | 140                             | 284                             |

Table 4. PV capacity required to reach wedge-level carbon reductions.

| Scenario                                    | Early growth (GW) | Const. growth (GW) | Late growth (GW) |
|---------------------------------------------|-------------------|--------------------|------------------|
| No PV emissions                             | Total             | Additional         | Total            | Additional       |
| Reference PV emissions reductions           | 774               | —                  | 764              | 756              |
| High emissions reductions\(^a\)            | 794               | 20                 | 792              | 28               | 811              | 55               |
| Low emissions reductions\(^b\)             | 785               | 11                 | 780              | 16               | 782              | 26               |
|                                             | 808               | 34                 | 814              | 50               | 849              | 93               |

\(^a\) A 75% reduction in the carbon intensity of PV and a $1 billion/GW PV factory cost (2008 US dollars) from 2008 to 2050.

\(^b\) No decrease in the carbon intensity of PV and a $3 billion/GW PV factory cost (2008 US dollars) from 2008 to 2050.

The intensity of each process estimated using an EIO LCA model (CMU-GDI 2008). Tracking array emissions are estimated assuming 50% of PV uses tracking and that tracking costs decrease from $0.50 W\(^{-1}\) to $0.40 W\(^{-1}\) by 2020 (2007 US dollars) where they stay through 2050 (Deutsche Bank 2009). We use a carbon intensity of 153 g Ce$/S (2007 US dollars) for tracking arrays and 67 g Ce$/S (2007 US dollars) for O&M (CMU-GDI 2008). The LCA model is based on 1997 data and we adjust the carbon intensities to units of 2008 US dollars using a GDP price deflator of 1.28 for this period. We assume annual mean O&M costs of 10 $50 /kW year and $35 /kW year for tracking and non-tracking PV systems\(^11\), and assume they linearly decrease to $15 /kW year and $10 /kW year, respectively, by 2050 to account for potential inverter cost reductions.

In addition to accounting for PV manufacturing emissions, we also calculate the carbon intensity of building PV manufacturing facilities and equipment. EIO methods were used for these estimates, based on a carbon intensity of 125 g Ce$/S (2008 US dollars) for PV factories and 117 g Ce$/S (2008 US dollars) for PV fabricating equipment. In the reference case, we assume that new buildings are constructed for PV manufacturing facilities, and we assume the cost of a 1.0 GW/year PV factory will decrease from $3 billion in 2008 to $1 billion by 2020 (2008 US dollars) (Maycock and Bradford 2007), where we assume it will stay through 2050. Factory cost reductions represent improvements in manufacturing technologies, and increases in manufacturing throughput over time. We assume a 30 year operational lifetime for manufacturing equipment, and a >50 year operation lifetime for factory buildings. In addition to the reference case we evaluate sensitivities to these assumptions, using a $1 billion/GW year factory cost for the entire analysis period (which could represent the use of existing factory buildings and increases in manufacturing throughput) and a $3 billion/GW year factory cost for the entire analysis period (which could represent shorter equipment lifetimes or higher equipment costs for new technologies). The results of the sensitivity analysis are shown in table 4.

We also considered the potential need for PV enabling technologies and associated impacts on system performance and carbon emissions. At the wedge level, PV would provide approximately 20% of the nation’s electricity demand. The variability of the solar resource increases the need for system operating reserves and may require a variety of enabling technologies including load shifting, smart appliances or energy storage (Denholm and Margolis 2007a, 2007b). As an upper bound on the associated carbon emissions, we assume that energy storage must be deployed for PV market fractions above 10% based on estimates from Denholm and Margolis (2007b), as shown in figure 7. This leads to storage requirements of approximately 2–3% of PV electricity for wedge scale PV penetration.

Adding storage capacity will lead to additional carbon emissions which are dependent on the storage technology used (Denholm and Kulcinski 2004). As an upper bound to storage emissions, we assume the storage device has a mean emission rate of 44 kg Ce/kWh\(^{-1}\) of storage capacity and a round trip efficiency of 75%. These performance parameters are based on vanadium-redox battery technology (Denholm and Kulcinski 2004), but storage requirements could be met using different technologies with lower embodied emissions such as pumped storage.
The total storage requirements for PV electrical energy is calculated as follows:

\[
\text{battery capacity} = \frac{\text{annual energy stored}}{8760 \times \text{battery capacity factor}} \tag{5}
\]

where the battery capacity factor represents the fraction of time that a battery spends discharging, which we assume to be 25% or 6 h of storage. The electrical energy losses associated with storage are calculated as follows:

\[
\text{PV output}(t) = \text{PV gen}(t) \times f_{\text{PV stored}}(t) \times \epsilon_{\text{storage}} + (1 - f_{\text{PV stored}}(t)) \tag{6}
\]

where PV output is the electrical energy seen by end users, PV gen is the energy generated by PV systems, \( \epsilon_{\text{storage}} \) represents the round trip efficiency and \( f_{\text{PV stored}} \) represents the total fraction of PV output requiring storage. Approximately 2% of PV energy requires storage at the 20% PV penetration required to reach wedge-level reductions, resulting in an energy loss of 0.5% assuming a round trip battery efficiency of 75%.

Figure 8 shows the carbon emissions from manufacturing and maintaining PV capacity for the three growth scenarios. The total PV manufacturing emissions increase at a rate that is significantly less than PV manufacturing capacity since we assume that PV will require less energy to produce and that the carbon intensity of the electricity market will decrease in proportion to PV market share. The increase in manufacturing efficiency is responsible for the majority of emissions reductions for three scenarios. We include a table with the growth in PV capacity and the associated PV carbon emission in appendix.

The total carbon emissions from US electricity generation are calculated by summing the variable emissions from fossil fuel use plus the fixed emissions from building PV factories, manufacturing PV capacity and battery storage capacity in the years they are produced (figure 8). This is expressed as follows:

\[
\text{CO}_2, \text{US Electricity Market}(t) = \sum_{i=1}^{\text{Fuel Types}} \text{electrical energy}_i(t) \times \text{carbon intensity}_i(t) + \text{CO}_2, \text{PV}(t). \tag{7}
\]

Figure 9 shows the total carbon emissions for the three PV growth scenarios and the reference case scenario. The carbon emissions from US electricity generation are shown both with and without PV manufacturing emissions by the solid and dashed lines respectively. The carbon emitted from manufacturing PV and battery storage capacity, seen as the difference between the solid and dashed lines in figure 9, remains less than 2.5% of the reference case emissions for all growth scenarios.

Table 4 summarizes the amount of cumulative PV capacity required to reach wedge-level carbon reductions for both the reference case scenario and the two bounding scenarios. Additional PV was required to offset the embodied carbon emissions from manufacturing PV and energy storage capacity, and we find that an additional 20 GW (2.6%), 28 GW (3.7%) and 55 GW (7.3%) of PV capacity are required in the early, reference and late adoption scenarios to offset PV manufacturing emissions. Fabricating PV modules contributes the largest share of carbon emissions, increasing from 70% in 2010 to 85% by 2050. Building PV factories and manufacturing equipment accounts for up to 30% of emissions during the initial years of growth, but decrease rapidly to less than 2.5% by 2020. Fabricating battery storage capacity accounts for less than 2% of emissions. Operations and maintenance, which is primarily inverter replacement, constitutes the remaining emissions. Thus, PV growth targets are primarily sensitive to the carbon intensity of PV manufacturing, and relatively insensitive to assumptions about inverter costs, factory costs and storage requirements.
Table 5. PV capacity required under different fuel displacement scenarios.

| Scenario                  | Total (GW) | Additional (GW) | Total (GW) | Additional (GW) | Total (GW) | Additional (GW) |
|---------------------------|------------|-----------------|------------|-----------------|------------|-----------------|
| Reference fuel displacement | 794        | —               | 792        | —               | 811        | —               |
| Low natural gas displacement | 698        | −96             | 684        | −108            | 699        | −112            |
| High natural gas displacement | 883        | 89              | 881        | 89              | 899        | 88              |

Figure 10. Assumed natural gas (NG) and coal displacement fractions as a function of PV penetration for the reference scenario and the higher and lower natural gas displacement scenarios.

Figure 11. Assumed natural gas (NG) and coal displacement fractions by year for the reference scenario and the higher and lower natural gas displacement scenarios.

3.2. Displaced fuel use

The reference case fuel displacement scenario represents a simplifying assumption based on Denholm et al. (2009). Calculating the actual mix of displaced generation in the future would require simulating the full US electricity market and making assumptions about the future capacity mix. Given the uncertainty in the future growth of US generation capacity and the affect of a carbon tax or cost on utility operations (Newcomer et al. 2008), we calculate a range of PV growth targets based on different fuel displacement scenarios rather than explicitly making these assumptions.

In the reference scenario, we estimate the decreasing natural gas displacement fraction by linearly decreasing from 100% to 0% natural gas displacement for increasing PV penetrations levels from 0% to 20%. As a lower and upper bound on the PV required to reach wedge-level reductions, we assume a similar linear decrease in the displaced natural gas fraction reaching 0% natural gas displacement (and 100% coal displacement) at 10% and 30% PV penetration fractions. Figure 10 shows the natural gas displacement fractions as a function of PV penetration for both the reference scenario and the higher and lower natural gas displacement scenarios.

Figure 11 shows the natural gas displacement fractions by year for the constant annual growth in PV manufacturing capacity (GW/year/year) scenarios. Since the carbon intensity of electricity generated by natural gas is less than that from coal, significantly more PV capacity will be required in the high natural gas displacement scenario, and similarly less in the low natural gas displacement scenario. The amount of PV required in the different scenarios to reach carbon reduction targets at the wedge scale and offset embodied PV emissions, is shown in table 5.

The amount of PV capacity required is highly dependent on the mix of displaced fuels, where 12–14% less PV capacity is required to reach carbon reduction targets in the low natural gas displacement scenarios and approximately 11% more PV capacity is required in the high natural gas displacement scenarios. This difference in PV capacity based on displaced fuel use is 2–5 times greater than the additional PV required to offset embodied manufacturing emissions, making uncertainty in the fuel displaced by PV electricity the key driver in uncertainty in estimating the amount of PV capacity required to reach carbon reduction goals. While predicting the actual avoided fuel mix in the future is highly conjectural, there are some fundamental limits to the fuel mix that can be offset. For example, in the high natural gas displacement scenario, the fraction of total generation produced by natural gas has been reduced to from 20% to 4%, leaving little gas generation left to meet peaking and load following requirements.

4. Near-term increase in carbon emissions

Since embodied PV emissions are released to the atmosphere during the manufacturing process, there has been considerable concern regarding the increase in carbon emissions associated with rapidly scaling up PV manufacturing capacity. In fact, net carbon emissions are likely to increase slightly in the near term.
since the manufacturing emissions in any given year are not yet offset by the carbon-free operation of installed PV capacity.

Figure 12 shows the near-term increase in carbon emissions for the constant growth and early growth scenarios. The constant growth scenario leads to a 0.1% increase in carbon emissions from the US electric sector for a duration of less than 3.5 years. The rapid early growth scenario leads to a net increase of up to 0.3% for up to 4 years. Thus, even the most aggressive scale up of the US PV industry leads to only a fraction of 1% increase in US electric sector carbon emissions, which is trivial compared to the cumulative carbon reductions from offsetting conventional coal and natural gas generation. The late growth scenario emissions are not shown in figure 12 since the cumulative installed PV capacity from two decades of slow PV growth completely offsets PV manufacturing emissions.

Figure 12 illustrates that the near-term increase in carbon emissions associated with a PV wedge scenario is both small in magnitude and duration. To emphasize this point, figure 13 shows the time required for PV growth scenarios to decrease carbon emissions below the AEO2009 scenario, for a range of fuel displacement scenarios from 0% coal and 100% natural gas to 100% coal and 0% natural gas. While our reference scenarios assume that natural gas will be displaced first, resulting in up to 4 years of increased carbon emissions, the duration of net carbon increase could be reduced to 1.5–2.5 years if coal fired electricity is preferentially displaced. The difference in the time required to reach net carbon reductions for the constant growth scenario and the early growth scenario is only 1 year, illustrating that the duration of the increase in carbon emissions is relatively insensitive to the magnitude of near-term PV growth.

Further insight on the near-term increase in carbon emissions associated with wedge-reduction scenarios could be gained by evaluating multiple wedge technologies. Many renewable energy technologies have lower carbon intensities per unit capacity and higher capacity factors than PV, and we would expect a smaller increase in their near-term carbon emissions. As an example, repeating our rapid growth scenarios for wind and assuming a 33% capacity factor (Wiser and Bolinger 2008) and all other reference case assumptions, we find that a US fraction of one wedge could be met with approximately 460 GW of installed wind capacity by 2050, excluding embodied carbon emissions. If embodied carbon emissions are included (Denholm et al 2005, Alsem and de Wild-Scholten 2006, Tremec and Meunier 2009), an additional 10 GW of wind capacity would be required by 2050 and the maximum near-term increase in carbon emissions would be less than 0.01% of the electric sector emissions for less than 1.5 years.

5. Conclusions

Substantial growth in the PV industry will be required for this technology to contribute carbon reductions at the wedge level as proposed by Pacala and Socolow (2004). For the US to displace a fraction of a wedge proportional to domestic electricity use (0.25 Gton C/year) by 2050, 792–811 GW of photovoltaic capacity would be required in our reference scenario, which includes additional PV capacity to offset embodied carbon emissions. This level of PV penetration could be reached by constructing one new 0.95 GW/year PV factory in the US each year from 2009 to 2050, which is in line with the projected global growth in PV manufacturing capacity of 4.1 GW/year (Mehta and Bradford 2009) and with the forecasted growth in US PV demand (Bartlett et al 2009). Thus the engineering and market challenge for the US to reach a fraction of one carbon reduction wedge could be to sustain current levels of growth in PV manufacturing capacity and market demand over time.

The embodied carbon emissions associated with scaling up both PV manufacturing capacity and fabricating PV systems can result in a small near-term increase in carbon emissions from the US electric sector. In the scenarios evaluated, it could take 3–4 years for PV to produce a net reduction in carbon emissions, with the net increase in carbon emissions peaking at approximately 0.2 Mton C/year, representing a 0.3% increase in US electric sector emissions. This increase is trivial compared to the cumulative carbon reductions from PV electricity offsetting conventional coal and natural gas generation.

Acknowledgments

The authors would like to thank Vasilis Fthenakis and Thomas Jenkin for valuable input.
Appendix

Table A.1. PV growth scenarios.

|                      | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|----------------------|------|------|------|------|------|------|------|------|------|
| Manufacturing capacity (GW/year/year) |      |      |      |      |      |      |      |      |      |
| Early                | 4.00 | 2.90 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| Constant             | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 |
| Late                 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 4.00 | 4.00 | 4.00 | 4.00 |
| Annual installed PV capacity (GW/year) |      |      |      |      |      |      |      |      |      |
| Early                | 5.2  | 24.1 | 25.3 | 25.6 | 26.0 | 26.4 | 26.8 | 27.1 | 27.5 |
| Constant             | 2.1  | 6.9  | 11.6 | 16.4 | 21.2 | 25.9 | 30.7 | 35.4 | 40.2 |
| Late                 | 0.3  | 0.6  | 0.9  | 1.2  | 1.5  | 17.8 | 37.8 | 57.8 | 77.8 |
| Cumulative installed PV capacity (GW) |      |      |      |      |      |      |      |      |      |
| Early                | 7    | 9    | 218  | 346  | 475  | 606  | 732  | 782  | 794  |
| Constant             | 4    | 29   | 78   | 150  | 247  | 367  | 507  | 650  | 792  |
| PV emissions:         |      |      |      |      |      |      |      |      |      |
| PV systems (Gton C/year) |      |      |      |      |      |      |      |      |      |
| Early                | 0.010| 0.036| 0.026| 0.026| 0.026| 0.026| 0.026| 0.026| 0.026|
| Constant             | 0.004| 0.010| 0.014| 0.018| 0.022| 0.027| 0.031| 0.035| 0.038|
| Late                 | 0.001| 0.001| 0.001| 0.001| 0.002| 0.020| 0.041| 0.059| 0.073|
| PV emissions:         |      |      |      |      |      |      |      |      |      |
| factories (Gton C/year) |      |      |      |      |      |      |      |      |      |
| Early                | 4.2 × 10^{-3}| 2.1 × 10^{-5}| 2.9 × 10^{-5}| 2.9 × 10^{-5}| 2.9 × 10^{-5}| 2.9 × 10^{-5}| 2.9 × 10^{-5}| 2.9 × 10^{-5}| 2.9 × 10^{-5}|
| Constant             | 9.9 × 10^{-4} | 6.8 × 10^{-4} | 3.7 × 10^{-4} | 3.7 × 10^{-4} | 3.7 × 10^{-4} | 3.7 × 10^{-4} | 3.7 × 10^{-4} | 3.7 × 10^{-4} | 3.7 × 10^{-4} |
| PV emissions:         |      |      |      |      |      |      |      |      |      |
| storage capacity (Gton C/year) |      |      |      |      |      |      |      |      |      |
| Early                | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Constant             | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Late                 | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Total PV emissions (Gton C/year) |      |      |      |      |      |      |      |      |      |
| Early                | 0.014| 0.038| 0.029| 0.026| 0.026| 0.026| 0.026| 0.026| 0.026|
| Constant             | 0.005| 0.011| 0.014| 0.018| 0.023| 0.027| 0.031| 0.035| 0.039|
| Late                 | 0.001| 0.001| 0.001| 0.001| 0.002| 0.021| 0.042| 0.061| 0.076|
| Avoided carbon       |      |      |      |      |      |      |      |      |      |
| emissions (Gton C/year) |      |      |      |      |      |      |      |      |      |
| Early                | −0.002| 0.013| 0.054| 0.097| 0.143| 0.192| 0.242| 0.255| 0.250|
| Constant             | −0.001| 0.004| 0.016| 0.034| 0.061| 0.098| 0.146| 0.197| 0.250|
| Late                 | 0.000| 0.001| 0.002| 0.003| 0.004| 0.011| 0.044| 0.118| 0.250|

References

Alema E A and de Wild-Scholten M J 2006 Environmental impacts of crystalline silicon photovoltaic module production 13th Int. Conf. on Life Cycle Engineering (Leaven, 2006) Conference Paper

Bartlett J E, Margolis R M and Jennings C E 2009 The effects of the financial crisis on photovoltaics: analysis of changes in market forecasts from 2008 to 2009 NREL Technical Report National Renewable Energy Lab, under review

BEA (Bureau of Economic Analysis), US Department of Commerce 2009 National Income and Product Accounts, table 2.3.5. Personal Consumption Expenditures by Major Type of Product

BTM Consulting 1999 Wind Force 10: A Blueprint to Achieve 10% of the World’s Electricity from Wind Power by 2010 (Ringkobing: BTM Consulting ApS) http://www.inforse.dk/doc/Windforce10.pdf

CMU-GDI (Carnegie Mellon University Green Design Institute) 2008 Economic Input–Output Life Cycle Assessment (EIO-LCA), US 1997 Industry Benchmark Model (Internet) http://www.eiolca.net

Denholm P and Kulcinski G 2004 Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems Energy Convers. Manag. 45 2153–72

Denholm P, Kulcinski G and Holloway T 2005 Emissions and energy efficiency assessment of baseload wind energy systems Environ. Sci. Technol. 39 1903–11

Denholm P and Margolis R M 2007a Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems Energy Policy 35 2852–61

Denholm P and Margolis R M 2007b Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies Energy Policy 35 4424–33

Denholm P and Margolis R 2008a Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States Energy Policy 36 3531–43

Denholm P and Margolis R 2008b Supply curves for rooftop solar PV generated electricity for the United States NREL/TP-6A0-44073

Denholm P, Margolis R and Milford J 2009 Quantifying avoided fuel use and emissions from solar photovoltaic generation in the western United States Environ. Sci. Technol. 43 226–32

Deutsche Bank 2009 Solar photovoltaic industry: looking through the storm Global Markets Research January 2009

EIA (Energy Information Administration), US Department of Energy 2009a Electric Power Annual 2007, Report no. DOE/EIA-0383(2009)

EIA (Energy Information Administration), US Department of Energy 2009b Annual Energy Outlook 2009 with Projections to 2030 (AEO2009), Report no. DOE/EIA-0348(2007)

EIA (Energy Information Administration), US Department of Energy 2009c Wind Energy Market Baseline Report: 2009 (AWEA09), Report no. DOE/EIA-0383(2009)

Forster P et al 2007 Changes in atmospheric constituents and in radiative forcing Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press)

Fthenakis V 2009 personal correspondence

Fthenakis V, Kim H C and Alema E 2008 Emissions form photovoltaic life cycles Environ. Sci. Technol. 42 2168–74
IEA (International Energy Agency) 2008 Trends in photovoltaic applications: survey report of selected IEA countries between 1992 and 2007 IEA-PVPS T1-17:2008

Kantner J, Mileva A and Kammen D 2009 Solar Photovoltaics, Gigaton Throwdown: Redefining What’s Possible for Clean Energy by 2020 June 2009 http://www.gigatonthrowdown.org

Maycock P and Bradford T 2007 PV Technology, Performance, and Cost: 2007 Update Greentech Media, Inc.

Mehta S and Bradford T 2009 PV Technology, Production, and Cost, 2009 Forecast: The Anatomy of a Shakeout Greentech Media, Inc.

Newcomer A, Blumsack S, Apt J, Lave L B and Morgan M G 2008 Electricity load and carbon dioxide emissions: effects of a carbon price in the short term Proc. 41st Hawaii Int. Conf. on System Sciences (2008)

Pacala S and Socolow R 2004 Stabilization wedges: solving the climate problem for the next 50 years with current technologies Science 305 968

REN21 2008 Renewables 2007 Global Status Report (Paris: REN21 Secretariat) (Washington, DC: Worldwatch Institute)

SEIA (Solar Energy Industries Association) 2009 US Solar Industry Year in Review 2008 www.SEIA.org.

Socolow R and Pacala S 2006 A plan to keep carbon in check Sci. Am. 295 50–7

Spath P L and Mann M K 2000 Life cycle assessment of a natural gas combined-cycle power generation system NREL/TP-570-27715 National Renewable Energy Lab

Spath P L, Mann M K and Kerr D R 1999 Life cycle assessment of coal-fired power production NREL/TP-570-25119 National Renewable Energy Lab

Tremeac B and Meunier F 2009 Life cycle analysis of 4.5 MW and 250 W wind turbines Renew. Sustain. Energy Rev. 13 2104–10

US Census 2009 The 2009 Statistical Abstract http://www.census.gov/compendia/statab/

Wiser R, Barbose G and Peterman C 2009 Tracking the Sun: the installed cost of photovoltaics in the US from 1998–2007 LBNL-1516E February 2009

Wiser R and Bolinger M 2008 Annual Report on US Wind Power Installation, Cost, and Performance Trends: 2007 LBNL-154E US Department of Energy and Lawrence Berkeley National Lab