Assessing the cost of carbon abatement strategies

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Introduction

This document describes a method of determining the cost and carbon reduction potential of various strategies to reduce greenhouse gas emissions. As examples, we will illustrate the method with three technologies: installation of solar photovoltaic (PV) power, installation of wind power, and deployment of electric vehicles (EVs).

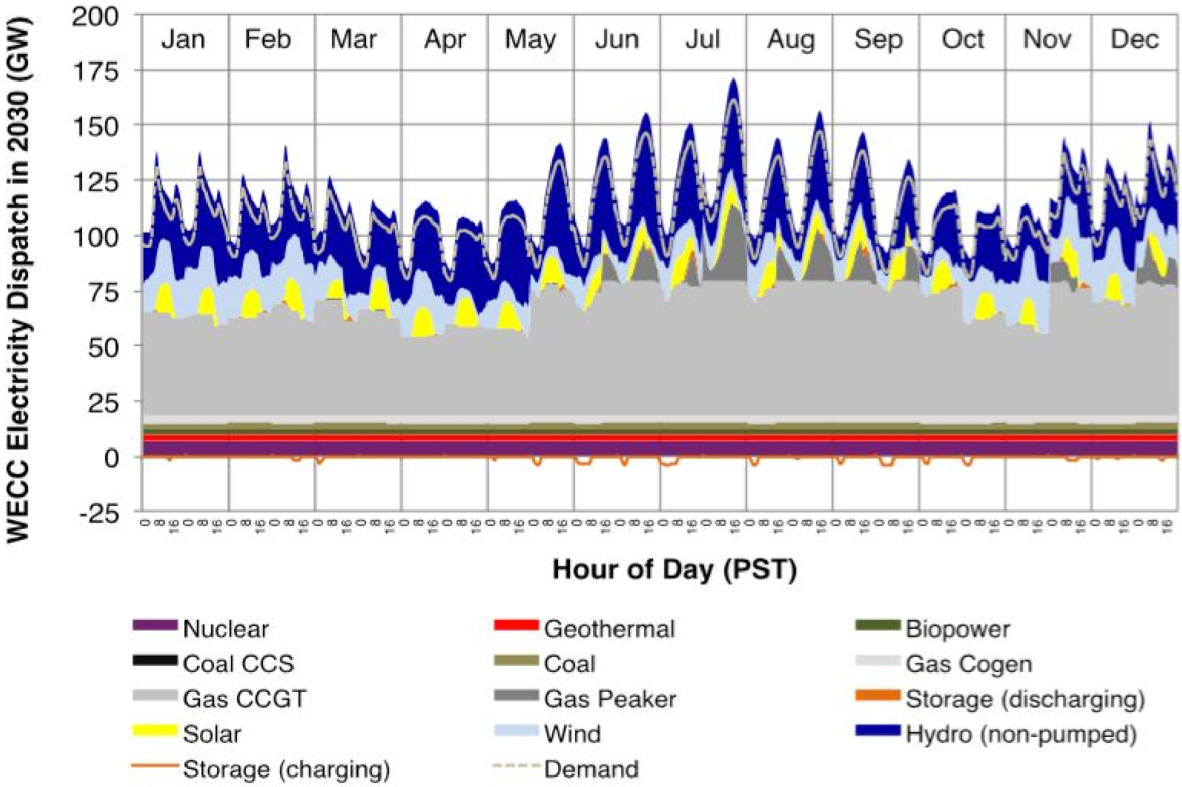
The cost and carbon value of each strategy will vary depending on the world region where it is implemented. We will use as examples the U.S., specifically California where data are readily available in the level of detail required for the calculation. For a fully-developed assessment, a model capable of making these calculations in multiple world regions will be necessary. A potential modeling tool for this purpose could be the Energy Policy Simulator developed by Energy Innovation, LLC.

Baseline

For solar PV and wind power, we must first determine baseline power generation that these technologies would displace. We assume that this displaced power generation technology is already built, and is used less often when the solar or wind power is generating power.

For solar PV that operates during daylight hours, the displaced power generation technology is typically natural gas generation technology in most parts of the U.S. For California, the technology is primarily natural gas combustion turbines during summer months and natural gas combined cycle plants during other periods. See below Figure, which shows generation across the interconnected Western U.S. electricity grid that feeds California.

Figure 3-11: Hourly Dispatch in the Base Scenario across WECC in 2030 for All Months



Source: Nelson et al. (2013). Note that "Gas CCGT" = natural gas combined cycle generation turbine, and "Gas Peaker" = natural gas combustion turbine.

For wind power that operates more sporadically throughout the day and season, an average mix of electric generation technologies could be used, though in California, it is known that wind operates more frequently at night, when the displaced power generation technology is typically combined cycle natural gas. In other regions of the country, wind power may follow different hourly patterns.

(To be more accurate, an electricity system simulation model must be run on an hourly basis over many representative days of the entire year, for cases both with and without the new technology, to determine exactly which power generation technologies are displaced, but we avoid doing this for this set of illustrative examples.)

For EVs, the assumed vehicle that the EV displaces is a gasoline-powered vehicle with the same basic style, interior capacity and performance characteristics. We assume that both vehicles are driven in the same manner, travel the same annual distance, and have the same lifetime. As for wind power, we assume that EV charging in California primarily takes place when combined cycle natural gas turbines are running.

Costs

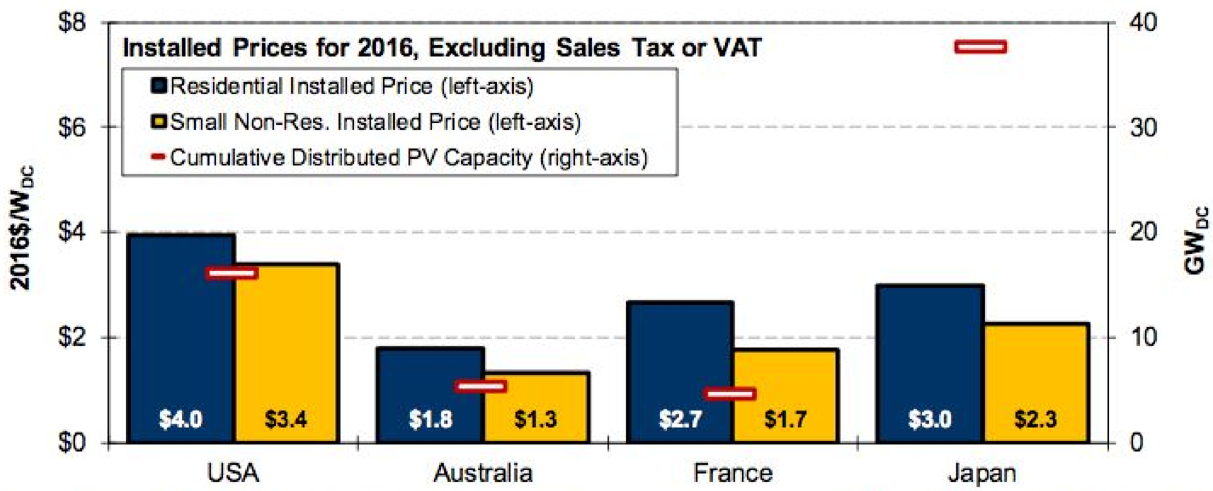
Recent installed costs for solar PV and wind power can be found in Barbose et al. (2017) and American Wind Energy Association (2018), respectively. Results are shown in the Table below for the U.S.

Table 1. Costs of solar PV and wind power

	Installed cost ($/W$_{DC}$)*	Levelized cost ($/MWh)
Residential solar PV	4.0	187 to 319
Non-residential solar PV	3.4	43 to 53
Wind power	1.59	30 to 60

** 2016 installed cost excluding sales tax or VAT. Sources: Barbose et al. (2017), American Wind Energy Association (2018), Lazard (2017)*

Note that recent trends in the cost of installed solar PV continue downward, so future costs may be lower than those presented here. Also, note that costs in different regions can vary considerably, as shown in the below Figure taken from Barbose et al. (2017).

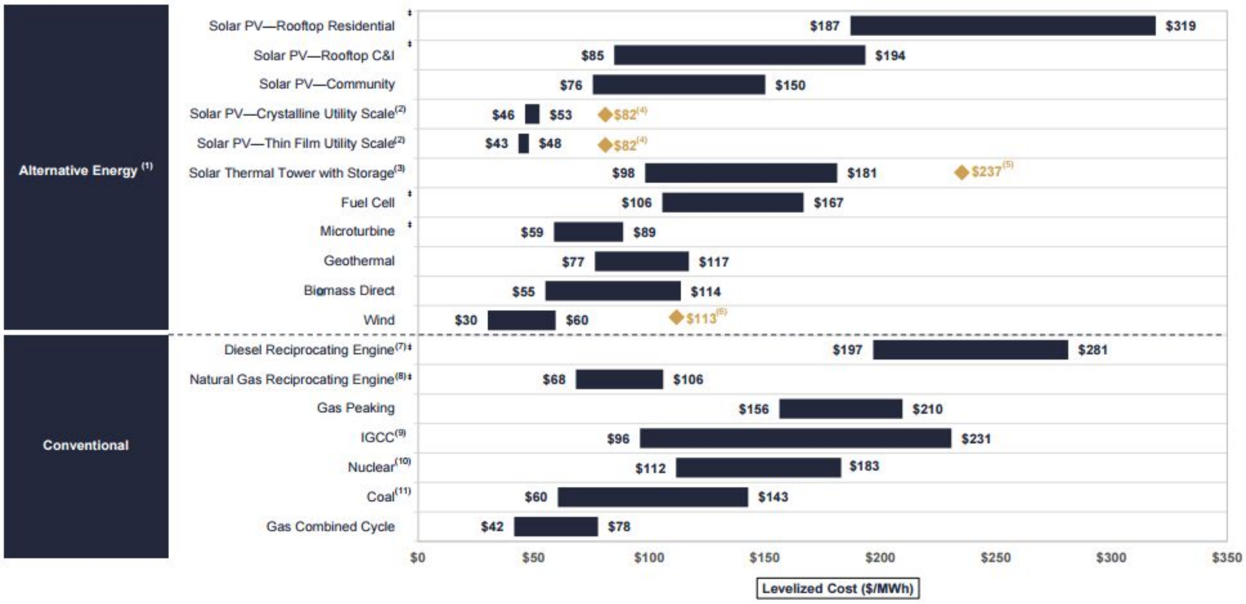


Notes: Data for Australia, France, and Japan are based on each country's respective IEA Photovoltaic Power Systems Programme's (PVPS) 2016 National Survey Report (Johnston and Egan 2017, L'Epine 2017, and Yamada and Ikki 2017).

Figure 12. Comparison of Installed Prices in 2016 across National Markets (Pre-Sales Tax/VAT)

Source: Barbose et al. (2017)

In addition to installed cost, the average capacity factor, or fraction of the year that the wind or solar plant operates at full capacity, as well as the plant lifetime, must be included and be self-consistent. The American Wind Energy Association (2018) document cites a Lazard (2017) analysis comparing the unsubsidized costs of different renewable as well as conventional electricity generation technologies:



Here we see that utility-scale solar PV costs between $43 and $53/MWh, whereas wind power costs between $30 and $60/MWh. By comparison, the avoided fuel cost of natural gas plants, assuming $3.50/MMBtu are $24/MWh for a combined cycle plant (assumed 50% efficiency) and $40/MWh for a combustion turbine (assuming 30% efficiency). According to Lazard, the full cost for natural gas generation plants is even higher: $42 to $78/MWh for combined cycle plants and $156 to $210/MWh for combustion turbine plants ("gas peaking" in above chart). Therefore, the net costs of constructing and operating solar PV or wind may well be negative. To be more conservative, however, we just consider the saved fuel costs of these natural gas plants for our cost estimations.

For EVs, one must calculate the purchase cost difference between an EV and default gasoline-powered vehicle, as well as differences in lifetime operational costs including energy and maintenance (including battery replacement for EVs). This difference is not straightforward to calculate, and will depend on the local cost of electricity or gasoline as well as other factors (annual mileage, driving style, weather, etc.). While recent analysis suggests it may be cheaper to own an EV (Douris, 2017), a conclusion confirmed also in earlier studies (e.g., Kochhan and Hörner, 2014), a more detailed recent study concludes that the cost of an EV will be higher than a gasoline-powered vehicle for many years to come (Harvey, 2018). Here we take the 2030 estimated difference in total cost of owning an EV versus a gasoline vehicle (expressed as net present value, assuming 15,000 km/yr and $3.8/gal. gasoline price) as our basis: ~$1,500 per vehicle. (Note that Kochhan and Hörner estimated that the price premium consumers are willing to pay for an EV may be as much as $4,000, which could be used as an upper limit.)

Emissions

We assume that all greenhouse gas (GHG) emissions, both real and avoided, are overwhelmingly due to CO_2. However, if non-CO_2 GHG emissions are included, they would be converted to CO_2-equivalent emissions using 100-year global warming potentials as provided by the Intergovernmental Panel on Climate Change's Fifth Assessment Report (Myhre et al., 2013).

We only consider emissions due to operation of the technology, because they dominate total life-cycle emissions, though for completeness, manufacturing as well as end-of-life disposal emissions should also be included. There are numerous sources of such emissions estimates if a more complete treatment is desired, such as Argonne National Laboratory's GREET model for vehicles. Numerous studies have tried to assess life-cycle emissions of solar PV and wind technologies.

Operational emissions from solar PV and wind power are zero, whereas emissions from natural gas plants depend on the efficiency (or "heat rate") of the plant. With a CO_2 combustion coefficient of 53.07 kg CO_2/million Btu (Energy Information Administration, 2016) and average efficiencies of 30% for combustion turbines and 50% for combined cycle turbines (based on Energy Information Administration, 2017), the average emission rates are 604 g/kWh for combustion turbines and 362 g/kWh for combined cycle turbines. [For the California electricity sector as a whole, 2016 carbon emissions were 47,008,000 metric tons CO_2 / 196,963,215 MWh = 239 g/kWh (Energy Information Administration, 2018).]

Operational emissions from EVs depend on the electricity system providing the electricity. Assuming overnight charging, we can use the same assumption as we did for wind power above and approximate the emissions as that from a natural gas combined cycle plant. The electric consumption rate of a typical small passenger EV (e.g., 2017 BMW i3 or Nissan LEAF) is ~30 kWh/100 mi., whereas a reference gasoline-powered vehicle (e.g., 2017 Honda Fit or Fiat 500) efficiency is ~2.9 gal/mi. (FuelEconomy.gov). With a gasoline CO_2 emissions content of 8.89 kg CO_2 / gal. (Energy Information Administration, 2016), this means that an EV emits ~40% as much CO_2 per mile as an equivalent gasoline-powered vehicle:

Vehicle type	**Efficiency**	**CO_2 content**	**CO_2 emissions**
Electric vehicle	30 kWh/100 mi.	0.362 kg CO_2/kWh	109 g CO_2/mi.
Gasoline vehicle	2.9 gal./100 mi.	8.89 kg CO_2/gal.	258 g CO_2/mi.
Ratio			42%
CO_2 savings			149 g CO_2/mi.

With an assumed lifetime mileage for passenger cars of 152,100 mi. (Lu, 2006), total lifetime savings per EV is ~22,700 kg CO_2.

Note that a more sophisticated analysis would include all life-cycle CO_2 emissions due to fuel production, vehicle manufacture and end-of-life disposal (e.g., Elgowainy et al., 2016). In this case, total greenhouse gas emissions for both electric and gasoline vehicles are considerably higher (e.g., with current technology, ~300 g CO_2/mi. for a 90-mi. electric vehicle and ~450 g CO_2/mi. for a gasoline vehicle), but the difference is also about ~150 g CO_2/mi.

Carbon value of investments

Here we combine our estimates from above to arrive at the average value of investments made in solar PV, wind power and electric vehicles:

Technology	**Cost difference**	**Carbon savings**	**Abatement cost**
Solar PV	$11 to $21/MWh	483 kg/MWh	$23 to $44/t CO_2
Wind	$6 to $36/MWh	362 kg/MWh	$17 to $100/t CO_2
Electric vehicle	$1,500	22,700 kg/vehicle	$66/t CO_2
Average of above			**$53/t CO_2**

Note: t = metric tons

Using average cost estimates from above, a portfolio consisting of ⅓ solar PV, ⅓ wind and ⅓ electric vehicles would cost $53/t CO_2. Therefore, a $200 billion investment in this portfolio could reduce cumulative emissions by 3.8 billion metric tons CO_2. Note that as carbon reductions accumulate, it will become more expensive to achieve the same incremental reductions, because the energy system becomes cleaner, making the carbon savings of a given investment smaller. However, costs of abatement strategies will also fall. For maximum accuracy, such calculations would need to be repeated on a regular basis (e.g., annually or every few years) as global energy systems evolve, to ensure current abatement costs are used.

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