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Defining a standard metric for electricity savings

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Abstract

The growing investment by governments and electric utilities in energy efficiency programs highlights the need for simple tools to help assess and explain the size of the potential resource. One technique that is commonly used in this effort is to characterize electricity savings in terms of avoided power plants, because it is easier for people to visualize a power plant than it is to understand an abstraction such as billions of kilowatt-hours. Unfortunately, there is no standardization around the characteristics of such power plants.

In this letter we define parameters for a standard avoided power plant that have physical meaning and intuitive plausibility, for use in back-of-the-envelope calculations. For the prototypical plant this article settles on a 500 MW existing coal plant operating at a 70% capacity factor with 7% T&D losses. Displacing such a plant for one year would save 3 billion kWh/year at the meter and reduce emissions by 3 million metric tons of CO_2 per year.

The proposed name for this metric is the *Rosenfeld*, in keeping with the tradition among scientists of naming units in honor of the person most responsible for the discovery and widespread adoption of the underlying scientific principle in question—Dr Arthur H Rosenfeld.

Keywords: electricity savings, energy efficiency, energy policy, climate change solutions, coal-fired power plants, back-of-the-envelope calculations, Arthur H Rosenfeld

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1. Introduction

In the three decades since the energy crises of the 1970s we have learned a great deal about the potential for energy efficiency and the means to deliver it cost effectively and reliably (Rosenfeld 1999). Back then, many analysts still held to the now discredited 'ironclad link' between energy use and economic activity, which implied that any reduction in energy use would make our society less wealthy (Craig *et al* 2002, Koomey 1984, Levine and Craig 1985, Lovins 1979). Now we know (from cross-country comparisons and technical analysis) that there are many ways to produce and consume goods and services, some energy efficient and others not (Carnahan *et al* 1975, Darmstadter *et al* 1977, International Energy Agency (IEA) 1997, Schipper and Lichtenberg 1976, Schipper *et al* 1992). And we know that the available efficiency resources are enormous, inexpensive, and largely untapped (particularly if whole-system clean-slate redesign is employed), making them an important option for reducing climate risks and improving energy security (APS 2008, Brohard *et al* 1998, Brown *et al* 2001, Lovins 2005, Lovins *et al* 2004). Finally, we know that tapping these resources requires more than getting energy prices right—we will also need to further develop and implement cost-benefit-tested non-price policies like minimum efficiency standards, Energy Star labeling programs, utility rebates, 'Golden Carrot' incentives, research and development, tax credits, and other programs whose goal is to align private financial incentives with the economic and environmental interests of society as a whole (APS 2008, Brown *et al* 2001, Koomey 1990, Koomey *et al* 1996, 2001, Krause and Eto 1988, Krause *et al* 1993, Krause *et al* 1995, Lovins 1992, Lovins *et al* 2004).

The increased focus on energy efficiency for shaping our energy future highlights the need for simple tools to help understand and explain the size of the potential resource. One technique that is commonly used in that effort is to characterize electricity savings in terms of avoided power plants, because it is easier for people to visualize a power plant than it is to understand an abstract concept like billions of kilowatt-hours. Unfortunately, there is no standardization around the size and operational characteristics of such plants.

In this letter we propose standard characteristics for an avoided power plant that have physical meaning and intuitive plausibility, for use in back-of-the-envelope calculations and characterizing energy savings results. We also propose naming the annual energy savings of such a plant as a new unit in Art Rosenfeld's honor (the *Rosenfeld*) because Dr Rosenfeld continues to be the most prominent advocate of characterizing efficiency savings in terms of avoided power plants.

2. Arthur H Rosenfeld's contributions

Dr Rosenfeld (figure 1) made a transition from particle physics to studying energy efficiency at the time of the first oil embargo (Rosenfeld 1999). Over the past 35 years he has been at the forefront of efforts to improve the efficiency of energy use around the world and has devoted special care to making the results of complex energy analysis understandable to a lay audience. For years, Dr Rosenfeld has characterized oil savings in terms of 'Arctic Refuges saved' and electricity savings in terms of 'avoided power plants' to emphasize that supply and demand side policy options are fungible and that replacing power plants with more efficient energy technologies would be beneficial for consumers' electricity bills and for the environment.

Figure 1. Arthur H Rosenfeld.

Dr Rosenfeld has in the past most commonly used a 1000 MW power plant operating at a 60 or 65% capacity factor as the standard power plant avoided by energy efficiency. These assumptions mirrored the capacity and operational characteristics of typical US nuclear power plants circa 1990, but since that time the capacity factors of such plants have increased to about 90%. No new nuclear plants have been completed in the US since 1996, so the appropriateness of this choice of assumptions has decreased over time. More recently, Dr Rosenfeld has used a 500 MW plant operating 5000 h per year as his standard avoided plant (Rosenfeld and Kumar 2001).

3. Criteria

Choosing characteristics of a typical avoided power plant is inevitably somewhat arbitrary—there is no single correct answer. In our view, those choices should meet the following criteria.

(1) *Simplicity of presentation and ease of recall*: round numbers of one significant figure should be preferred to more accurate numbers with several decimal places of precision because they are easier to remember and use.

Moreover, 'average' power plant sizes and capacity factors change each year, so a value with several decimal places of precision would have no longevity in any case.

(2) *Intuitive plausibility*: the parameters chosen should reflect people's general understanding of power plants and their operation in the utility system.

(3) *Physical meaning*: the chosen characteristics should reflect real-world attributes of the physical systems in which power plants are embedded and should be expressed as savings *at the meter* (to account for transmission and distribution losses).

(4) *Policy relevance*: the main result for avoided power plants would be electricity savings (which is an important metric for energy policy). Carbon savings associated with those energy savings (reflecting climate change, the most important environmental challenge facing humanity) should also be estimated, but electricity savings are the key focus. Costs and non-CO_2 emissions for avoided power plants vary greatly by technology, by country, and over time, so including them would make this task needlessly complicated.

The next step is to assess the key parameters for characterizing power plants to see which choices might meet those criteria. To make that assessment easier, we add two additional constraints.

(1) *We focus on power plants avoidable in the long run.* Utility emissions savings can be the result of either short run operational changes or long run retirement and construction decisions. Emissions savings from operational changes are much more difficult to characterize in a general way than are long-term changes (analyzing the former is very situation dependent and typically requires complicated production-cost/dispatch simulation modeling).

(2) *We assume that the standard avoided power plant should be coal-fired*. Between 2000 and 2007, 151 new coal-fired power plants were proposed in the United States; 10 have been completed, 25 more are under construction, and 59 have been canceled or indefinitely deferred (Calwell and Moorefield 2008). In 2007, existing coal plants totaled more than 300 GW (out of almost 1000 GW total installed capacity in the US).

Coal plants generate about half of all US electricity and were responsible for about one third of total US carbon emissions in 2007. They are also ubiquitous in other countries responsible for substantial percentages of world carbon emissions (e.g., China and India). Truly facing the climate challenge will require the retirement or displacement of hundreds or thousands of such plants (Black 2009, Caldeira *et al* 2003, Krause *et al* 1992, Meinshausen *et al* 2009). Finally, the capacity factors of coal plants are relatively insensitive to fuel price changes (compared to natural gas plants) so their operational characteristics are more predictable than for some other plants.

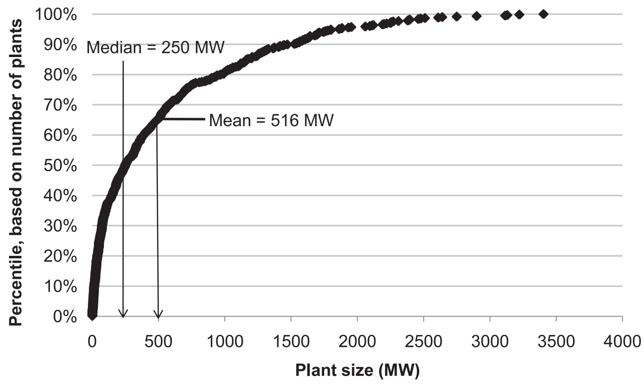

Figure 2. Cumulative distribution of capacity for existing US coal-fired power plants in 2007. Source: US Energy Information Administration, form EIA-860 Annual Generator Report Database (www.eia.doe.gov/cneaf/electricity/page/eia860.html).

4. Characteristics of coal-fired power plants

This section describes our review of the literature for each key characteristic of coal-fired power plants in advance of choosing parameters for a typical plant.

4.1. Capacity

Power plants vary greatly in their capacity (measured in megawatts, MW, or million watts), which can be expressed as a nameplate (nominal) rating or as net capacity after subtracting out power needed to run the plant.

The Energy Information Administration or EIA (US DOE 2009a) gives characteristics of new conventional power plants for the US. Pulverized coal plants with scrubbers fall at 600 MW.

As shown in figure 2[3] the median nameplate capacity for existing non-cogenerating US coal plants in 2007 was 250 MW, with a mean of about 500 MW and a range of less than a megawatt to about 3500 MW (www.eia.doe.gov/cneaf/electricity/page/eia860.html). Most of the smaller plants (less than 200 MW) tend to be older (1960s or earlier), while the larger plants tend to be newer (1970s or later).

EIA's *Electric Power Annual 2007* (US DOE 2009b) shows that total capacity for US coal-fired power generation is remarkably stable over the period 1996–2007, starting and ending at just over 300 GW (table 1). There have been a few retirements and new plants constructed, but the US has seen no significant change in total coal capacity over this period.

4.2. Capacity factors

The capacity factor is defined as

$$\text{Capacity factor} = \frac{\text{Actual generation/year (BkWh)}}{\text{Maximum generation/year (BkWh)}}. \quad (1)$$

[3] See Koomey and Hultman (2007) for similar cumulative distribution graphs describing historical data on nuclear power plants in the US.

Table 1. Characteristics of existing US coal-fired power plants.

	Coal-fired capacity (GW)	Net generation (TWh)	Capacity factor (%)	Coal consumed (million short tons)	Heat content of utility coal (MBtu/short ton)	Average HHV efficiency (%)
1996	313	1795	65.2	907	20.55	32.9
1997	314	1845	67.2	932	20.52	32.9
1998	316	1874	67.7	946	20.52	32.9
1999	315	1881	68.1	950	20.49	33.0
2000	315	1966	71.0	995	20.51	32.9
2001	314	1904	69.2	973	20.34	32.8
2002	315	1933	70.0	988	20.24	33.0
2003	313	1974	72.0	1014	20.08	33.1
2004	313	1978	71.9	1021	19.98	33.1
2005	313	2013	73.3	1041	19.99	33.0
2006	313	1991	72.6	1031	19.93	33.1
2007	313	2016	73.6	1047	19.91	33.0
Average			70.2			33.0

[a] Coal consumed, capacity, and net generation include all coal-fired power plants in the US, including utility and non-utility central station plants as well as industrial cogeneration plants.
[b] Coal-fired capacity, net generation and coal consumed taken from US DOE (2009b). Heat content of coal taken from table A-5 in US DOE (2008). MBtu = million Btus.
[c] Capacity factor calculated from capacity and net generation assuming 8760 h for non-leap years and 8784 h for leap years.
[d] Power plant efficiency (higher heating value) calculated by converting net generation to Btus assuming 3412 Btus kWh^{-1} and then dividing by the product of coal consumed and heat content of utility coal.

Table 2. US average transmission and distribution (T&D losses) over time.

	Total electric industry sales (TWh)	Direct use (TWh)	Total exports (TWh)	Losses and unaccounted for (TWh)	T&D losses (%)
1996	3101	153	3	231	7.1
1997	3146	156	9	224	6.8
1998	3264	161	14	221	6.4
1999	3312	172	14	240	6.9
2000	3421	171	15	244	6.8
2001	3394	163	16	202	5.7
2002	3465	166	16	248	6.8
2003	3494	168	24	228	6.2
2004	3547	168	23	266	7.1
2005	3661	150	20	269	7.0
2006	3670	147	24	266	6.9
2007	3765	159	20	264	6.7
Average					6.7

[a] Data on electric industry sales, direct use, exports, and losses are taken from US DOE (2009b).
[b] T&D losses calculated as a percentage of sales plus direct use plus exports.

Dividing numerator and denominator by the number of hours per year (8766 h when averaged across leap and non-leap years) we get

$$\text{Capacity factor} = \frac{\text{Average output capacity (MW)}}{\text{Rated (maximum) capacity (MW)}}. \quad (2)$$

Coal plants can have a wide range of capacity factors: they are usually operated for baseload electricity but are flexible enough to serve all but the lowest of intermediate loads as well. Their capacity factors are relatively insensitive to coal prices though they can be influenced when the price for the main competing fuel in the power sector (natural gas) fluctuates greatly.

New coal plants typically have high capacity factors (up to 90%). Capacity factors for existing plants in the US increased significantly over the 1996–2007 period, averaging about 70% (as shown in table 1). The stock of existing plants includes many older plants that are smaller, less efficient, and more polluting than new plants. They have long since been depreciated, so utilities have an incentive to keep them running as long as the marginal costs are not too high (and as long as environmental regulations do not impose additional costs or constraints that make them uneconomic).

4.3. Transmission and distribution losses

Table 2 shows data from EIA's *Electric Power Annual 2007* (US DOE 2009b) on the supply and disposition of electricity in the US from 1995 to 2007. Losses are expressed as a percentage of the sum of electricity sales, direct use by power plants, and exports. These losses range from 5.7% to 7.1% with a simple average of 6.7% over that period.

Table 3. Direct carbon emissions factors for fuels used by utilities to generate electricity.

	M tons C/quad	kg C/GJ	gC/kWh.f	Index NG = 1.0
Natural gas	14.47	13.7	49.4	1.00
Distillate oil	19.95	18.9	68.1	1.38
Residual oil	21.29	20.2	72.6	1.47
Coal	25.83	24.5	88.1	1.78

[a] Carbon emissions factors (Mt-C/quadrillion Btus) taken from EIA data for 2006 (downloaded from www.eia.doe.gov/environment.html). It is unclear if these data have already built in a combustion fraction but we assume so. Combustion fractions are typically very close to 1.0 for fossil fuels in utility plants in any case.
[b] All energy values based on higher heating value (HHV) of the fuels.
[c] kWh.f = energy content of fuel converted to kWh using 3412 Btu kWh^{-1}.

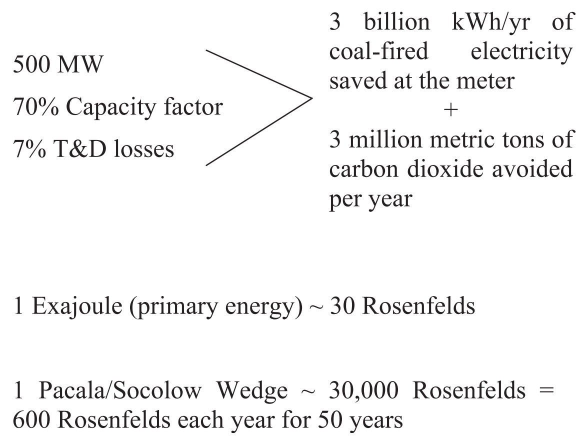

Figure 3. Summary of the Rosenfeld unit.

4.4. Carbon emissions factors for fossil fuels

The EIA (www.eia.doe.gov/environment.html) gives historical data on the carbon content of fuels for US electric utilities. The data for the latest year available (2006), expressed in higher heating value (HHV) terms, are shown in table 3. Coal emits almost 80% more carbon than natural gas per unit of heat released.

4.5. Power plant efficiencies

Large coal steam plants have HHV efficiencies of 30–40%, depending on their age, level of pollution control, and technology type. For typical new 600 MW coal plants in 2008, EIA gives an estimate of 37% HHV efficiency (US DOE 2009a). The average efficiency of existing coal steam plants in the US for the period 1996–2007, derived using the heat content of utility coal from US DOE (2008) and the other parameters in table 1, is 33%, which does not vary much over this period.

5. Defining the Rosenfeld

We experimented with different combinations of plant capacities and capacity factors to meet the criteria listed above, focusing mainly on the characteristics of existing US coal plants. We choose this approach because of the rich data characterizing these plants and because most existing coal plants will need to be retired if we're to substantially reduce carbon emissions by the middle of this century, as climate stabilization requires.

As summarized in table 4 and figure 3, we've defined the Rosenfeld unit assuming the average coal plant capacity of 500 MW, a capacity factor of 70% (the average capacity factor of existing US coal plants from 1996 to 2007), and system-wide T&D losses of 7% (rounded up from 6.7% for ease of recall). This combination of parameters would yield annual electricity delivered at the meter of about 3 BkWh/year. Using the carbon burden for US utility coal and the efficiency of average existing coal steam plants, the emissions saved are almost exactly 3 million metric tons of CO_2 (Mt CO_2) per year.

If measured in terms of site energy, there are 100 Rosenfelds per exajoule, and in primary energy terms there are about 30 Rosenfelds per exajoule. Another nice equivalence factor that emerges from these numbers is that each kilowatt-hour of coal-fired electricity delivered to the meter emits about 1 kg of CO_2.

6. Using the Rosenfeld

This simplification aids in the creation of quick calculations and cogent interpretation of analysis results from studies of energy efficiency. To use the Rosenfeld, analysts have to remember the numbers associated with the power plant characteristics (500 MW, 70% capacity factor, 7% T&D losses, 33% HHV efficiency), and the number 3 (which evokes 3 billion kWh saved at the meter, 3 million metric tons of carbon dioxide avoided per year, and 30 Rosenfelds per exajoule of primary energy).

Consider the recent authoritative study on energy efficiency by the American Physical Society (APS 2008). Figure 25 in that study shows potential US residential sector efficiency savings of almost 600 billion kWh/year in 2030. What does that number mean in terms of power plants avoided?

Six hundred billion kWh/year is the equivalent of about 200 Rosenfelds (600/3), or 200 typical coal-fired power plants, which together emit 600 million metric tons of CO_2 per year. This simple calculation adds real physical meaning to the electricity savings (but it is no substitute for more sophisticated approaches). Other important studies that would have benefitted from using this approximation include Brown *et al* (2008), EPRI (2009), Koomey *et al* (1991), Meier *et al* (1983), Rosenfeld and Hafemeister (1988), Rosenfeld *et al* (1993), and any other efficiency potentials studies that do not include a full integrated analysis of supply and demand side options.

Another widely used approximation for understanding carbon reductions is that of the 'stabilization wedge', popularized by Pacala and Socolow (2004). Each wedge represents cumulative carbon reductions over a 50-year period of 25 billion metric tons of carbon, or 91.7 billion metric tons of CO_2. Each Rosenfeld saves 3 million tons of CO_2

Table 4. Estimating electricity delivered and carbon emitted from a typical coal plant in the US.

	Units	Value	Notes
Electricity generated			
Capacity	MW	500	a
Capacity factor	%	70%	b
Hours per year	Hours	8766	c
Assumed T&D losses	%	7%	d
Total electricity generated at the busbar	Billion kWh/year	3.07	e
Total electricity delivered to the meter	Billion kWh/year	2.87	f
Site energy (HHV)	Quadrillion Btus/year	0.010	g
	Exajoules/year	0.010	h
Primary energy (HHV)	Quadrillion Btus/year	0.032	i
	Exajoules/year	0.034	h
Carbon emitted			
Coal carbon burden (based on HHV)	gC/kWh.fuel	88.1	j
Efficiency (based on HHV)	%	33%	k
Carbon burden at the busbar	gC/kWh.elect generated	267	l
Carbon burden at the meter	gC/kWh.elect delivered	286	m
Carbon emissions	Million metric tons C/yr	0.82	n
	Million metric tons CO_2/yr	3.01	o

[a] Capacity is based on average existing US coal plants from EIA-860 survey results (www.eia.doe.gov/cneaf/electricity/page/eia860.html).

[b] Capacity factor is the average for existing US coal plants from 1996 to 2007 from table 1.

[c] Hours per year is an average over leap years and non-leap years.

[d] T&D (transmission and distribution) losses are typical for the US utility system (from table 2), rounded up to 7% for ease of recall.

[e] Total electricity generated at the busbar is the product of capacity, capacity factor, and hours per year, expressed using the American notation of billion equaling 10^9.

[f] Total electricity delivered to the meter is total electricity generated divided by (1 + percentage T&D losses).

[g] Site energy in quadrillion Btu/year calculated by multiplying kWh per Rosenfeld at the meter by 3412 Btus kWh^{-1}.

[h] Quadrillion btus converted to exajoules using the factor 1055.1 joules/Btu.

[i] Primary energy in quadrillion Btu/year calculated by converting the efficiency described in footnote k to a heat rate (primary energy per kWh), then multiplying that heat rate times (1 + percentage T&D losses) and multiplying again by the number of kWh per Rosenfeld.

[j] The carbon burden of coal is expressed in grams of carbon (C) per kWh of fuel (fuel converted to kWh assuming 3412 Btus kWh^{-1}). This carbon burden is taken from EIA for 2006, as described in table 3.

[k] Power plant efficiency, in higher heating value (HHV) terms, is the average for existing US coal plants from 1996 to 2007 from table 1.

[l] Carbon (C) burden at the busbar (calculated in grams of carbon per kWh generated) is calculated as the ratio of the coal C burden from table 3 and the power plant efficiency (both in HHV terms).

[m] C burden at the meter is the carbon burden at the busbar times (1 + percentage T&D losses).

[n] C emissions in million metric tons are the product of electricity consumed at the meter and the C burden at the meter.

[o] Carbon dioxide emissions in million metric tonnes are equal to C emissions times the ratio of molecular weights of carbon dioxide (44) and carbon (12).

per year, so a full wedge is equivalent to 91 700/3 or about 30 000 Rosenfelds (equivalent to fully eliminating 600 coal-fired power plants (or 300 GW) for their entire 50-year lifetimes).

For those situations where the avoided carbon emissions would be quite different from those of a coal plant, we show table 5, which gives the relationship between the carbon emissions factors for a coal plant and average emissions factors for different power plant technologies (from US DOE (2009a)), for the power sectors of different countries (from US DOE (2009b) for the US and Wheeler and Ummel (2008) for other countries), and for California (from Mahone *et al* (2009)). Natural gas plants are significantly less carbon intensive than coal. In places where the avoided power plant is an advanced natural gas combined cycle (typical for recently constructed gas plants) the emissions per kWh are 63% lower than that of an existing coal plant, resulting in annual emissions displaced of about 1 million metric tons of CO_2 per year for one Rosenfeld of electricity savings. In addition, table 5 shows that China and India, two of the largest and most

Table 5. Carbon emissions factors for electricity delivered to the meter.

	Fuel	Efficiency HHV (%)	Emissions factor gC/kWh fuel	Emissions factor gC/kWh.elect.delivered	Index Existing coal = 1.0	Notes
Existing plants						
Steam turbine	Coal	33.0	88.1	286	1.00	a,b
Steam turbine	Residual oil	32.8	72.6	237	0.83	a,c
Steam turbine	Distillate oil	32.8	68.1	222	0.78	a,c
Steam turbine	Natural gas	32.6	49.4	162	0.57	a,c
Gas turbine	Distillate oil	25.8	68.1	282	0.99	a,c
Gas turbine	Natural gas	29.8	49.4	177	0.62	a,c
Combined cycle	Distillate oil	31.0	68.1	235	0.82	a,c
Combined cycle	Natural gas	45.8	49.4	115	0.40	a,c
New plants						
Steam turbine, scrubbed	Coal	37.1	88.1	254	0.89	a,d
Advanced combined cycle	Natural gas	50.5	49.4	105	0.37	a,d
Average power sector carbon emissions factor by country 2007 (rank in 2007 power sector emissions in square brackets)						
China [1]				279	0.98	e
United States [2]				174	0.61	f
India [3]				259	0.91	e
Russia [4]				156	0.54	e
Germany [5]				197	0.69	e
Japan [6]				117	0.41	e
United Kingdom [7]				179	0.63	e
Australia [8]				287	1.00	e
South Africa [9]				296	1.03	e
South Korea [10]				143	0.50	e
Indonesia [18]				213	0.74	e
France [27]				28	0.10	e
Brazil [44]				16	0.06	e
World average 2007				175	0.61	e
California 2008						
Average				119	0.42	g
Marginal				156	0.55	g

[a] Emissions factors for fossil fuels taken from table 3.

[b] Steam turbine efficiency for average existing US coal plants from 1996 to 2007 taken from table 1.

[c] Steam turbine, gas turbine, and combined cycle efficiencies for existing oil and gas plants calculated from higher heating value (HHV) heat rates in the Electric Power Annual 2007 (US DOE 2009b), table A7, which represent an average for existing plants in 2007. The Electric Power Annual table does not differentiate between residual oil and distillate oil steam turbine efficiencies so we assume these are the same.

[d] Efficiencies for 2008 new plants derived from heat rates in Assumptions to the AEO 2009 (US DOE 2009a), table 8.2.

[e] Carbon emissions factors for the power sectors in different countries and the world in 2007 taken from the CARMA database (www.carma.org), documented in Wheeler and Ummel (2008). We apply 7% T&D losses to the CARMA emissions factors to bring them back to the meter, fully cognizant of the substantial differences in line losses between these countries but lacking any consistent data source. The total power sector emissions for the top 10 countries in 2007 represents about 77% of the world power sector total.

[f] Average carbon emissions factors for the US in 2007 derived from CO_2 emissions for central station and combined heat and power plants reported by the Electric Power Annual 2007 (US DOE 2009b) and the sum of utility sales, electricity exports, and internal electricity use for industrial customers from table 2 (also taken from Electric Power Annual 2007).

[g] California average and marginal power sector emissions for 2008 derived as a simple average from the typical hourly average and marginal emissions factors in the model documented in Mahone *et al* (2009) and corrected for 7% transmission and distribution losses to estimate the emissions factor at the meter.

rapidly growing economies, have average power sector carbon emissions factors that are close to that of the existing coal plant used in this study, indicating that most of their electricity generation comes from coal.

7. Limitations

All simplifications are imperfect, and this one is no exception. The specific characteristics of electricity systems (like power plant capacity factors, efficiencies, coal carbon content, and line losses) all vary greatly around the world. Thus, no single number will apply everywhere, and trying to create an approximation that perfectly characterizes all situations is futile and antithetical to the spirit of this entire exercise. So we accept that this simplification is useful, but limited.

The Rosenfeld is most useful when applied to studies of energy efficiency in isolation from the electricity supply side, because it lends context to such studies that otherwise would require a detailed analysis of avoided power plants. Even given the limitations of an approximation like this, the contextual depth and conceptual understanding that it can bring to energy efficiency studies make it well worth applying.

One of the most important caveats to the use of this simplification relates to the load shape impacts of efficiency options, which are typically summarized in terms of conservation load factor or CLF (Koomey *et al* 1990a, 1990b). The Rosenfeld approximation is most accurately applied to electricity savings from a broad efficiency portfolio with CLFs between 50% and 100%.[4] It should not be used for efficiency options with low CLFs that save electricity mostly at times of peak load (like those for air conditioners), because the avoided power plants are more likely to be gas-fired peaking plants with characteristics quite different from those of coal plants.

It is most appropriate to apply the Rosenfeld to annual electricity savings. To fully displace a power plant, which typically lasts for fifty years, efficiency savings will need to continue for the life of that plant. Analysts should use caution when treating cumulative electricity savings over time with this approximation.

Policy studies assessing the emissions reductions from efficiency and supply side options will generally distinguish between the average and marginal emissions factors for the power system. The marginal emissions factor is the reduction in emissions from decreased power generation divided by the amount of electricity savings driving those reductions (it can be calculated for either the short or long run). The estimated long run marginal emissions savings may or may not equal the emissions savings for coal plants calculated above (and they vary greatly by utility, state, or country, as shown in table 5). Care must therefore be used when applying the Rosenfeld to the results from emissions reduction studies.

To retire a power plant, the most important condition is that there be a resource to displace the generation of that plant, be it energy efficiency or another power plant. Of course, the choice of *which* power plant to retire is a function of economics—more specifically, it is a function of the economic incentives facing the electric utility, and the utility's incentives may or may not be aligned with the optimal outcome for society. Many existing coal plants are fully depreciated and their marginal costs are low. In the absence of a change in policy, the utility won't retire these plants—instead, new resources will be deferred or other, higher marginal cost resources will be displaced.

The amount of carbon savings calculated in this letter for one Rosenfeld (based on an avoided existing coal plant) assumes that one or more additional things happen to affect this economic calculus.

(1) A price on carbon emissions will be put in place that significantly raises the marginal cost of coal plants;
(2) increased regulation of criteria pollutant emissions will create large retrofit costs or increased marginal costs (many existing coal plants have up until now been 'grandfathered' so that they are allowed to emit many more criteria pollutants than new coal plants); and/or;
(3) retiring coal plants will become an explicit policy goal and incentives or standards will be put in place to encourage this outcome.

Because of the urgency of the climate problem and because of coal's significant contribution to it, we believe these changes are likely for many countries in the coming decade. Each of these actions represents a significant shift from the status quo, but more importantly, they represent an internalization of societal costs that heretofore have not been included in the operational and investment decisions of electric utilities. They are not by themselves sufficient to guarantee significant coal plant retirements, but in combination with investments in energy efficiency or new low carbon power generation resources (which would be the driving force for such retirements) they would allow that outcome.

8. Conclusions

The Rosenfeld can best be used in rough back-of-the-envelope calculations and high-level summaries of analysis results for less technical audiences. If an efficiency technology or policy would save 3 BkWh/year at the meter, it saves one Rosenfeld, or one 500 MW coal plant operating at 70% capacity factor in that year (assuming 7% T&D losses). It also saves 3 million metric tons of CO_2/year (assuming all the savings come from conventional coal plants). In addition, avoiding 600 coal-fired power plants of this size over their 50-year lifetimes (i.e. 50×600 or 30 000 Rosenfelds) saves the same amount of carbon dioxide (about 90 000 $MtCO_2$) as one Pacala/Socolow wedge, which is a nice link to another widely used analytical simplification of this type.

These parameters satisfy the initial criteria of simplicity of presentation, ease of recall, intuitive plausibility, physical meaning, and policy relevance. We encourage other analysts to use this new unit as a way to increase conceptual understanding of the scope of the climate challenge and to honor Art Rosenfeld, whose efforts to create a more hopeful and sustainable future continue to inspire us all.

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