Micropower Database: How Distributed Renewables and Cogeneration are Beating Nuclear Power Stations

Technical Annex	2
Title	Methodology
Date Modified	May 3, 2008
Contact Person	Bennett Cohen bcohen@rmi.org (970) 927-7312

Rocky Mountain Institute
2317 Snowmass Creek Road
Snowmass, CO 81654
(970) 927-3851

METHODOLOGY

COST AND CLIMATE DATA (refers to spreadsheet tab "Climate_Data" and graphs to left)

1. Assumptions: Natural gas carbon intensity 0.19 kg CO_2/kWh from Oak Ridge National Labs "Bioenergy Conversion Factors" (available at http://bioenergy.ornl.gov/papers/misc/energy_conv.html). Cogeneration efficiencies from World Alliance on Decentralized Energy (WADE) (available at http://www.localpower.org/deb_tech_gt.html). Combined Cycle Gas Turbine efficiency is assumed to be 50%. Levelized Gas price is assumed to be $7.72/MMBtu for centralized generation, which comes from the high fuel price scenario in the MIT *Future of Coal* study (available at: http://web.mit.edu/coal/) adjusted to 2007 dollars. A one-dollar premium per MMBtu is included for remote sources.

2. Adjustment to 2007 Dollars: Implicit price deflators come from the Bureau of Economic Analysis *National Income and Products Accounts*, Table 1.1.9 "Implicit Price Deflators for Gross Domestic Product" (available at: http://www.bea.gov/bea/dn/nipaweb/TableView.asp?SelectedTable=13&FirstYear=2002&LastYear=2007&Freq=Qtr).

3. Transmission and Distribution costs: Three cents used for all centralized sources, from *Nuclear power: economics and climate-protection potential* (available at: http://www.rmi.org/sitepages/pid257.php#E05-14), adjusted to 2007 dollars. We include a distribution cost of 0.1 cent/kWh for onsite generation.

4. Firming and Integration cost: All generation sources except for wind include a 0.1 ¢/kWh cost for firming and integration. Nuclear data comes from the reserve margin costs found in the backup spreadsheets of Koomey and Hultman's *A reactor-level analysis of busbar costs for US nuclear plants*. Other sources were assumed to have similar costs.

5. Nuclear cost breakdown and carbon intensity: Cost breakdown comes from the MIT *Future of Nuclear* study (available at: http://web.mit.edu/nuclearpower/). This study combines the Operation and Maintenance (O&M) cost with the fuel cost. These costs were split using the ratio available at http://www.iea.org/Textbase/nptable/2007/tackling_t2_1.pdf. The higher cost numbers come from a study done by Keystone and can be found at http://www.keystone.org/spp/documents/FinalReport_NJFF6_12_2007(1).pdf. Transmission and Distribution costs were not included in the total cost. Nuclear power is essentially carbon neutral, except for electricity used during enrichment. Depending on what the source of the electricity is, there may be carbon associated with nuclear generation. The negligible carbon emission included in this analysis comes from a Vattenfall study (available at http://www.world-nuclear.org/info/inf11.html).

6. Coal cost breakdown and carbon intensity: All data comes from MIT *Future of Coal* study, for a supercritical pulverized coal plant, without sequestration. Capital cost for this study was increased 30% per the footnote in Table 3.1 of the *Future of Coal*, which suggests a real cost escalation of 25-30% from 2004 to 2007. Carbon intensity also comes from the *Future of Coal* study.

7. Combined-Cycle Gas Turbine cost breakdown and carbon intensity: O&M cost and Capital cost come from *Cost and Performance Baseline for Fossil Energy Plants* (available at: http://204.154.137.14/energy-analyses/pubs/deskreference/B_NGCC_FClass_051607.pdf). Fuel costs and carbon intensity calculated from assumptions on plant efficiency, fuel cost, and fuel carbon content.

8. Large wind farm cost breakdown and carbon intensity: capital cost calculated after subtracting an empirical O&M cost of 0.5¢/kWh from median price (net of PTC) for 2004-05 installations, whose range was 2.4–6.5¢/kWh and median was ~3.5¢. Data taken from *Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2006* (LBL-41435 available at: http://www1.eere.energy.gov/windandhydro/pdfs/41435.pdf). The 2006-installations mean, 4.9¢ with a range of 3.0–6.4¢, escalated far more from 2005 than can be accounted for by steel and other commodity factor costs, and undoubtedly reflects temporary turbine-making capacity shortage due to late PTC renewal by Congress. However, somewhat higher 2007 capex is possible as both commodity and shortage effects work through the contract stream. Based on historic capex experience shown in the report, a post-scarcity price ~3.5¢ even counting higher commodity prices is reasonable. LBL-41435 shows a mean of 0.327¢/kWh in mixed dollars for nine major US wind-integration studies completed 2003–06. We conservatively round up to 0.4¢ to get 2007 $. BPA's 0.3¢ wind-firming tariff is often undercut by "virtual peakers" who aggregate and dispatch demand response. Wind resources have zero carbon emissions during operation.

9. Combined-Cycle Industrial Cogen cost breakdown and carbon intensity: O&M cost assumed to be 0.5 cents/kWh, which is at the low end of the 0.3-1.0 ¢/kWh O&M cost given by WADE at http://www.localpower.org/deb_tech_gt.html. We assume that capital cost is the same as for non-cogenerating combined cycle gas turbines. Though there may be slightly higher cost on a per kWh basis for these smaller units, there may be cost savings since they displace separate boilers. The cost takes into account a credit for the value of recovered heat. The heat credit is calculated by determining the amount of fuel required to deliver a kWh of electricity, then calculating the amount of heat captured while burning that much fuel, and finally calculating the value of fuel that would have been needed to run a separate boiler to provide that heat. From a carbon emission standpoint, cogen gets a carbon credit because it displaces carbon emissions that would have come from a separately fueled boiler.

10. Building-scale cogen cost breakdown and carbon intensity: O&M cost assumed to be 1.0 ¢/kWh, which is at the high end of the 0.3-1.0 ¢/kWh O&M cost given by WADE at http://www.localpower.org/deb_tech_gt.html. We assume that capital cost is the same as for non-cogenerating combined cycle gas turbines. Though there may be slightly higher cost on a per kWh basis for these smaller units, there may be cost savings since they displace boilers. The cost takes into account a credit for the value of recovered heat, which is calculated in the same way as above, as is the carbon credit from recovered heat.

11. Recovered heat industrial cogen cost breakdown and carbon intensity: This process captures waste heat and waste fuel streams from industrial processes to produce electricity or useful heat. See *Nuclear power: economics and climate-protection potential* (available at: http://www.rmi.org/sitepages/pid257.php#E05-14) for the methodology. Since this process relies on waste streams, there are no carbon emissions associated with this.

12. Energy efficiency cost breakdown and carbon intensity: Efficiency is represented as a capital

cost with no carbon emissions. Many utility efficiency programs have a cost of saved energy of 1 ¢/kWh. Many more efficiency opportunities are available at 4 ¢/kWh.

NUCLEAR

1. Annual Installations 1990–2006: The bulk of nuclear historical data on which we relied came directly from the International Atomic Energy Agency's *Nuclear Power Reactors in the World (2006)* (available at http://www-pub.iaea.org/MTCD/publications/PDF/RDS2-26_web.pdf). This directly lists, by year, annual connections to the grid in MWe (net). It also details all the nuclear power reactors shut down by country; with a little work one can sort these out by date. The 2006 *Nuclear Power Reactors in the World* only includes data through the end of 2005. We used numbers for 2006 from the 2007 edition of *Nuclear Power Reactors in the World*.

2. Upratings 1990–2006: The number of net additions calculated above, however, does not include uprating in capacity of existing plants. Surprisingly the IAEA's *Nuclear Power Reactors in the World* does not keep track of upratings (which are becoming increasingly common due to regulatory restriction on new constructions). Instead when a plant's capacity is changed, the Agency merely erases the old and inserts the new number. This means that when using IAEA's numbers, if one was to calculate 1990's capacity today, it would be different to the total computed in 1990. In phone interviews, both Warrick Pipe of the World Nuclear Association (www.wna.org) and Ron Hagen of the DOE confirmed that this is standard industry practice.

This does not invalidate the IAEA data; rather, it merely means that one must take extra steps to properly represent upratings in capacity. With lack of further documentation, we used the 1991 IAEA capacity numbers (as quoted by *The World Nuclear Industry Status Report*, Greenpeace, WISE-Paris, and Worldwatch (May 1992) as a reference (http://www.energyprobe.org/energyprobe/reports/ep303-28p_final.pdf). The difference between the IAEA's 2006-computed 1991 capacity and the historical number is 3,587 MWe (net). We made the assumption that the upratings, which are the cause of this discrepancy, have been changed at a constant rate over the years. Not having 1990 data, we extended the uprating trend backward one year. This methodology yields the "upgrade factor" seen in the Nuclear Source Data spreadsheet. Since we have 2006 and 2007 editions of *Nuclear Power Reactors in the World*, the capacity on a reactor-by-reactor basis can be compared, which let us calculate the uprating for 2006.

3. Electrical Output and Capacity Factor 1990–2006: While IAEA's *Nuclear Power Reactors in the World* contains good historical information on capacity net of upgrades, it is missing data on worldwide electrical output. The most complete data on nuclear electrical output we could find were those collected by the Energy Information Administration, *International Energy Annual 2005* (Table 2.7). While the data extend all the way back to 1990, the most recent year is 2005. We then were able to adjust IAEA capacity numbers (as explained above) and EIA output numbers to compute a capacity factor for 1990–2005. Output for 2006 was given by Jiri Mandula at IAEA.

4. Annual Installations 2007–2010: In similar fashion to the historical data calculations, we tallied expected connections and shutdowns to find an estimated value for new MWe (net) for each year. Connections and shutdowns in 2005 to date were taken from the IAEA PRIS homepage and crosschecked with IAEA's *Nuclear Power Reactors in the World* and the World Nuclear Association's Reactors Database (http://www.world-nuclear.org/reference/reactorsdb_index.php).

IAEA's *Nuclear Power Reactors in the World* lists reactors under construction and expected connection to the grid. A number of reactors under construction (most of which are in Eastern Europe and Russia) did not have a scheduled completion date. We investigated each of these reactors separately to find the most recent updates on their progress.

To determine expected shutdowns we relied on the World Nuclear Association's Reactors Database. They list scheduled shutdowns of reactors. While it is possible that some of these reactors may have their operating life extended, and others may be shut down prematurely, we accepted the data as given. We tallied the new connections and shutdowns to find the expected net new MWe (net) for each year for the period 2007– 2010. Our estimated total worldwide capacity for 2010, without upratings, is 381,275 MWe (net).

5. Upratings 2007–2010: To account for future upratings we extended the trend calculated for historical upratings. This yielded approximately 197 MWe (net) of uprated capacity in 2007, increasing to 234 MWe (net) of uprated capacity in 2010. While this is clearly not a perfect representation, we checked the methodology with Ron Hagen of the DOE and Nick Lenssen of Primen Energy and Worldwatch – both of whom thought it a reasonable estimate.

6. Electrical Output 2007–2010: Unlike the historical data from which we calculated implicit capacity factors from capacity and output, for our projections we used assumed capacity factors in order to determine outputs. The 2004 IEA *World Energy Outlook* (http://www.worldenergyoutlook.org/) makes the assumption that worldwide capacity factors will be 88.51% by 2010. This is an implicit capacity factor in the Agency's data, which we calculated from the estimated capacity and output for the year. To find capacity factors in intermediate years, we assumed a linear increase from our last historical point, 82.1% in 2006, to IEA's estimate of 88.51% in 2010.

NON-BIOMASS DECENTRALIZED COGENERATION

1. Global Capacity 2004: The World Alliance of Decentralized Energy (WADE) produces the *World Survey of Decentralized Energy* annually (www.localpower.org). According to the 2005 survey, world decentralized energy totaled 282.3 GWe at the end of 2004. As not to double-count, we must subtract out PV (all of which is assumed by WADE to be decentralized), decentralized wind, and decentralized biomass cogeneration.

WADE's 2005 survey cites PV production in 2003 and 2004 as 744 MWe and 967 MWe respectively. These numbers are higher than the ones we used from Worldwatch's 2005 *Vital Signs*, but are the numbers they added so these are the numbers to subtract. Looking back at the 2004 *World Survey of Decentralized Energy*, WADE cites PV production in 2001 and 2002 as 390 MWe and 561 MWe, respectively, which are almost the exact values we found. To account for production prior to 2001, we subtract cumulative PV production through 2000, which is 1451 MWe. Doing all this successfully backs PV out from the total estimate of decentralized energy and leaves us with approximately 278.2 GWe of capacity.

Backing out historical additions of wind is considerably easier. WADE notes that the 2005 survey was first time the Alliance included decentralized wind. Subtracting these decentralized wind additions (785 MWe in 2003/2004) leaves us with approximately 277.4 GWe of decentralized cogeneration at the end of 2004. We will subtract biomass once we have found decentralized cogeneration totals for all years.

2. Annual Installations 2000–2006: WADE's 2007 survey cites total, standby and peaking capacity for all years. Standby and peaking were subtracted from the total. 2005 and 2006 data include units under 1 MW. These units were subtracted for consistency with other years.

3. Global Capacity 2010: In similar fashion to the 2004 global capacity, we will begin with total decentralized energy and then subtract PV and wind. The 2005 WADE survey cites, as a target for decentralized energy, 14% of total world capacity by 2012. In personal communications with WADE director Michael Brown, he conceded that realistic projections would be closer to 12%. WADE used IEA's projection of 4783 GWe of global capacity in 2012, which therefore translates to approximately 574 GWe of decentralized energy by 2012, using the more realistic 12%.

Starting at 927 MW in 2004 and growing at the higher estimate of 30%, PV will have a cumulative capacity of 32.8 by 2010. Subtracting this from our running total leaves us with 541.2 GWe.

Between 2002, when WADE started including wind in its capacity additions, and 2012, wind will have added approximately 271 GWe of capacity, according to IEA. Since During 2003 and 2004, new global wind capacity totaled 16,142 MWe, of which only 784 was decentralized according to WADE—this equates to 4.9% of new added capacity. If this trend were to continue, approximately 13.2 GWe of decentralized wind will be added between 2002 and 2012. Subtracting this from the 2012 total we are left with 528 GWe of decentralized cogeneration.

4. Annual Installations 2005–2012: Using the global capacities for decentralized cogeneration in 2004 and 2012 we can interpolate a smooth curve for the intermediate years. Using a general equation of a+bx+x^c, we manipulated the coefficients to match our data. The three constraints we used to find the three coefficients were the net additions of 12,900 MWe in 2003 and 16,900 MWe in 2004, and the total capacity of 528 GWe in 2012.

5. Biomass adjustments 2000-2012: Realizing that a small percentage of decentralized cogeneration runs on biomass, we had to subtract this out to avoid double-counting. It turned out difficult to establish a firm number for the percentage of biomass in decentralized cogeneration. In personal communications with Michael Brown, director of WADE, he estimated that the current amount of biomass equals 3–5%, potentially rising to 6–8% by 2012. We therefore subtracted from the total decentralized cogeneration 4% of capacity in 2004, rising to 7% in 2012. This leaves us with an estimate of decentralized non-biomass cogeneration.

6. Capacity Factor 2000–2012: Having neither electrical output nor capacity factors from any traditional sources, we again turned to help of Michael Brown of WADE. He provided an estimated average capacity factor in terms of hours per year: "7000-7500, possibly more." Running 7,250 hours per year equates to a capacity factor of 82.8%, which we applied uniformly to all years under consideration.

WIND

1. Annual Installations 1990–2007: Cumulative wind capacity for the period 1990–2002 is taken from the European Wind Energy Association's *Current Status of the Wind Industry, 2005* (http://www.ewea.org/documents/factsheet_industry2.pdf). Cumulative wind capacity for the period 2003–2005 is taken from Global Wind Energy Council (GWEC) *Global Wind 2006 Report* (http://www.gwec.net/fileadmin/documents/Publications/gwec-2006_final_01.pdf). Cumulative wind capacity for the period 2006–2007 is taken from GWEC update

(http://www.gwec.net/uploads/media/GWEC_charts___table.pdf). The delta indicates the net new additions for 1991–2004. Unverified capacity additions for 1990 are taken from Worldwatch's 2003 *Vital Signs* (http://www.worldwatch.org/pubs/vs/2003/).

2. Annual Installations 2008–2010: Cumulative wind capacity estimates are taken from Global Wind Energy Council (GWEC) *Global Wind 2007 Report* (http://www.gwec.net/uploads/media/Global_Wind_2007_Report_final.pdf). The delta indicates the net new additions for 2008–2010.

3. Capacity Factors 1990–2010: EWEA's *Wind Force 12* estimates that the 2003 capacity factor was 24% and will jump to 28% in 2011. From 2004–2010 capacity factors were interpolated. For 1990–2002 capacity factors were extrapolated using the same linear trend as for 2004–2010.

PHOTOVOLTAICS

1. Annual Installations 1990–2006: Worldwatch's 2005 *Vital Signs* (http://www.worldwatch.org/pubs/vs/2005/) lists PV production from 1990–2004. We actually substituted the 2004 estimate with a more refined number from the EPIA Photovoltaic Barometer (2005). Production for 2005 and 2006 comes from the European Commission and Solarbuzz respectively. Production doesn't equal the number of installations because of lag time and expanding production. We assumed that all panels produced are installed by the end of the next calendar year. To find the percentage of PV panels which are produced and installed in the same year, we used Solarbuzz's 2005 Marketbuzz (http://www.solarbuzz.com/Marketbuzz2005-intro.htm) for the 2004 installation data and solved the following equation: $761*(1-X) + 1194 * X = 927$. This approximates the percentage of panels that are installed in the same year they are produced. Using this percentage and the aforementioned assumption, we found an estimate for installations for each year.

2. Cumulative Installed Capacity 1990–2006: We first found the 1989 cumulative PV production by simply subtracting the 1990 production from the 1990 cumulative total. Using the assumption that all PV panels produced in 1989 or before were installed by the end of 1990, we then simply added the annual installations in following years. We assumed a 25-year lifespan of the panels, which is commonly accepted as a PV pane's lifespan (though some modern panels now come with a 25-year *guarantee*). Therefore, in 1996 we start retiring the very first PV panels, which were made in 1971.

3. Annual Installations 2007–2010: Two scenarios were used with different assumptions. The more conservative scenario assumed 3200 MW of installation in 2010 came from Solarbuzz in 2004. This corresponds to about a 16% annual growth rate. The more aggressive scenario assumed a 30% annual growth rate, which was found in SolarToday (May/June 2005). The more aggressive scenario is used for all analysis and graphs.

4. Capacity Factor 1990–2010: The IEA's *World Energy Outlook* contains predictions of PV capacity and output for 2010. From these were able to calculate IEA's implicit PV capacity factor. The report also has data for 2002, but PV production and output were so small that both numbers are rounded to 1.00. This causes the loss of too many significant figures to determine the capacity factor. We therefore used the 2010 capacity factor for all years under consideration.

SMALL HYDRO

1. Annual Installations 2000–2010: According to the International Association for Small Hydro (IASH) (http://www.iash.info/), at the end of 2004 there was 47 GWe of small hydro in the world. World Energy Council uses <10MW as the definition of small hydro, http://www.worldenergy.org/wecgeis/publications/reports/ser/hydro/hydro.asp. REN21 has data for small hydro capacity from 2004 to 2006, but they use a different convention (<10MW throughout the world except China and India where the upper bound is 50MW and 30MW respectively). Since 2004 overlapped with the IASH, we assumed the fraction of hydro under 10MW to the REN21 convention was constant. We counted this same fraction of the 2005 and 2006 capacities reported by REN21. We then extrapolated out for previous and future years. Assuming exponential growth this translates to 54.95 GWe by 2010. Using simple exponential growth from 2004 to 2010, we can interpolate worldwide capacity in the intermediate years. Extrapolating backwards from 2004, we can approximate capacity for previous years.

2. Capacity Factor 2000–2010: According to ISHA's analysis, the 54.95 GWe of capacity in 2010 is expected to produce 220,700 MWe. This translates to a capacity factor of 45.8%, which is logically lower than large-scale hydro (large hydro operations are able to rely on their reservoir capacity to smooth power distribution through the season.) We assumed that this capacity factor is a good estimate for all years as small hydro technology is reasonably mature.

BIOMASS

1. Annual Installations 2000–2010: The incremental capacity additions, for 2000–2002 and projections from 2007–2010, have all been taken from work done by Navigant Consulting (http://www.navigantconsulting.com, http://www.acore.org/pdfs/Frantzis.pdf). We used IEA's 2002 total global capacity (from the *World Energy Outlook*) as a reference value and worked backward and forward to find yearly total capacities. 2004–2006 capacities came from REN21 *Global Renewable Status Report* for years 2005 through 2007. These values were used, and then projections from Navigant were used for 2007 to 2010. Doing this we came to a 2010 total that exceeded IEA's estimate (55.7 GW opposed to 53 GW). We therefore rescaled the 2007–2010 increments to conform to this lower number.

2. Capacity Factor 2000–2010: Both the 2002 and 2010 capacity factors were calculated from IEA's capacity and output for these years. As the capacity factors were identical at 70%, we assumed all intermediate capacity factors were uniform.

GEOTHERMAL

1. Annual Installations 2000–2010: The incremental capacity additions, both historical (2000–2002) and projected (2007–2010), have all been taken from work done by Navigant Consulting. Historical capacity additions for 2004–2006 have been taken from *BP Statistical Review of World Energy 2007*, which cites International Geothermal Association as the source. Due to lack of data for capacity additions in 2003, we used the Navigant projection for that year. We used IEA's 2002 total global capacity as a reference value and worked backwards and forwards to find yearly totals for the period 2000–2010. Doing this we came to a 2010 total that fell short of IEA's estimate (12.2 GW opposed to 13 GW). We therefore rescaled the 2007–2010 increments to conform to this higher number.

2. Capacity Factor 2000–2010: Both the 2002 and 2010 capacity factors were calculated from IEA's capacity and output for these years, 72% and 78% respectively. For intermediate years, we simply

assumed a linear increase from 2002 to 2010. Capacity factors for 2000 and 2001 were extrapolated using the same linear trend.