Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part I – Definitions)

by Vaclav Smil
May 8, 2010

[Editor's note: This is Part I of a five-part series by Vaclav Smil that provides an essential basis for the understanding of energy transitions and use. Dr. Smil is widely considered to be one of the world's leading energy experts. His views deserve careful study and understanding as a basis for today's contentious energy policy debates. Good intentions or simply desired ends must square with energy reality, the basis of Smil's worldview.]

Energy transitions – be they the shifts from dominant resources to new modes of supply (from wood coal, from coal to hydrocarbons, from direct use of fuels to electricity), diffusion of new prime movers (from steam engines to steam turbines or to diesel engines), or new final energy converters (from incandescent to fluorescent lights) – are inherently protracted affairs that unfold across decades or generations.

Many factors combine to determine their technical difficulty, their cost and their environmental impacts. A great deal of attention has been recently paid to the pace of technical innovation needed for the shift from the world dominated by fossil fuel combustion to the one relying increasingly on renewable energy conversions, to the likely costs and investment needs of this transitions, and to its environmental benefits, particularly in terms of reduced CO_2 emissions.

Inexplicably, much less attention has been given to a key component of this grand transition, to the spatial dimension of replacing the burning of fossil fuels by the combustion of biofuels and by direct generation of electricity using water, wind, and solar power. Perhaps the best way to understand the spatial consequences of the unfolding energy transition is to present a series of realistic *power density* calculations for different modes of electricity generation in order to make revealing comparisons of resources and conversion techniques. Detailed calculations will make it easy to replicate them or to change the assumptions and examine (within realistic constraints) many alternative outcomes.

Sorting Out the Definitions

Energy density is easy – power density is confusing. *Energy density* is simply the amount of energy per unit weight (gravimetric energy density) or per unit volume (volumetric energy density). With energy expressed (in proper scientific terms) in joules or less correctly in calories (and in the US, the only modern state that insists on using outdated non-metric measures, in BTUs), with weight in grams (and their multiples), and with volume in cubic centimeters, liters (dm^3) or cubic meters, energy density is simply joules per gram (J/g) or joules per cubic centimeter (J/cm^3) or, more commonly, megajoules per kilogram (MJ/kg) and megajoules per liter (MJ/L) or gigajoules per ton (GJ/t) and gigajoules per cubic meter (GJ/m^3).

One look at energy densities of common fuels is enough to understand while we prefer coal over wood and oil over coal: air-dry wood is, at best, 17 MJ/kg, good-quality bituminous coal is 22-25 MJ/kg, and refined oil products are around 42 MJ/kg. And a comparison of volumetric energy densities makes it clear why shipping non-compressed, non-liquefied natural gas would never work while shipping crude oil is cheap: natural gas rates around 35 MJ/m^3, crude oil has around 35 GJ/m^3 and hence its volumetric energy density is thousand times (three orders of magnitude) higher. An obvious consequence: without liquefied (or at least compressed) natural gas there can be no intercontinental shipments of that clean fuel.

You can start explaining some of the limits and possibilities of everyday life or historical progress by playing with energy densities: the more concentrated sources of energy give you many great advantages in terms of their extraction, portability, transportation and storage costs, and conversion options. If you want to pack the minimum volume of food for a mountain hike you take a granola bar (17 J/g) not carrots (1.7 J/g). And if you want to fly across the Atlantic you will not power gas turbines with hydrogen: the gas has gravimetric density greater than any other fuel (143 MJ/kg) but its volumetric density is a mere 0.01 MJ/L while that of jet fuel (kerosene) is 33 MJ/L, 3,300 times higher.

Power density is a much more complicated variable. Engineers have used power densities as revealing measures of performance for decades – but several specialties have defined them in their own particular ways. The first relatively common use of the ratio is by radio engineers to express power densities of isotropic antennas as a quotient of the transmitted power and the surface area of a sphere at a given distance (W/m^2). The second one refers to volumetric or gravimetric density of energy converters: when evaluating batteries (whose mass and volume we usually try to minimize) power density refers to the rate of energy release per unit of battery volume or weight (typically W/dm^3 or W/kg); similarly, in nuclear engineering power density is the rate of energy release per unit volume of a reactor core. WWW offers a perfect illustration of this engineering usage: top searches for "power density" turn up calculators for isotropic antennas (the first common engineering use I noted above), and a Wikipedia stub refers to power density of heat engines in kW/L (the second common use as volumetric power density of energy converters).

To make it even more confusing, the international system of scientific units calls W/m^2 heat flux density or irradiance, the latter referring clearly to incoming radiation (electromagnetic energy incident on the surface) – and Piotr Leonidovich Kapitsa, one of the most influential physicists of the 20th century (Nobel in 1978), favored using W/m^2 for the most fundamental evaluation of energy converters by calculating the flux of energy through their working surfaces. The original late 19th century application of this measure (Umov-Poynting vector) referred to the propagation of electromagnetic waves but the same principle applies to energy flux across a turbine or to diffusion rates in fuel cells. Power density has been used recently in this sense in order to calculate a flux across the (vertical) area swept by a wind turbine (more on this in the wind power density section).

For the past 25 years I have favored a different, and a much broader, measure of power density as perhaps the most universal measure of energy flux: W/m^2 of horizontal area of land or water surface rather than per unit of the working surface of a converter. Perhaps the greatest advantage of this parameter is that it can be used to evaluate and to compare an enormous variety of energy fluxes ranging from natural flows and exploitation rates of all energy sources (be they fossil or renewable) to all forms of energy conversions (be it the burning of fossil fuels or water- or wind-driven electricity generation). That is why I chose power density as a key analytical variable to evaluate all important biospheric and anthropogenic energy flows in my first synthesis of general energetics in1991 and why I had recently revised and substantially expanded that coverage in my book *Energy in Nature and Society: General Energetics of Complex Systems*. The MIT Press (2008).

Not many people have been using this powerful and revealing measure frequently and appropriately, hardly a surprise given the generally abysmal understanding of fundamental energetics. But, finally, power density expressed as energy flux per unit of horizontal surface has been receiving more attention because of the growing interest in renewable energy resources and their commercial conversions to fuels and electricity. Invariably, power densities of these stocks and flows are considerably lower than power densities and uses of fossil fuels, those highly concentrated stores of ancient photosynthetic production – and these differences are a key factor in determining the potential contribution of renewable energies to the world's future fuel and electricity supply.

In this brief primer I will illustrate these contrasts by quantifying power densities of six modes of electricity generation: I will either make assumptions that closely correspond to representative modes of current operations or I will introduce actual generating facilities as typical examples. In subsequent posts I will first calculate the most common range of power densities of coal- and wood-fired (a renewable) electricity generation followed by power densities for natural gas-fired gas turbine-driven process; this will be followed by power densities of three new renewable conversions: a thermal station burning plantation-grown wood, solar photovoltaic plants, concentrating solar plants, and large wind farms.

Source: http://www.masterresource.org/2010/05/smil-density-definitions-i/

Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part II – Coal- and Wood-Fired Electricity Generation)

by Vaclav Smil
May 10, 2010

Baseline calculations for modern electricity generation reflect the most important mode of the U.S. electricity generation, **coal combustion in modern large coal-fired stations**, which produced nearly 45% of the total in 2009. As there is no such thing as a standard coal-fired station I will calculate two very realistic but substantially different densities resulting from disparities in coal quality, fuel delivery and power plant operation. The highest power density would be associated with a large (in this example I will assume installed generating capacity of 1 GW_e) mine-mouth power plant (supplied by high-capacity conveyors or short-haul trucking directly from the mine and not requiring any coal-storage yard), burning sub-bituminous coal (energy density of 20 GJ/t, ash content less than 5%, sulfur content below 0.5%), sited in a proximity of a major river (able to use once-through cooling and hence without any large cooling towers) that would operate with a high capacity factor (80%) and with a high conversion efficiency (38%).

This station would generate annually about 7 TWh (or about 25 PJ) of electricity. With 38% conversion efficiency this generation will require about 66 PJ of coal.

> 1 GW x 0.8 = 800 MW
> 800 MW x 8,766 hours = 7.0 TWh
> 7.0 TWh x 3,600 = 25.2 PJ
> 25.2 PJ/0.38 = 66.3 PJ

Assuming that the plant's sub-bituminous coal (energy density of 20 GJ/t, specific density of 1.4 t /m^3) is produced by a large surface mine from a seam whose average thickness is 15 m and whose recovery rate is 95%, then under every square meter of the mine's surface there are 20 t of recoverable coal containing 400 GJ of energy. In order to supply all the energy needed by a plant with 1 GW_e of installed capacity, annual coal extraction would have to remove the fuel from an area of just over 16.6 ha (166,165 m^2), and this would mean that coal extraction required for the plant's electricity generation proceeds with power density of about 4.8 kW/m^2:

> 15 m^3 x 0.95 x 1.4 t = 19.95 t
> 19.95 t x 20 GJ/t = 399 GJ
> 66.3 PJ/399 GJ = 166,165 m^2
> 800 MW/166,165 m^2 = 4,814.5 W/m^2

A much larger area has to be occupied by the plant itself, but in a mine-mouth power plant without coal storage yard, with once-through cooling and with the disposal of fly ash into the excavated area the station's complete infrastructure (boiler and turbogenerator halls, electrostatic precipitators, maintenance buildings, offices, roads, parking) could cover as little as 600,000 m^2. This means that the total area whose other uses would be preempted every year by coal extraction and the permanent infrastructure of a coal-fired power plant would be roughly 766,000 m^2 and the power density of the entire extraction-generation enterprise would be about 1,000 W/m^2:

$$800 \text{ MW}/766{,}000 \text{ m}^2 = 1{,}044.4 \text{ W/m}^2$$

An even larger area would be needed by a plant located far away from a mine (supplied by a unit train or by barge), and from a major river (hence requiring cooling towers), burning lower-quality sub-bituminous coal (18 GJ/t) extracted from a thinner (10 m) seam and containing relatively high shares of ash (over 10%) and sulfur (about 2%) and having a low capacity factor (70%) and conversion efficiency (33%). Coal extraction needed to supply this plant would proceed with power density of only about 2.5 kW/m^2:

$$1 \text{ GW} \times 0.70 = 700 \text{ MW}$$
$$700 \text{ MW} \times 8{,}766 \text{ hours} = 6.14 \text{ TWh}$$
$$6.14 \text{ TWh} \times 3{,}600 = 22.09 \text{ PJ}$$
$$22.09 \text{ PJ}/0.33 = 66.94 \text{ PJ}$$
$$10 \text{ m}^3 \times 0.95 \times 1.4 \text{ t} = 13.3 \text{ t}$$
$$13.3 \text{ t} \times 18 \text{ GJ/t} = 239.4 \text{ GJ}$$
$$66.94 \text{ PJ}/239.4 \text{ GJ} = 279{,}615 \text{ m}^2$$
$$700 \text{ MW}/279{,}615 \text{ m}^2 = 2{,}503.4 \text{ W/m}^2$$

Moreover, such a plant would occupy a much larger site — but not mainly because of its off-loading (train or barge) facilities and coal yard capable of storing fuel for several weeks of operation. Most of the additional land would be occupied by ash disposal and settling ponds, flue gas desulfurization facilities, and on-site ponds for storing the resulting slurry. Actual numbers for America's largest coal-fired electricity generating plant, Robert W. Scherer in Georgia with installed capacity of about 3.5 GW, indicate the actual claims: coal storage yard of 36 ha, and an ash-settling pond of 120 ha (designed to last for the plant's lifespan of some 50 years) with the plant's total operating area covering about 1,400 ha (all data from Georgia Power). With an average load factor of 75% this translates to power density of close to 190 W/m^2. After including the coal extraction part, the entire mining-generation system would have overall power density of about 175 W/m^2. In order to provide a useful approximate bracketing we might thus conclude that, depending on their specific circumstances, most large modern coal-fired power plants generate electricity with power densities ranging over an order of magnitude, from just around 100 W/m^2 to 1,000 W/m^2.

With this base range in mind, we can now proceed to examine power densities of natural gas-fired generation using large gas turbines and then four major modes of renewable electricity generation.

Wood-Fired Electricity Generation

Photosynthesis is an inherently inefficient way of converting electromagnetic energy carried by visible wavelengths of solar radiation into chemical energy of new plant mass: global average of this conversion is only about 0.3% and even the most productive natural ecosystems cannot manage efficiencies in excess of 2%. The best conversion rates for trees grown for energy can be achieved in intensively cultivated monocultural plantations. Depending on the latitude and climate, these can be composed of different species and varieties of willows, pines, poplars, eucalyptus or leucaenas. Burning sawmill residues or wood chips in fairly large boilers in order to generate steam and/or electricity is a well-established and a fairly efficient practice – after all, energy density of dry wood (18-21 GJ/t) is much like that of sub-bituminous coal.

But if we were to supply a significant share of a nation's electricity by using tree phytomass we would have to establish extensive tree plantations that would require fertilization, control of weeds and pests and, if needed, supplementary irrigation –- and even then we could not expect harvests surpassing 20 t/ha, with rates in less favorable locations as low 5-6 t/ha and with the most common yields around 10 t/ha. Harvesting all above-ground phytomass and feeding it into chippers would allow for 95% recovery of the total field production but even if the fuel's average energy density were 19 GJ/t the plantation would yield no more than 190 GJ/ha, resulting in harvest power density of 0.6 W/m^2:

10 t/ha x 19 GJ = 190 GJ/ha
190 GJ/31.5 Ms = 6,032 W
6,032 W/10,000 m^2 = 0.6 W/m^2

A wood-fired power plant with installed capacity of 1 GW, capacity factor of 70% and conversion efficiency of 35% would require an annual harvest of about 330,000 ha of plantation growth, an equivalent of a square nearly 58 x 58 km:

1 GW X 0.7 = 700 MW
700 MW/0.35 = 2 GW
2 GW/0.6 W/m^2 = 3.33 Gm^2 (333,333 ha)
$\sqrt{3.33\ Gm^2}$ = 57,735 m

Total area needed by a wood-fired electricity-generating plant is negligible when compared to enormous area of land claimed by phytomass production: even if the generating station and its associated structures were to occupy 3,000 ha it would change the total land claim by less than 0.1%.

Low power densities of this mode of electricity generation prevent it from capturing anything but a very minor share of the overall supply. If only 10% of the US electricity generated in 2009 (that is 395 TWh or 1.42 EJ) had to be fueled by wood, then (with average 35% conversion efficiency) the country would require about 4 EJ (nearly 129 GW) of wood chips. With average power density of 0.6 W/m^2 this would claim about 215 Gm^2 of wood plantations and that area (215,000 km^2) would be equal to nearly as much land as the entire Idaho or Utah.

This basic calculation also shows why even a realistically impressive increase of future phytomass harvest (due to better hybrids or to entirely new transgenic trees) would not make any fundamental difference as far as the very low power densities of phytomass production are concerned. Improvements of up to 25% would still require at least 250,000 ha of plantation trees to supply a plant with 1 GW_e capacity. With even a doubling of today's mean (at this time entirely unrealistic), such a plant would still need annual harvests of all above-ground phytomass from a square of 40 x 40 km.

Plantation of fast-growing hybrid poplars: whole-tree harvesting of this phytomass has power densities below 1 W/m^2.

Source: http://www.masterresource.org/2010/05/smil-density-coal-wood-ii/

Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part III – Natural Gas-Fired Electricity Generation)

by Vaclav Smil
May 11, 2010

Boilers of electricity-generating stations burning coal can be converted to burn liquid or gaseous hydrocarbons (fuel oil, even crude oil, and natural gas) and such conversions were fairly common during the 1960s and the early 1970s. Burning natural gas rather than coal has clear environmental advantages (it generates less, or no, sulfur dioxide and no fly ash) but the overall conversion efficiency of the boiler-steam turbogenerator unit changes little. In contrast, gas turbines, particularly when coupled with steam turbines, offer the most efficient way of electricity generation. This results in much higher power densities than is the case with coal-fired plants. Overall densities of the fuel extraction and electricity generation process are also kept high because of the relatively high power densities of natural gas production (depending on the field they vary by more than an order of magnitude, with minima around 50 W/m^2, maxima well over1 kW/m^2) and even more by the fact that new gas-powered generation often does not need any major new infrastructure as it can tap the supply from existing fields and pipelines.

Gas turbines were first commercialized for electricity generation by Brown Boveri in Switzerland during the late 1930s but in the US their installations became common only during the late 1960s, spurred by the November 1965 US Northeast blackout that left 30 million people without electricity for up to13 hours. Nationwide capacity of gas turbines rose from just 240 MW in 1960 to nearly 45 GW by 1975, a nearly 200-fold rise in 15 years. This ascent was interrupted by high hydrocarbon prices (as well as by stagnating electricity demand) but it resumed during the late 1980s. By 1990 nearly half of the 15 GW of all new capacity ordered by the US utilities was in gas turbines and by 2008 almost exactly 40% of the US summer generating capacity (397.4 GW) was installed in gas-fired units, either single- or combined-cycle gas turbines (CCGT). Unlike a single gas turbine that discharges its hot gas, CCGT uses the turbine's hot exhaust gases to generate steam for a steam turbine, boosting overall efficiency. While the best single gas turbines can convert about 42% of their fuel to electricity, CCGT convert as much as 60% and are now the most efficient electricity generators.

Their other obvious advantages in comparison to coal-fired units include their small footprint; rapid response (they can full power in minutes, making a perfect choice for peak-load operations); fuel flexibility (they can burn gaseous and liquid fuels); high reliability; availability in a wide range of capacities, from less than 1 MW to more than 500 MW for CCGT (Siemens now has a 340-MW turbine that will produce 530 MW in combined cycle arrangement, GE's MS9001H comes close with 480 MW); and convenient maintenance. Gas turbines can be also deployed rapidly: Pratt & Whitney's 25 MW MOBILEPAC (belonging to a popular class of aeroderivative machines, essentially grounded jet engines) moved on two trailers, is ready in 8 hours.

P&W's MOBILEPAC, 25 MW_e (a modified FT8 jet engine) on a trailer: the most compact and nearly instantly installable multi-MW electricity generator on the market.

A 25-MW mobile gas turbine can occupy as little as 140 m^2; with its control trailer, access roads, fuel and electricity connections and a perimeter buffer, it could still fit within a 40 x 15 m rectangle. P&W's 60 MW SwiftPac (and its control housing) erected on concrete foundations needs less than 700 m^2 and it can be ready to run in 21 days.

P&W's SwiftPac, 60 MW gas turbine with a minimal footprint: control trailer in the right foreground; fire extinguisher on the front left wall indicates the scale.

Compact size of powerful gas turbines means that multi-unit installations can be easily accommodated within the existing sites of established electricity-generating stations. By turning to gas turbines as their dominant way of new capacity additions, utilities in Europe and North America have eliminated the necessity of contentious application and approval processes for new plant sites. Didcot-B in Oxfordshire is a perfect example of this option. This 1.360-GW_e gas turbine plant was built between 1994 and 1997 within a larger pre-existing site of Didcot-A, a 2-GW_e coal-fired station completed in 1968. Construction of that large coal-fired plant had created a great deal of local opposition, but a gas-fired plant of more than two-thirds of the coal plant's capacity was accommodated without any problems within the original plant's area, occupying less than 10% of the entire site. Alternatively, gas turbine plants can be fitted into odd spaces within urban areas.

Didcot-B, 1,360-MW_e gas turbine electricity generating plant
in Oxfordshire (trees and cars provide the scale).

No other modes of large-scale electricity generation occupy as little space as do gas turbines: besides their compactness they do not require any fly ask disposal or flue gas desulfurization. With an average load factor of about 40% (recent US mean), mobile gas turbines generate electricity with power densities higher than 15 kW/m^2 and large (>100 MW) stationary set-ups can easily deliver 4-5 kW/m^2.

Didcot power station: coal-fired Didcot-A (generator hall and a tall stack are center right, coal storage and the three cooling towers at the bottom of the image). Gas-fired Didcot-B, shown in detail in the previous image, is just below the top group of three cooling towers.

Source: http://www.masterresource.org/2010/05/smil-density-gas-iii/

Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part IV – New Renewables Electricity Generation)

by Vaclav Smil
May 13, 2010

Photovoltaic Electricity Generation

Satellite measurements put the solar constant – radiation that reaches area perpendicular to the incoming rays at the top of the atmosphere (and that is actually not constant but varies with season and has negligible daily fluctuations) – at 1,366 W/m^2. If there were no atmosphere and if the Earth absorbed all incoming radiation then the average flux at the planet's surface would be 341.5 W/m^2 (a quarter of the solar constant's value, a sphere having four times the area of a circle with the same radius: $4\pi r^2/\pi r^2$). But the atmosphere absorbs about 20% of the incoming radiation and the Earth's albedo (fraction of radiation reflected to space by clouds and surfaces) is 30% and hence only 50% of the total flux reaches the surface prorating to about 170 W/m^2 received at the Earth's surface, and ranging from less than 100 W/m^2 in cloudy northern latitudes to more than 230 W/m^2 in sunny desert locations.

For an approximate calculation of electricity that could be generated on large scale by photovoltaic conversion it would suffice to multiply that rate by the average efficiency of modular cells. While the best research cells have efficiencies surpassing 30% (for multijunction concentrators) and about 15% for crystalline silicon and thin films, actual field efficiencies of PV cells that have been recently deployed in the largest commercial parks are around 10%, with the ranges of 6-7% for amorphous silicon and less than 4% for thin films. A realistic assumption of 10% efficiency yields 17 W/m^2 as the first estimate of average global PV generation power density, with densities reaching barely 10 W/m^2 in cloudy Atlantic Europe and 20-25 W/m^2 in subtropical deserts.

PV panels are fixed in an optimal tilted south-facing position and hence receive more radiation than a unit of horizontal surface but the average power densities of solar parks are low. Additional land is needed for spacing the panels for servicing, for access roads, inverter and transformation facilities and for service structures, and only about 85% of a panel's DC rating will be transmitted from the park to the grid as AC power. Olmedilla de Alarcón, the world's largest solar park in Spain, has installed capacity of 60 MW of peak power (MW_p) but its annual generation of 85 GWh (or 9.7 MW of electricity as an average annual rate) translates to capacity factor of just 16%. Portuguese Moura (46 MW_p, 88 GWh or 10 MW of average annual generation) has the capacity factor of nearly 22% and the capacity factor for Germany's largest solar park (Waldpolenz rated at 40 MW_p) is only 11%. Power density of Olmedilla is only 9 W/m^2, that of Moura almost 8 W/m^2 while Waldpolenz rates just above 4 W/m^2.

Olmedilla 85 GWh/year = 9.7 MW 9.7 MW/108 ha = 9 W/m^2
Moura 88 GWh/year = 10 MW 10 MW/130 ha = 7.7 W/m^2
Waldpolenz 40 GWh/year = 4.56 MW 4.56 MW/110 ha = 4.1 W/m^2

The largest solar PV parks thus generate electricity with power densities that is roughly 5-15 times higher than for wood-fired plants but that is at best 1/10 and at worst 1/100 of the power densities of coal-fired electricity generation. Again, if only 10% of all electricity generated in the US in 2009 (395 TWh or about 45 GW) were to be produced by large PV plants, the area required (even with average power density of 8 W/m^2) would be about 5,600 km^2. No dramatic near-term improvements are expected either in the conversion efficiency of PV cells deployed on MW scale in large commercial solar parks or in the average capacity factors. But even if the efficiencies rose by as much as 50% within a decade this would elevate average power densities of optimally located commercial solar PV parks to no more than 15 W/m^2.

Olmedilla PV plant with 162,000 panels and 60 MW_p generates electricity with average power density less than 9 W/m^2 of its total area.

Concentrating Solar Electricity Generation

Concentrating solar power (CSP) projects use tracking parabolic mirrors in order to reflect and concentrate solar radiation on a central receiver placed in a high tower. This technique has several technical advantages compared to PV, above all: higher conversion efficiencies (thanks to a conventional steam-powered generation) and the possibility to augment the solar-heated steam by fuel combustion. Still, power densities of CPS are not all that different from PV generation.

Europe’s first commercial solar tower, PS (Planta Solar) 10, completed by Abengoa Solar in Sanlúcar la Mayor in 2007, is rated at 11 MW_p. With annual generation of 24.3 GWh (87.5 TJ, 2.77 MW), its capacity factor is 25%. Its heliostats occupy 74,880 m^2 (624 x 120 m^2), and the entire site claims about 65ha; the facility’s power density is thus about 37 W/m^2 factoring in the area taken up by the heliostats alone, and a bit more than 4 W/m^2 if the entire area is considered. PS20 (completed in 2009) is nearly twice the size (20 MW_p; 48.6 GWh or 175 TJ/year at average power of 5.55 MW and capacity factor of nearly 28%). Its mirrors occupy 150,600 m^2 and hence the project's heliostat power density is, at 36.85 W/m^2, identical to that of PS10 but, with its entire site covering about 90 ha, its overall power density is higher at about 6 W/m^2.

Abengoa's two large CSP plants near Sanlúcar la Mayor (Sevilla), PS10 in operation and PS20, in the foreground, shown still under construction.

Bright Source Energy's proposed Ivanpah CSP in San Bernardino, CA should have an eventual rating of 1.3 GW_p and it is expected to generate 1.08 TWh (3.88 PJ) a year and deliver on the average 123.3 MW with a capacity factor of just 9.5%. Heliostat area should be 229.6 ha and the entire site claim is 1645 ha. This implies power densities of 53.75 W/m^2 for the heliostats and 7.5 W/m^2 for the entire site. Again, no stunning improvements of these rates are expected any time soon and hence it is safe to conclude that optimally located CSP plants will operate with power densities of 35-55 W/m^2 of their large heliostat fields and with rates no higher than 10 W/m^2 of their entire site area.

Wind-Powered Electricity Generation

Wind turbines have fairly high power densities when the rate measures the flux of wind's kinetic energy moving through the working surface (the area swept by blades) of this now so popular energy converter. In the windiest, mid-continental regions of America this power density is commonly above 400 W/m^2 – but power density expressed as electricity generated per m^2 of the area occupied by a large wind farm is a small fraction of that high rate. This is primarily due to necessarily generous spacing of wind turbines (no less than five and up to ten rotor diameters) that is required in order to minimize wake interference. As a result, even a wind farm composed of large 3 MW Vestas turbines with a rotor diameter of 112 m and spacing of six diameters apart will have peak power density of 6.6 W/m^2 and even a relatively high average capacity factor of 30% would bring that down to only about 2 W/m^2.

Actual power densities vary with average wind speeds and turbine sizes. Altamont, America's pioneering large wind farm in California, rates only 0.6 W/m^2, Puget Sound Energy's Wild Horse (with a high capacity factor of 32%) has power density of 2 W/m^2. The world's largest offshore wind installation, London Array in the outer Thames estuary – designed to have a capacity of 1 GW_p, annual generation of 31 TWh (354 MW) and an area of 245 km^2 – will have power density of just 1.44 W/m^2. A good approximation of expected power densities for large scale wind generation (year-round average, not the peak power) should not be thus higher than 2 W/m^2. If 10% of the US electricity generated in 2009 (395 TWh or 45 GW) were to be produced by large wind farms their area would have to cover at least 22,500 km^2, roughly the size of New Hampshire.

Spacing of wind turbines and access roads at the Altamont Pass wind farm in California.

Source: http://www.masterresource.org/2010/05/smil-density-new-renewables-iv/

Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part V – Comparing the Power Densities of Electricity Generation)

by Vaclav Smil
May 14, 2010

America's dominant mode of electricity generation is via combustion of bituminous and sub-bituminous coal in large thermal stations. All such plants have boilers and steam turbogenerators and electrostatic precipitators to capture fly ash, but they burn different qualities of coal that may come from surface as well as underground mines, have different arrangements for cooling (once-through using river water or various cooling towers) and many have flue gas desulfurization to reduce SO_2 emissions. Consequently, these conversions of chemical energy in coal to electricity feature widely differing power densities: for the power plants alone they are commonly in excess of 2 kW/m^2 and can be as high as 5 kW/m^2. When all other requirements (coal mining, storage, environmental controls, settling ponds) are included, the densities inevitably decline and range over an order of magnitude: from as low as 100 W/m^2 to as much as 1,000 W (1 kW)/m^2.

In contrast, compact gas turbines plants (the smallest ones on trailers and larger facilities that can be rapidly assembled from prefabricated units), which can be connected to existing gas supply, can generate electricity with power density as high as 15 kW/m^2. Larger stations (>100 MW) using the most efficient combined-cycle arrangements (with a gas turbine's exhaust used to generate steam for an attached steam turbine) will operate with lower power densities, and if new natural gas extraction capacities have to be developed for their operation then the overall power density of gas and electricity production would decline to a range similar to that of coal-fired thermal generation or slightly higher, that is in most cases to a range of 200-2000 W/m^2.

Photosynthesis is an inherently inefficient energy conversion process, and production of biomass has large space requirements. Even with an intensively cultivated plantation of fast-growing trees, a wood-burning electricity generation plant would not have power densities higher than 0.6 W/m^2, and for most operations the rate would be below 0.5 W/m^2. Space demand for such facilities, then, would be two to three orders of magnitude (100 to 1,000 times) greater than for coal- or gas-fired electricity generation.

Photovoltaic plants can generate electricity with much higher power densities than wood-burning station — converting solar radiation to new biomass has overall efficiency no better than 1% while even relatively inefficient PV cells have efficiencies around 5% and today's best commercial facilities go above 10%. Taking only the PV cell area into consideration, this translates to power densities of mostly between 10-20 W/m^2. But when all ancillary space requirements are included, the typical density range declines to 4-9 W/m^2, an order of magnitude higher than for wood-powered generation but one to three orders of magnitude lower (that is demanding 10 to 1,000 times more space) than the common modes of fossil fueled electricity production.

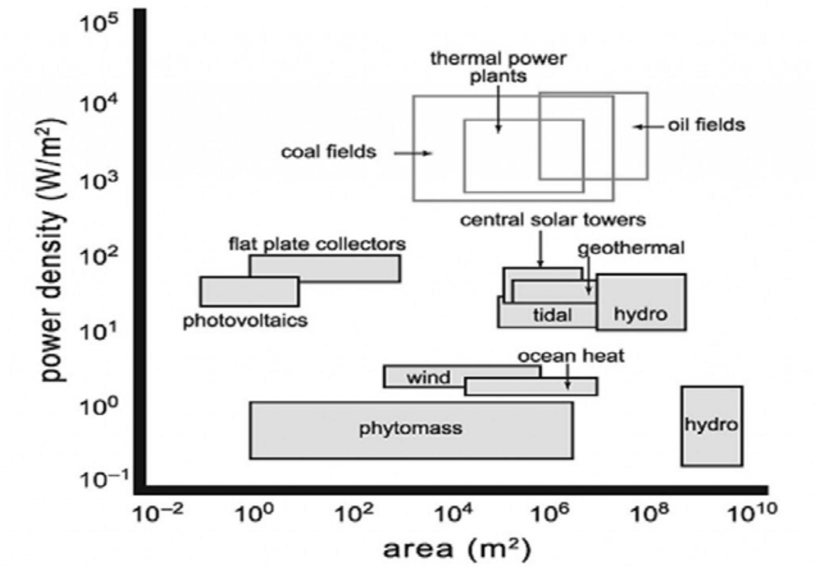
Power densities for central solar power are slightly higher, with rates as high as 45-55 W/m^2, when only the area of heliostats is considered, but with overall power densities (including spacing, access roads and the tower facilities) on the order of 10 W/m^2. Finally, wind-driven electricity generation has power densities similar to, or slightly higher than, wood-burning stations, with most new installations using powerful (1-6 MW) turbines fitting into a range between 0.5-1.5 W/m^2.

Power Source	**Power Density (W/m^2)**	
	Low	**High**
Natural Gas	200	2000
Coal	100	1000
Solar (PV)	4	9
Solar (CSP)	4	10
Wind	0.5	1.5
Biomass	0.5	0.6

Implications of these differences are manifold. Changing the power density-determined infrastructure of energy systems that were created over more than a century for electricity generation from fossil fuel combustion will not be easy. A fossil-fuelled civilization has been securing the supply of its most flexible form of energy by “shifting downward,” that is by generating electricity with power densities 1-3 orders of magnitude higher than the common power densities with which electricity is used in buildings, factories and cities. In a civilization that would rely only on renewable energy flows, but that would inherit today’s urban and industrial systems, we would produce electricity at best with the same power densities with which they would be used –- but more often we would have to concentrate diffuse flows of solar radiation, wind, and biomass in order to bridge power density gaps of 2-3 orders of magnitude.

This new energy infrastructure would increase fixed land requirements and preempt any other form of land use in areas devoted to PV cells, heliostats or fast-growing wood plantations. Most of the area occupied by large wind farms could be used for crops or grazing but other land uses would be excluded, and large areas dotted with wind turbines would require construction and maintenance of access roads as well as the creation of buffer zones not suitable for permanent human habitation. And in all cases of renewable energy conversion, much more land would be needed for more extensive transmission rights-of-way in order to export electricity from sunny and windy regions, or from areas suited for mass-scale biomass production, to major urban and industrial areas.

As a result, these new energy infrastructures would have to be spread over areas ten to a thousand times larger than today’s infrastructure of fossil fuel extraction, combustion and electricity generation: this is not an impossible feat, but one posing many regulatory (environmental assessments of affected areas, rights-of-way permission and inevitable lawsuits), technical and logistic challenges. *Higher reliance on renewable energies may be desirable (mainly because of perceived environmental and strategic reasons) and technical advances would also make it an increasingly appealing economic choice –- but inherently low power* *densities of these conversions will require a new system of fuel and electricity supply that will be able to substitute for today's dominant practices only after decades of gradual development.*



Power densities of fossil fuel extraction, thermal electricity generation and renewable modes of electricity production. Reproduced from: V.Smil *Energy Transitions: History, Requirements, Prospects* (Praeger: 2010).

Source: http://www.masterresource.org/2010/05/smil-density-comparisons-v/

Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part I â€“ Definitions). By Vaclav Smil -- May 8, 2010. [Editorâ€™s note: This is Part I of a five-part series by Vaclav Smil that provides an essential basis for the understanding of energy transitions and use. Dr. Smil is widely considered to be one of the worldâ€™s leading energy experts.Â In this brief primer I will illustrate these contrasts by quantifying power densities of six modes of electricity generation: I will either make assumptions that closely correspond to representative modes of current operations or I will introduce actual generating facilities as typical examples. Electricity is becoming a luxury good in Germany, and one of the country's most important future-oriented projects is acutely at risk. After the Fukushima nuclear accident in Japan two and a half years ago, Merkel quickly decided to begin phasing out nuclear power and lead the country into the age of wind and solar. But now many Germans are realizing the coalition government of Merkel's CDU and the pro-business Free Democrats (FDP) is unable to cope with this shift. Of course, this doesn't mean that the public has any more confidence in a potential alliance of the center-left So