Renewable Energy Analysis: Geospatial Analysis and Maps (U.S.)

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Federal Energy Management Program (FEMP) Renewable Energy Geospatial Map Tool

http://maps.nrel.gov/femp

- Coverage: Continental United States, Alaska, and Hawaii
- High-level, annualized economic calculation:
  - Economic calculations for photovoltaics (PV), wind, solar water heating, solar vent air preheat
  - Economic results: savings-to-investment ratio, payback period, levelized cost of energy
  - Discount rates and escalation rates compliant with 10CFR436
  - With and without potential savings from available renewable energy incentives at the state and federal level
  - Other layers that might be relevant to planning renewable energy projects, such as:
    - Renewable energy resource data (hydropower, geothermal, biomass)
    - Land ownership
    - Environmentally sensitive areas
    - Topographical relief.

Technology Configurations

Reciprocating engine combined heat and power (CHP)

Reciprocating CHP with seasonal storage

Combustion turbine CHP

Combustion turbine CHP with seasonal storage

PV + 0-hour battery

PV + 4-hour battery

PV + 12-hour battery

Concentrating solar power (CSP) + 0-hour storage (TES)

CSP + 4-hour TES

CSP + 12-hour TES

Wind + 0-hour battery

Wind + 4-hour battery

Wind + 12-hour battery

Solar water heating (SWH) with diurnal storage

SWH with seasonal storage

Annual Energy Delivery and Capacity Factor

$$\mathrm{CF} = \frac{E}{TP_{rated}}$$

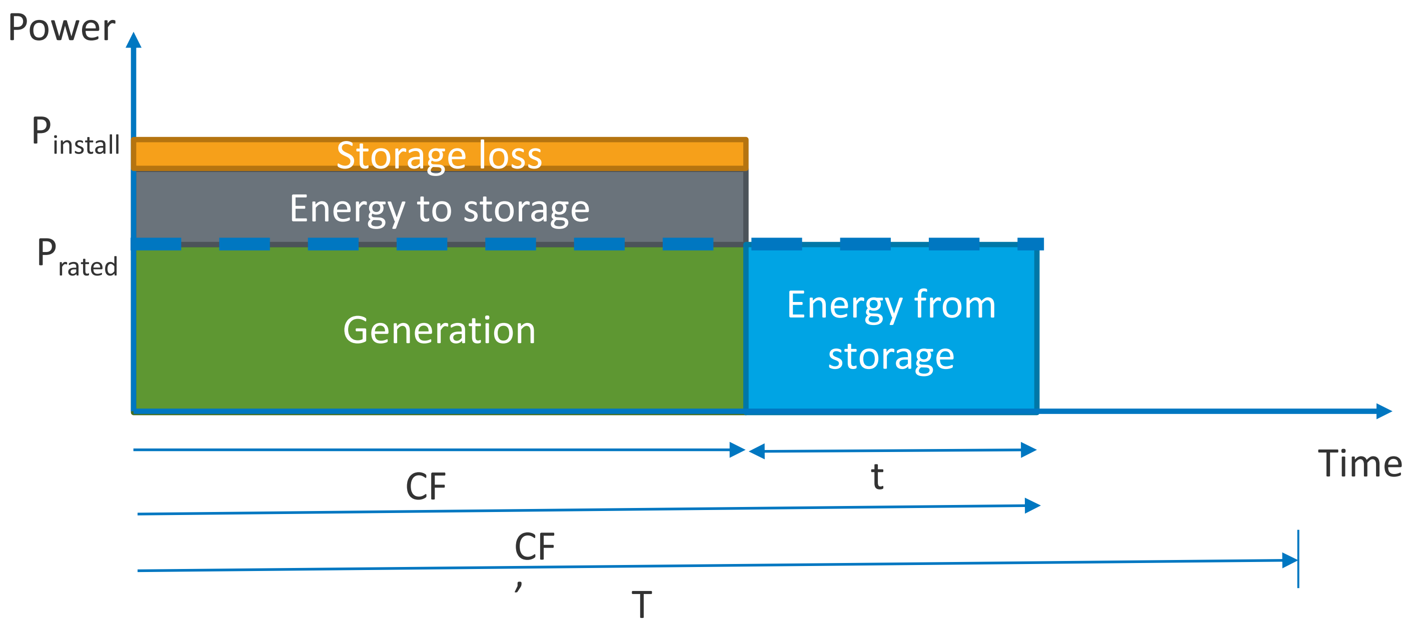
$$E = Prat_{ed} * CF * T$$

$$P_{rated} = \frac{E}{CF\ T}$$

Definitions of P_{rated} and CF must be consistent with each other.

- E = annual energy delivery (kWh/yr) of the systems
- CF = capacity factor, energy delivery (kWh/yr) divided by rated power, P_{rated} (kW), and divided by total time period, T (h); percentage of time a system delivers its rated capacity
- Capacity factor includes balance-of-system losses (AC capacity factor).

Storage extends Capacity Factor of a Rated Power



CF = capacity factor based on resource availability

CF’ = CF + t/T

T = hours of storage (that the power level, P_{rated}, might be extended)

T = time period over which resource CF is defined (T = 24 hr/day or 8760 h/year)

$P_{install} = P_{rated}(1+t/(CF*T))//\eta_{storage}$

Initial and Annual Operating Costs of each Technology Configuration

Initial cost:

$C_{initial} = C_{intial\ fixed} + c_{gen\ unit} * P_{install} + c_{storge\ unit} * t * P_{rated}$

$C_{initial\ fixed}$ = fixed project development costs ($)

$C_{gen\ unit}$ = unit cost per kW of installed capacity ($/kW)

$C_{storage\ unit}$ = unit cost per kWh cost of storage technology (battery) ($/kWh)

$C_{storage\ unit\ seasonal}$ = unit cost per kWh cost of seasonal thermal storage (pit storage) ($/kWh)

Operation-and-maintenance (O&M) cost:

$C_{OM} = C_{fixed\ O\&M} + P_{installed} * C_{gen\ O\&M} + c_{storage\ O\&M} * t * P_{rated}$

$C_{fixed\ O\&M}$ = fixed O&M cost independent of size

$C_{gen\ O\&M}$ = unit O&M cost per kW of installed generation capacity ($/kW)

$C_{storage\ O\&M}$ = unit O&M cost per kWh cost of storage technology (battery) ($/kWh), or for seasonal thermal storage technology (pit storage) ($/kWh-thermal)

Fuel Use and Heat Recovery for Combined Heat and Power

- The general approach includes fuel use, such as natural gas or biomass fuel. The amount of fuel used per year is:

$F = P_{installed}$* (CF*8760 /η_{elec}) [1-(1-η_{elec}) HRF /η_{conv}]

  - F= fuel used per year to provide rated electric generation (kWh/yr)
  - η_{elec} = efficiency of electric generator; reciprocating engine η_{elec} = 0.34, combustion turbine η_{elec} = 0.25
  - Conversion factor of 3412 Btu/kWh to convert into the more common BTU unit for fuels.

HRF = fraction of the waste heat from the power generation process that is recovered

  - Reciprocating engine HRF = 0.5, combustion turbine HRF = 0.67 because all the waste heat is in the exhaust stream and is easier to recover (EPA 2017)
  - **Assume all heat is used!** Either:
    - The CHP system is small compared to the thermal demand load.
    - Storage is sufficient to couple heat generation with heat demand.

$\eta_{conv.}$ = efficiency of conventional heating system, assumed $\eta_{conv.}$ = 0.84 for all options

fc = the cost of fuel in units of $/kWh.

Present Worth Factor

Future costs (O&M) and energy cost savings

Present worth factor (PWF)

The present value of annual costs or revenues during the analysis period are “escalated” according to an inflation rate, i, and then “discounted” to their present value.

PWF = (1+i)/(d-i)*(1-((1+i)/(1+d))^N)

I = inflation rate, I = 0.02 in this analysis

D = discount rate, d = 0.03 in this analysis

N = years of analysis period, N = 25 in this analysis.

The discount rate and inflation rates are specified by the National Institute of Standards and Technology (2019). From the *Annual Supplement to Handbook 135 Energy Price Indices and Discount Factors for Life Cycle Cost Analysis,* updated annually (http://energy.gov/eere/femp/building-life-cycle-cost-programs). Complies with 10CFR436 regulation.

Example:

PWF (I = 0.2%, d = 3%, N = 25 yr) = 22.1 years

In other words, a savings of $1/yr for 25 years = $22 today (net present value)

Levelized Cost of Energy

- Levelized cost of energy (LCOE) is the annual operating cost including annualized capital cost; less savings in conventional fuels in the numerator, divided by electrical energy produced in the denominator.

$LCOE = \{C/PWF + (C_{OM}+F*fc)\}/P_{rated}/\ CF'/(8760)$

- Here we calculate LCOE per unit of rated capacity, $P_{rated}=1$.

Sources of Data

Energy Production

- PV: 4-km resolution, satellite data from 1998 – 2017, National Solar Radiation Database (NSRDB, https://nsrdb.nrel.gov); performance modeled with the System Advisor Model using PVWatts default submodule
- SHW: Annual average 10 km resolution solar resource data for a fixed flat plate system with tilt = latitude; 40% system efficiency
- CSP: 4-km resolution, satellite data from 1998 – 2017, NSRDB annual average direct normal irradiation; performance modeled with the System Advisor Model for 2 axis tracking system
- Wind: 2-km resolution wind speed at 100m hub height modeled for 2007 – 2013, WIND Toolkit (https://www.nrel.gov/grid/wind-toolkit.html); performance modeled with the System Advisor Model for wind turbines selected based on annual average wind speed

Annual average commercial electricity cost extracted from ABB Energy Velocity Suite and EIA State Electricity data tables

Other variables have static values, independent of location.

Cost Assumptions for Each Technology Configuration

Case	$C_{unit\ gen}$ ($/kW)	$C_{unit\ storage}$ ($/kWh)	$C_{unit\ seasonal\ storage}$ ($/kWh, thermal)	$C_{O\&M\ gen}$ ($/kW/year)	$C_{O\&M\ storage}$ ($/kWh/year)
PV +0-hour battery	$ 1,783.00	$ 380.00	$ -	$ 22.00	$ 36.32
PV +4-hour battery	$ 1,783.00	$ 380.00	$ -	$ 22.00	$ 36.32
PV +12-hour battery	$ 1,783.00	$ 380.00	$ -	$ 22.00	$ 36.32
CSP + 0-hour TES	$ 3,486.00	$ 422.22	$ -	$ 38.89	$ 4.71
CSP + 4-hour TES	$ 3,486.00	$ 422.22	$ -	$ 38.89	$ 4.71
CSP + 12-hour TES	$ 3,486.00	$ 422.22	$ -	$ 38.89	$ 4.71
Wind +0-our battery	$ 1,624.00	$ 380.00	$ -	$ 41.00	$ 36.32
Wind +4-our battery	$ 1,624.00	$ 380.00	$ -	$ 41.00	$ 36.32
Wind +12-hour battery	$ 1,624.00	$ 380.00	$ -	$ 41.00	$ 36.32
Reciprocating CHP	$ 2,200.00	$ 48.00	$ 1.50	$ 83.00	$ -
Reciprocating CHP w/seasonal storage	$ 2,200.00	$ 48.00	$ 1.50	$ 83.00	$ -
Combustion turbine CHP	$ 3,400.00	$ 48.00	$ 1.50	$ 54.00	$ -
Combustion turbine CHP w/seasonal storage	$ 3,400.00	$ 48.00	$ 1.50	$ 54.00	$ -
SWH diurnal storage	$ 1,570.00	$ 48.00	$ -	$ 16.67	$ 0.29
SWH seasonal storage	$ 1,570.00	$ 48.00	$ 1.50	$ 16.67	$ 0.29

Map Algebra Example

LCOE PV with 0 hours storage =

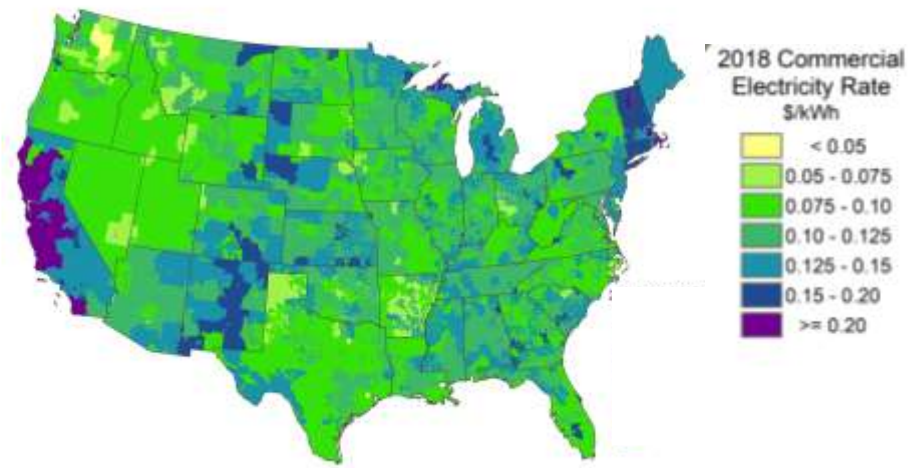
(1783 $/kW)/(22.1 years) + (22 $/kW-yr)

kWh/kW

=

LCOE ($/kWh)

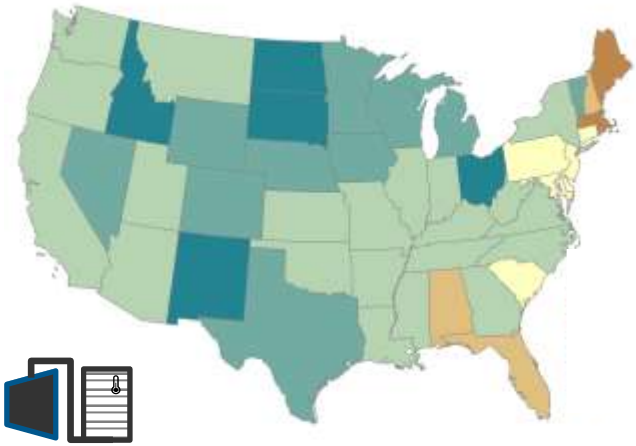
Conventional electricity:



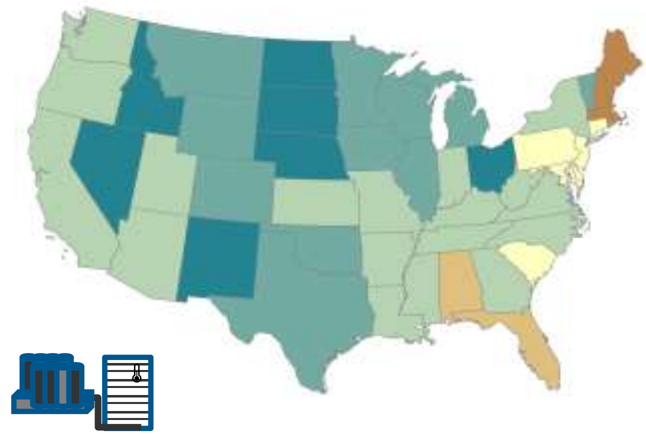
Electricity rates are highest in California and the northeast, but also in other places such as New Mexico, and they are lowest in the northwest.

Natural gas:

Natural gas rates are highest in the northeast, and they are lowest in the Dakotas, New Mexico, and Ohio.

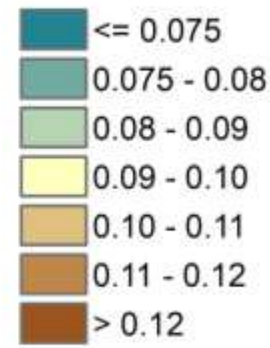


CHP with combustion turbine



CHP with reciprocating engine

LCOE $/kWh

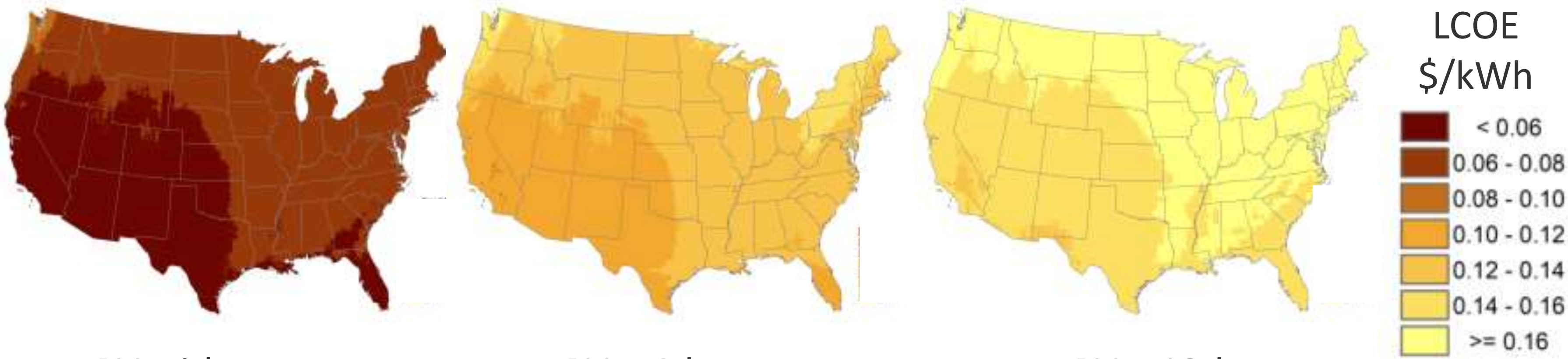


CHP combustion turbine with seasonal storage

CHP reciprocating engine with seasonal storage

CHP is most cost-effective where electricity rates are high and gas rates are low (spark spread), such as in the Dakotas and in Ohio but also in New Mexico.

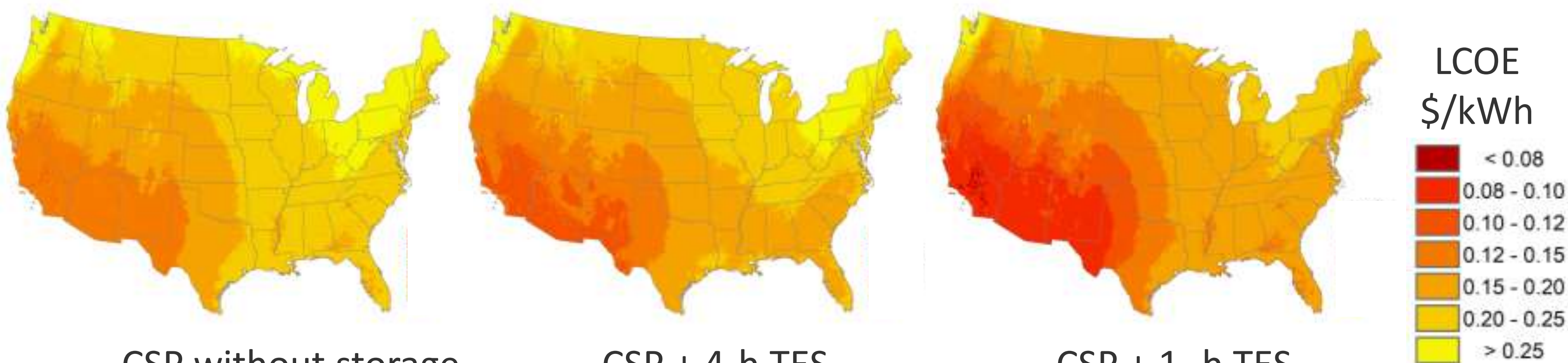
Photovoltaics



PV without storage PV + 4-h storage PV + 12-h storage

PV uses both direct and diffuse solar radiation, so the LCOE is rather uniform across the country, though it is approximately $0.02/kWh less in the sunny southwest and approximately $0.02 higher than average in the cloudier northeast and northwest.

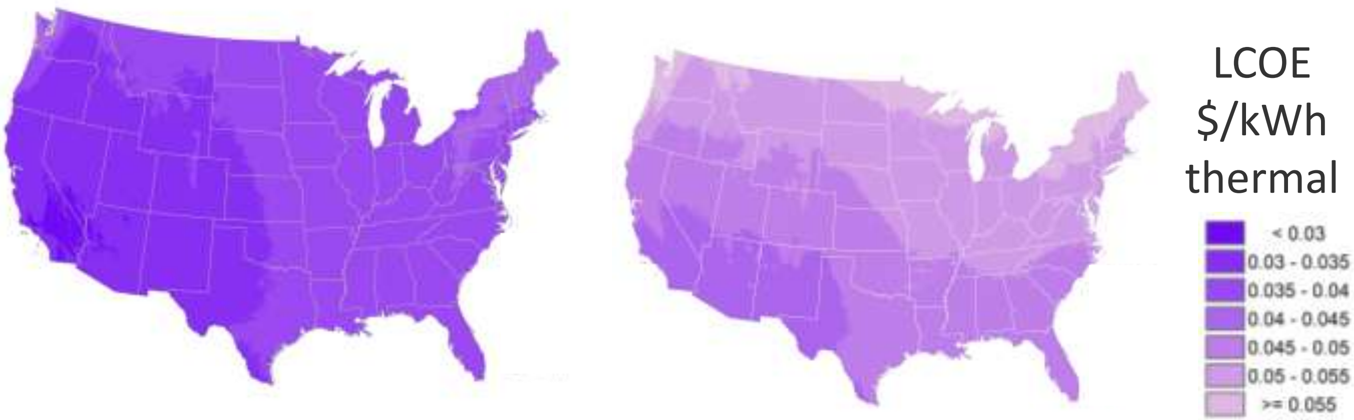
Concentrating Solar Power



CSP without storage   CSP + 4-h TES   CSP + 1- h TES

CSP can focus only direct solar radiation, so the LCOE is lowest in the desert of south-central California and in the southwest, where skies are clear and the humidity is low. The LCOE is much higher in the northeast and northwest, where solar radiation is less intense and more scattered (diffuse) because of clouds.

Solar Water Heating



SWH with diurnal storage   SWH with seasonal storage

SWH systems use both direct and diffuse solar radiation, so the LCOE is rather uniform across the country; it is best in the sunny southwest, but is viable in all parts of the country.

Wind Energy

Wind without storage Wind + 4-h storage Wind + 12-h storage

Wind power is most cost-effective in the Great Plains states of North Dakota and South Dakota, Nebraska, Kansas, Oklahoma, and Texas. In general, the Rocky Mountains and Sierras present a barrier to winds, although these high-resolution data show that winds are concentrated in mountain passes, such as in southern Wyoming and several spots in California, such as Tehachapi Pass and San Gorgonio Pass, which were early locations of wind energy development.

Thank you!

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