A Review of Renewable Sources of Electricity Derived from Natural Energy Flows

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1. Introduction

Amongst the sources of *renewable energy* are those driven by *natural energy flows* including solar radiation (solar energy and its derivatives), geothermal heat (from the interior of the earth), and gravitational energy (mainly from the moon) [1], in order of annual flow capacity:

- Solar
- Ocean
- Wind
- Geothermal
- Hydro

None of the above sources rely on the combustion of organic materials, and none are exhaustible on a human time scale. Thus they offer the potential to contribute to an ideal sustainable, carbon-free energy future.

Prospects for utilization of these sources for electricity generation depend on various interrelated *technical, economic*, and *social* factors. *Technical* factors include resource availability, characteristics of conversion technology, compatibility with the electrical grid, and life cycle energy gain. *Economic* factors include the inherent cost of deployment along with subsidies or penalties imposed by governmental institutions. *Social* factors encompass a range of human and environmental considerations.

In this review we address primarily the technical factors, but economic and environmental factors are mentioned. Our objective is to assess feasibility and risks in the context of plans for a major expansion of the role of renewables in the energy portfolio of the 21st century.

We provide a brief review of renewable sources, their energy capture and conversion systems, and a comparative summary of key metrics. We discuss the benefits and challenges including issues related to integration into the power grid.

We then consider plans for future expansion of renewables in the US as envisioned in a study by the National Renewable Energy Laboratory (NREL) along with scenarios developed under the auspices of the Intergovernmental Panel on Climate Change (IPCC) covering the global supply of electricity, indentifying risks that could impede the plans.

2. Review of renewable sources

2.1. Solar Energy

Solar energy is generated by nuclear fusion reactions in the sun. Incoming solar radiation (*irradiance*) is described by the *solar constant*, ~ 1.36kW/m^2, corresponding to the energy flux at all wavelengths incident on a unit plane perpendicular to the sun's rays at a distance of 1 astronomical unit (AU), the mean distance from the sun to the earth. Under ideal atmospheric conditions the peak irradiance at the surface of the earth on the equator is ~ 1kW/m^2, around 75% of the solar constant. The global mean irradiance is somewhat less, based on earth's planetary albedo of 30 ~ 35%. Seasonal variations in daily mean irradiance vary from 25 percent at locations close to the equator 100% at the poles, owing to the ellipticity of earth's orbit and the tilt of its axis. The global range of *solar potential* per m^2 of fixed, optimally inclined surface area roughly spans a factor of ~ 3.

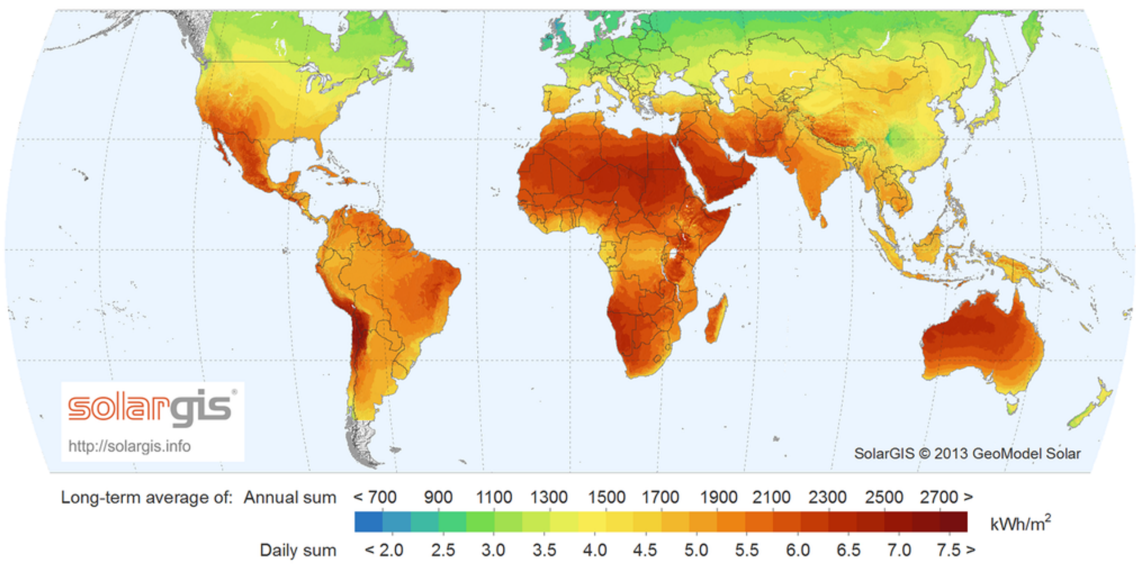

Figure 1 – Global solar potential

Electricity production from solar energy can be divided in two categories, namely Concentrated Solar Power (CSP) and Photovoltaic (PV), each of which contribute to the total potential solar energy resource. Although CSP and PV systems could be deployed offshore, the technical potential is typically based on the assumption of land-based systems only.

At any given site, solar irradiance is subject to variation on several time scales, including random minute-by-minute variation due to cloudiness, diurnal cycles, seasonal cycles, and inter-annual differences. Unless mitigated by energy storage, variations in solar irradiance directly influence the electric power output and determine the overall *capacity* *factor*[1]. Solar energy sources provide power on an intermittent basis, and are not characterized as *dispatchable*[2].

For any CSP or PV system, the return on investment, in terms of money invested and energy invested, depends on mean irradiance at the site where the system is installed. Thus the extent to which these systems are ultimately deployed will be determined by the availability and viability of sites that result in a higher return in investment than competing electricity sources, after consideration of the costs to transmit power from those sites to consumers. Viability of sites with sufficiently high irradiance will be determined based on competition with other land uses, terrain, and remoteness.

2.1.1. Concentrated Solar Power (CSP)

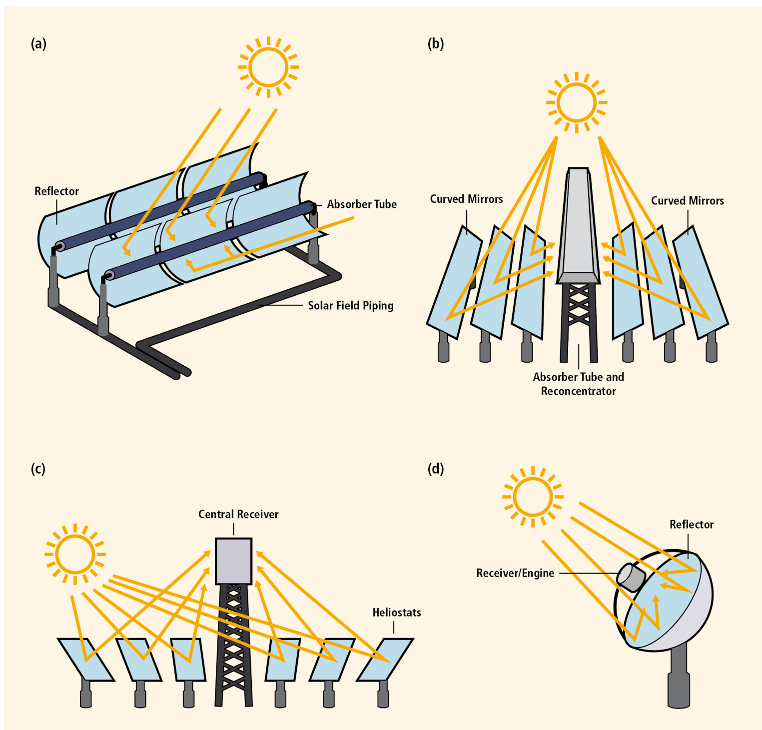

Figure 2 - Schematic diagrams showing the underlying principles of four basic CSP configurations: (a) parabolic trough, (b) linear Fresnel reflector, (c) central receiver/power tower, and (d) dish systems

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[1] Ideally a power generating facility that produces electricity would operate continuously, 24 hour per day and 365 days per year, at its full (nameplate rated) power output capacity. However, owing to variability of the input power source (e.g. solar or wind power) and/or other factors (need for maintenance) any power generating facility will fall short of this goal. The net capacity factor of a power plant is defined as the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity continuously over the same period of time. http://www.nrc.gov/reading-rm/basic-ref/glossary/capacity-factor-net.html

[2] Dispatchable generation refers to sources of electricity that can be dispatched at the request of power grid operators; that is, generating plants that can be turned on or off, or can adjust their power output on demand. https://en.wikipedia.org/wiki/Dispatchable_generation

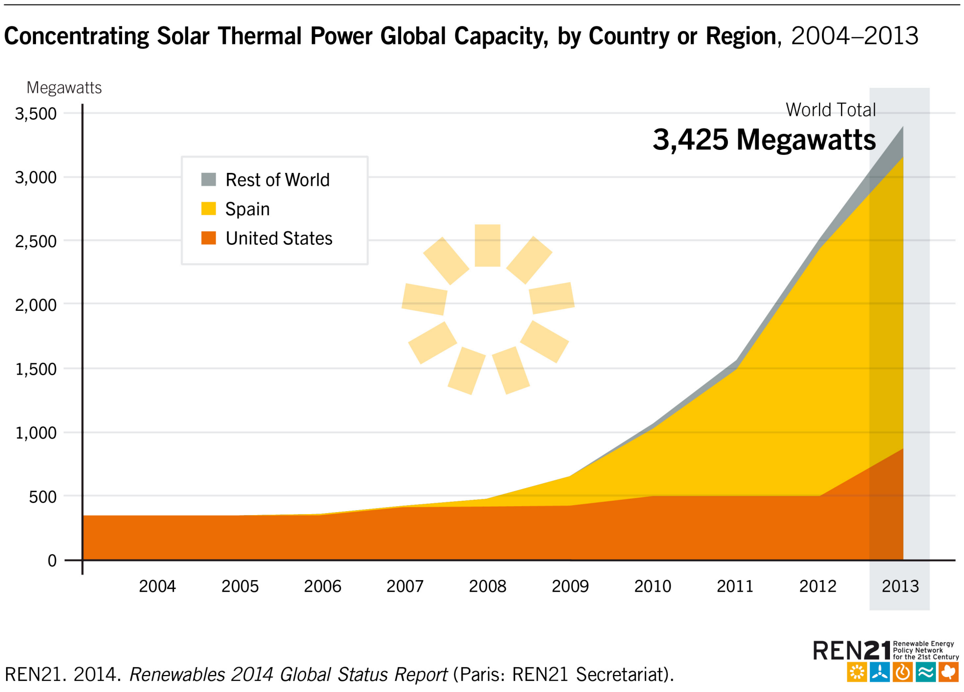

Figure 3 – Global Growth of CSP Capacity

As depicted in Figure 2, CSP electricity generation relies on optical concentration of direct solar energy to heat fluids to drive heat engines and electrical generators. To maximize efficiency, these systems rely on mirrors that are parabolic and/or actively controlled to track the angle of the incoming rays of the sun. Net conversion efficiency of commercially demonstrated CSP plants is 15 ~ 20% with capacity factor ~ 20% [4]. Capacity factor can be increased by adding thermal storage.

CSP technology has experienced rapid growth in the past five years (Figure 3) and has reached commercial readiness as evidenced by large facilities now in operation in the US, Spain, and the Middle East.

Figure 4 – "Ivanpah", worlds largest CSP facility, 392MW (2014), located in Mojave Desert, California, USA

Figure 5 – "PS10", 11MW (2004), located in Seville, Spain

Figure 6 – "Solnova", 250MW (2014), Seville, Spain

2.1.2. Photovoltaic (PV) Solar Power

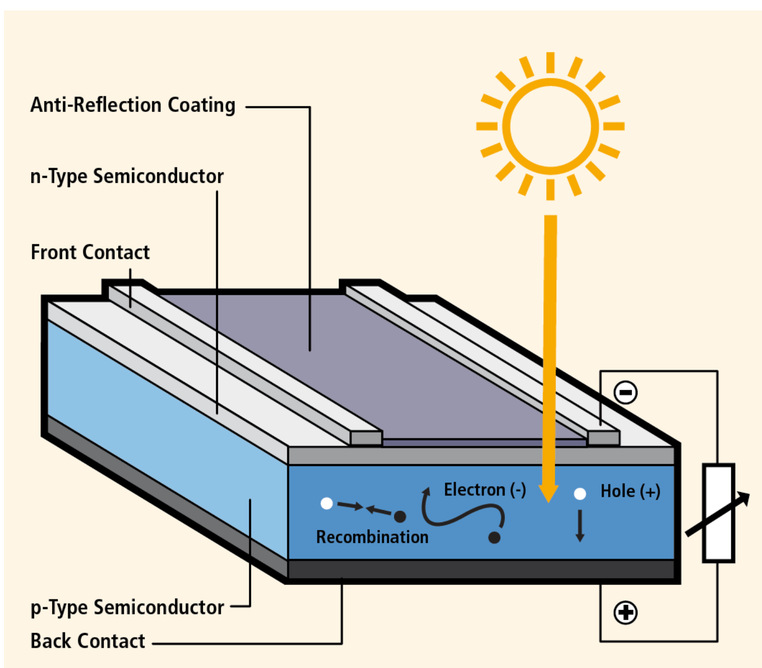

Figure 7 - Generic cross-section illustrating the operation of a solar cell

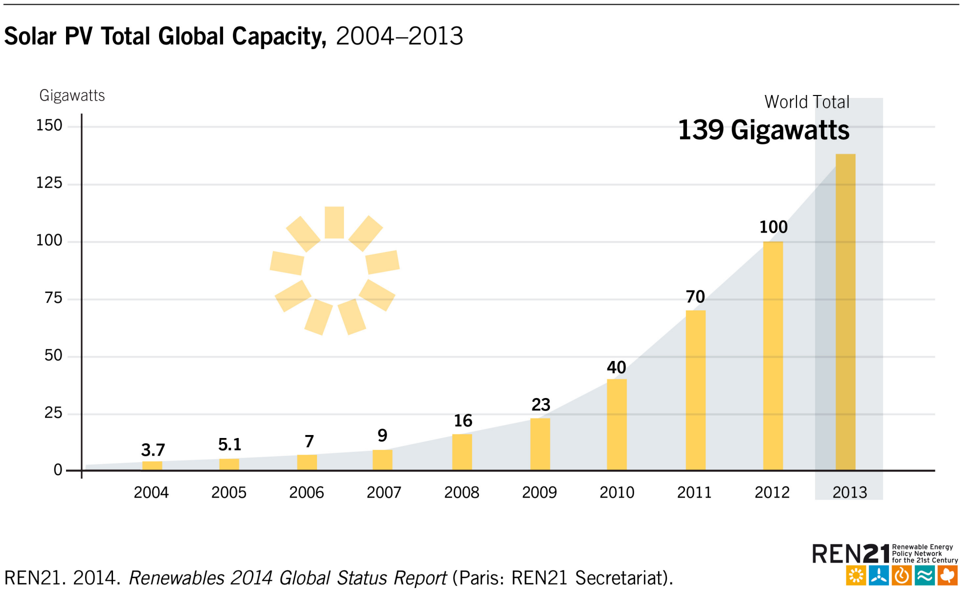

Figure 8 – Global Growth of PV Capacity

Photovoltaic (PV) solar power relies on the photovoltaic effect whereby light (photons), from both direct and diffuse solar radiation, shining on a semiconductor such as silicon generates electron-hole pairs resulting in an electric field that is available as a DC source to drive current through a load (

Figure 7). Most presently available commercial solar panels are based on silicon technology and exhibit efficiency, in terms of electrical energy produced divided by incident solar energy, in the range of 10 ~ 20% when new and clean. Conversion of DC output of PV sources to AC voltage for electrical utilization is accomplished using power electronic "inverters" which are typically ~ 98% efficient. Future technological advance is expected to raise the efficiency of the photovoltaic cells to some higher level, perhaps up to 40%, which would increase the overall system efficiency. PV systems range from small rooftop installations to large "utility-scale" systems. Capacity factor of existing PV installations in the US is 28% [4].

PV technology has experienced rapid growth in the past decade (Figure 8) and has reached commercial readiness as evidenced by large facilities now in operation, particularly in the US (primarily California). For example, the Topaz facility (Figure 9, Figure 10) in San Luis Obispo, CA, constructed between 2011 and 2014 utilizes 9 million CdTe photovoltaic modules spread over an area ~ 25 km^2, and has a peak rated power of 550MW. Topaz was the largest worldwide until the Solar Star project came on line in 2015 near Rosamond, California with a peak rated power of 579MW using 1.7 million solar panels, spread over ~13 km^2.

Figure 9 – PV Panels (total of 9 million) at "Topaz", 550MW (2014), San Luis Obispo County, CA, USA

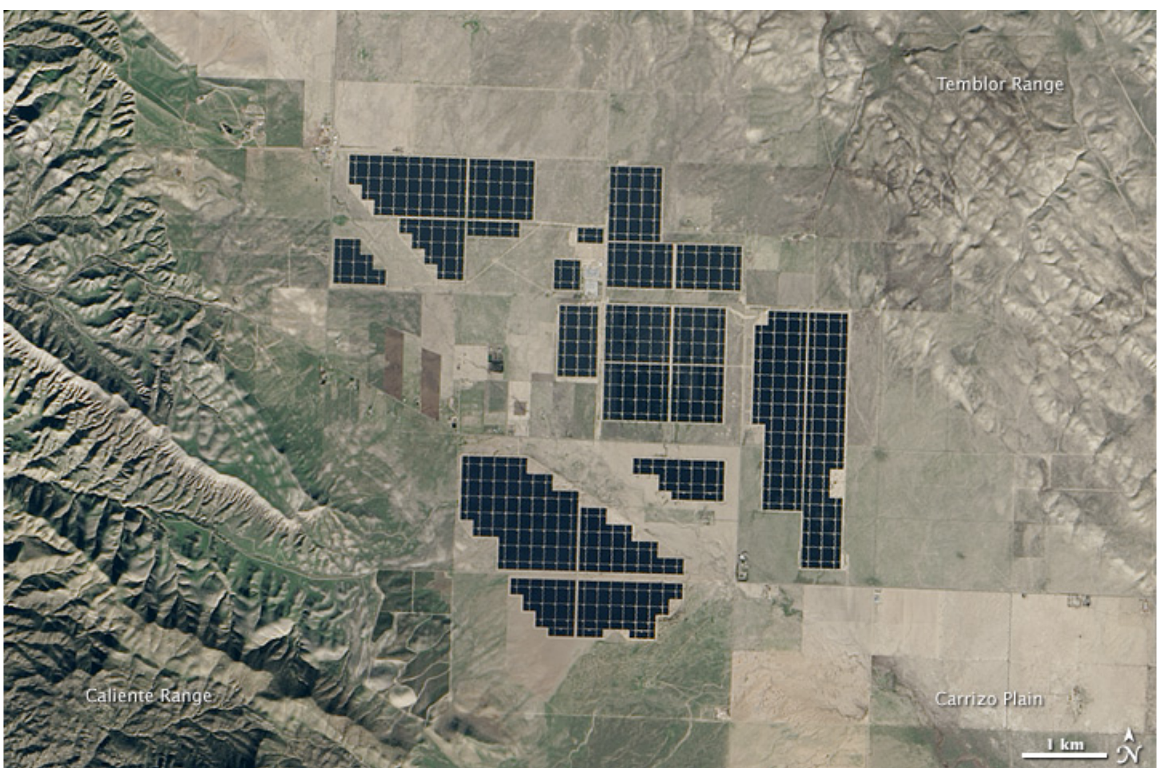

Figure 10 – Satellite View of Topaz facility (~ 25 km^2)

2.2. Ocean Energy

The oceans are the world's largest solar energy collector and energy storage system [1]. The total theoretical potential is derived from the incoming solar energy. Ocean energy can be harnessed using conversion technologies typically grouped into categories that exploit waves, tides, currents, thermal gradients, and salinity gradients [5]. Although the theoretical potential is large, ocean energy exploitation, other than tidal power (which is very limited in available sites, e.g. Shiwa Lake, Korea, 254MW and Rance, France, 240MW), remains in a nascent phase.

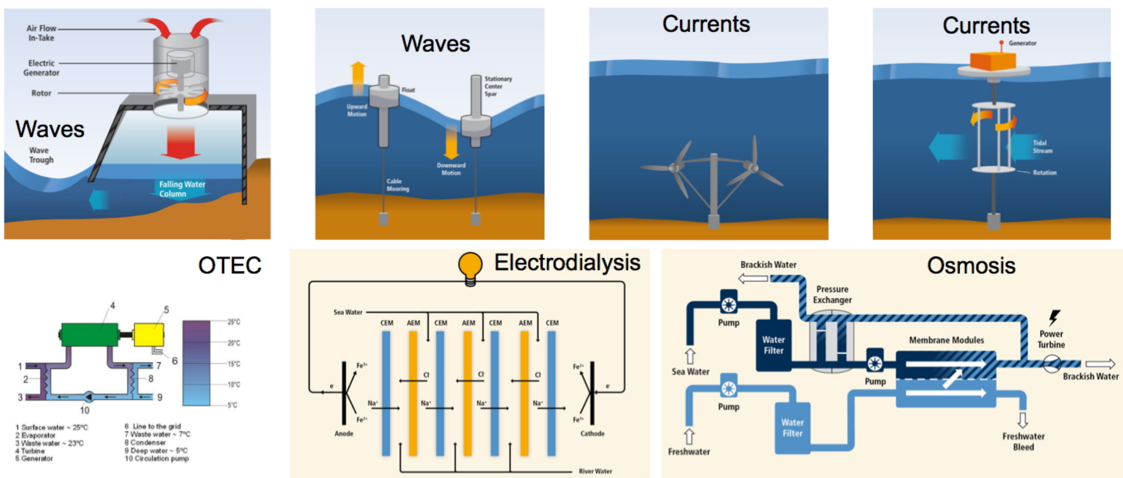

Figure 11 – Various Ocean Energy Conversion Technologies

The ocean energy technology with the greatest potential is Ocean Thermal Energy Conversion (OTEC). OTEC uses the ocean's warm surface water to vaporize a working fluid with a low-boiling point, such as ammonia. The vapor expands and spins a turbine coupled to a generator to produce electricity. The vapor is then cooled by seawater that has been pumped from a deeper ocean layer, where the temperature is about 5°C, condensing the working fluid back into a liquid. The efficiency of the cycle is strongly determined by the temperature differential and is viable primarily in equatorial areas where the year-round temperature differential is at least 20°C.

Considering that ocean energy is not generally anticipated to make a major contribution to global energy production in the 21st century we do not evaluate it further herein.

Figure 12 – Rance Tidal Power Station, 24 generators @ 10MW, total 240MW (1967), located in Brittany, France

2.3. Wind Energy

Winds develop when solar radiation reaches the Earth's surface unevenly, creating temperature, density, and pressure differences. Tropical regions have a net gain of heat due to solar radiation, while polar regions are subject to a net loss. This means that the Earth's atmosphere has to circulate to transport heat from the tropics towards the poles. The Earth's rotation further contributes to semi-permanent, planetary-scale circulation patterns in the atmosphere. Topographical features and local temperature gradients also alter wind energy distribution. While the total kinetic energy of the Earth's winds is enormous, the exploitable technical and economic potentials of wind energy depends on the availability of technology for conversion to electricity at ground, at sea and potentially at high altitudes [6].

The kinetic energy due to wind flow at velocity v is proportional to v^3. According to the Betz Limit, the maximum power extraction by a wind turbine is 59% of the total power available in the wind flow through the area swept by the turbine blades. In practice efficiencies of ~ 50% are realized.

Wind Power Density (WPD) is used as a measure of mean annual power available per square meter of swept area, and is tabulated for different heights above ground, including the effect of wind velocity and air density. The National Renewable Energy Laboratory wind power classification scheme [9] establishes seven classes of wind power density at elevations of 30 m and 50 m and recommends that sites with mean velocity > 7 m/s (Class 4 or higher at 30 m or Class 3 or higher at 50 m) are viable.

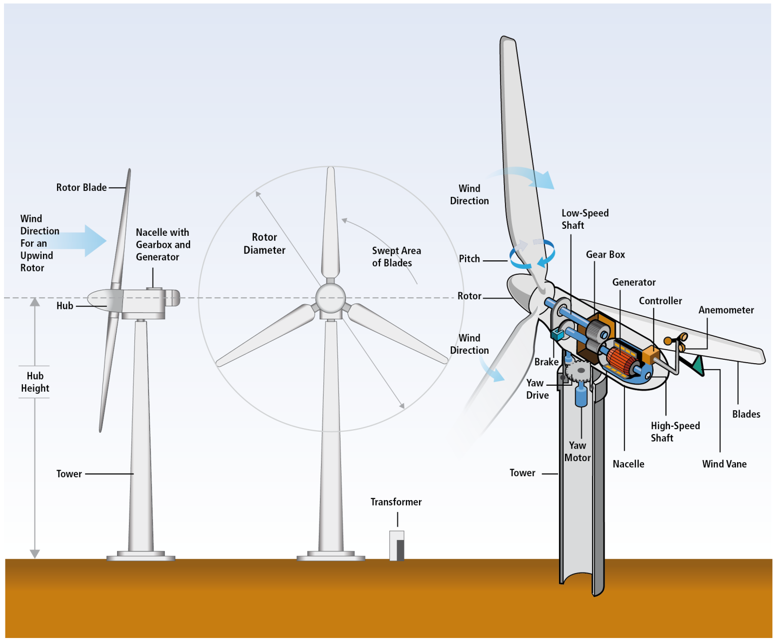

Figure 13 - Basic components of a modern, horizontal-axis wind turbine with a gearbox

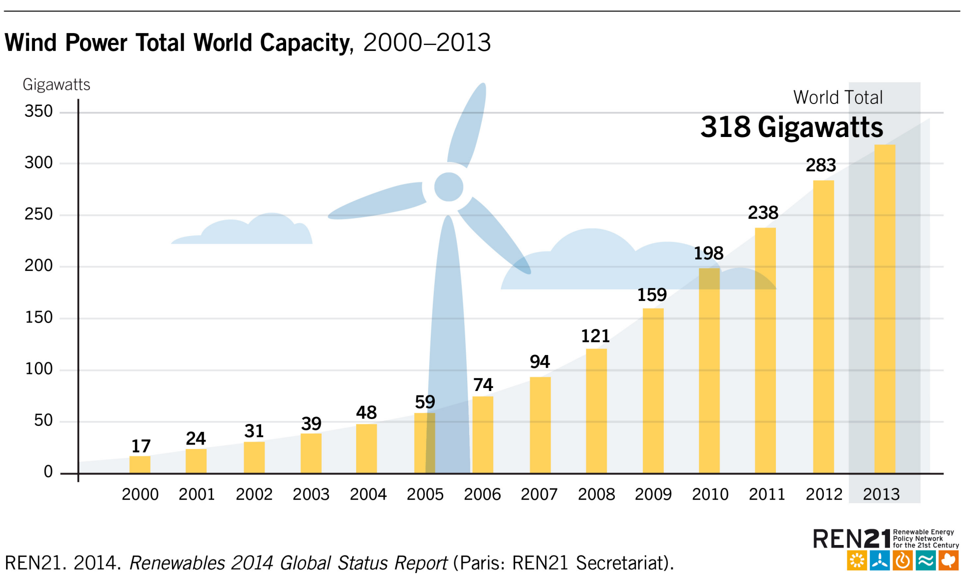

Figure 14 – Growth of Global Capacity of Wind Power

The world's most advanced wind turbines[3] have ratings ~ 8MW with hub height up to 135 m and blade diameter up to 160 m (Figure 13). Power output varies with wind speed, for example gradually increasing power over the range of 5-15 m/s and saturating at rated power at wind speeds > 15 m/s.

Wind speed fluctuates continuously, and as a result, the power from a wind turbine or plant is subject to variation [8]. Short-term variations result in fluctuations of average wind power from one hour to the next. Longer-term variations result lead to variations in daily, seasonal, and yearly wind energy production. Short-term wind speed changes with duration from several seconds to minutes, such as turbulence and gusts, will manifest as the ramping of turbine or plant output power in varying degrees. To some degree the short-term effects average out when the integrated power of multiple wind power sites is considered. Longer-term changes in the underlying wind conditions will result in inter-annual, seasonal, monthly, and diurnal variations of output energy.

Unless mitigated by energy storage, variations in wind speed directly influence the electric power output and reduce the overall capacity factor. Wind energy sources provide power on an intermittent basis, and are not considered dispatchable.

For wind energy, like solar energy, the return on investment, in terms of money invested and energy invested, depends on mean wind speed at the site (and elevation) where the system is installed. Thus the extent to which these systems are ultimately deployed will be determined by the availability and viability of sites that result in a higher return in investment than competing electricity sources, after consideration of the costs to transmit power from those sites to consumers. Viability of sites with sufficiently high mean wind speed will be determined based on competition with other land uses, terrain, and remoteness.

Wind energy has experienced rapid growth in the past decade and has reached commercial readiness (Figure 14). It is a technically and commercially mature technology as evidenced by large facilities now in operation worldwide, both on-shore (Figure 15) and near-shore (Figure 16), and a significant contribution already being made to global electricity production.

[3] ENERCON E-126 (http://www.enercon.de/en/products/ep-8/e-126/), VESTAS V164 wind turbine (http://www.mhivestasoffshore.com/v164-8-0-mw-breaks-world-record-for-wind-energy-production/)

Figure 15 – World's Largest Wind Farm – "Alta Wind Energy Center", 490 turbines, 1320 MW (2011), Tehachapi Pass, California, USA

Figure 16 – World's Largest Offshore Wind Farm – "London Array", 175 turbines, 630 MW (2011), Thames Estuary, UK

2.4. Geothermal Energy

Geothermal energy [2,10] is based on thermal energy from the earth's interior stored in rock, trapped steam, and liquid water, amounting to a heat content ~ 10^{13} EJ arising from a combination of residual heat from planetary accretion, heat produced through radioactive decay, and possibly other sources. Heat flows to the earth's surface at a rate of ~ 40TW (1,200 EJ/year) and is replenished at a rate of 860 EJ/year from radiogenic sources. Geothermal energy is considered sustainable because the heat source will not be exhausted on a human time scale, and while tapping the resource leads to localized depletion, the resultant gradient leads to replenishment.

Geothermal energy is extracted using wells that produce hot fluids from natural hydrothermal reservoirs (Figure 17) or by cold water injection and hot water recovery ("enhanced" or "engineered" geothermal systems, EGS, Figure 18). Electricity is generated by conventional steam-condensing turbines or with binary cycles where the geothermal fluid passes through a heat exchanger supplying a loop of another working fluid with a low boiling point, which vaporizes and drives a turbine.

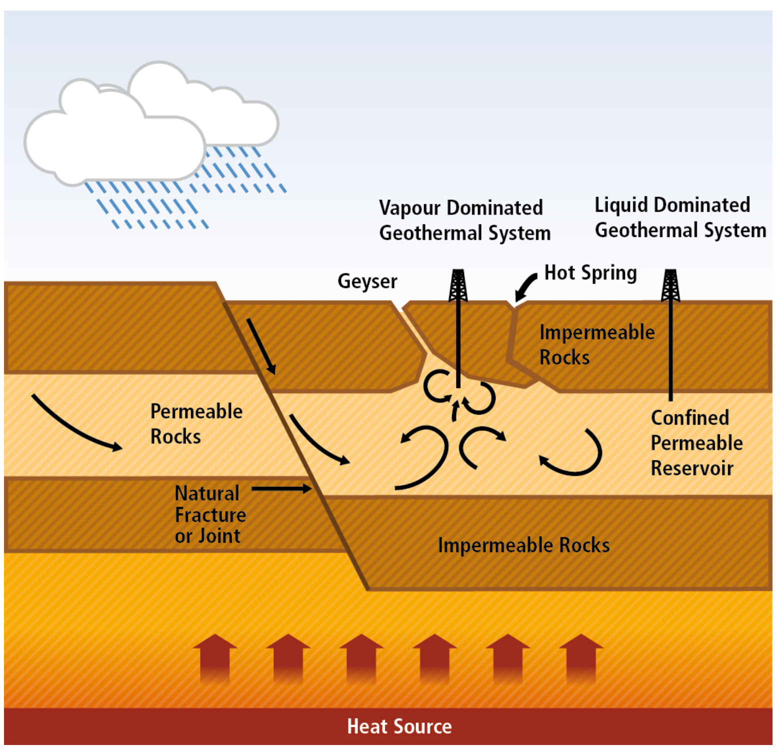

Figure 17 – Geothermal Extraction from Natural Hydrothermal Reservoirs

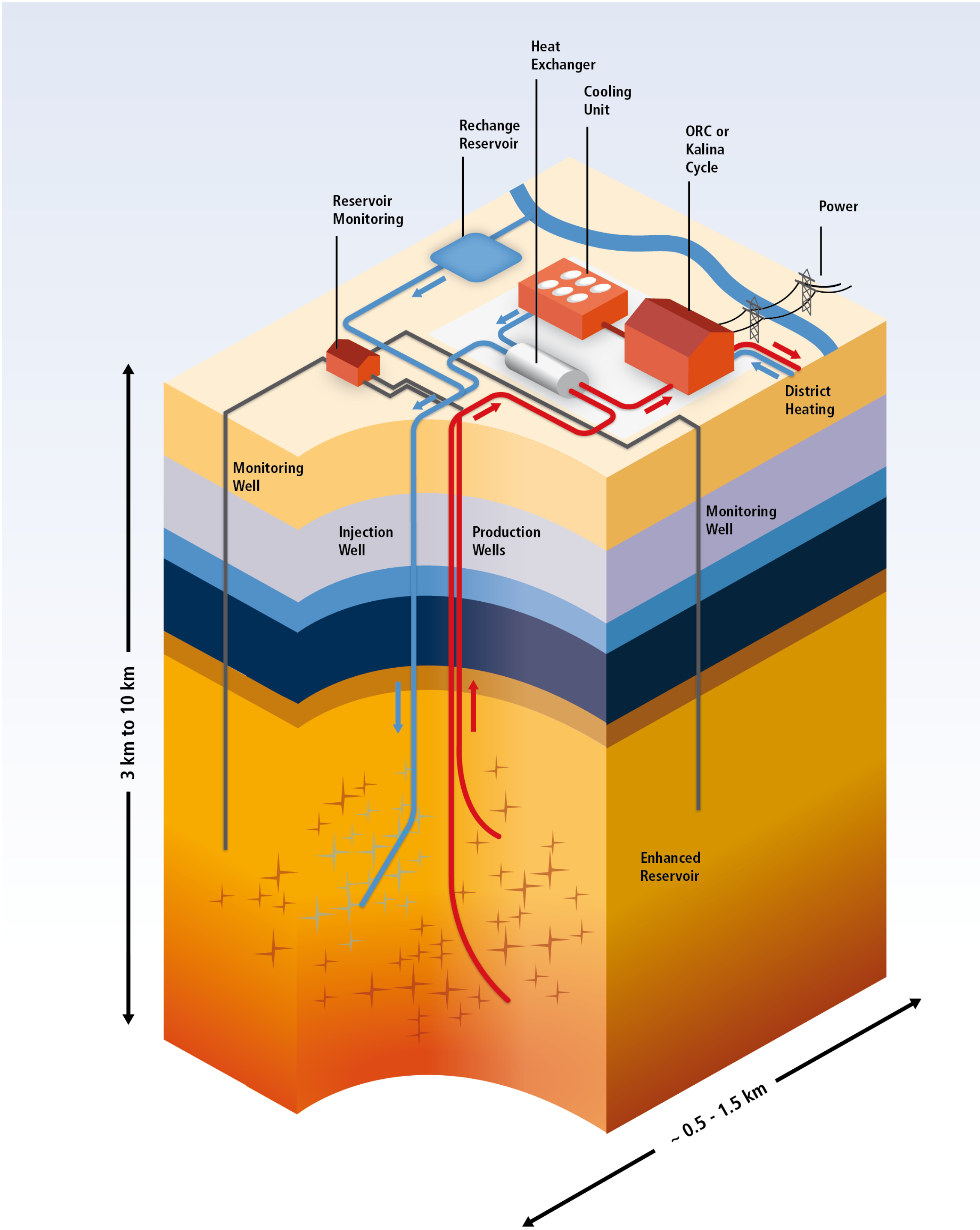

Figure 18 – EGS ("enhanced" or "engineered" geothermal system)

Geothermal wells are drilled to depths as great as 5 km using methods similar to oil and gas drilling, to exploit low temperature sources (70-150°C) that can supply binary conversion and higher temperature sources (>150°C) that are compatible with steam turbines. Due to the *geothermal gradient*, deeper drilling yields higher temperatures and greater accessible energy. However, geothermal resources are not evenly distributed, with the most accessible sources located near tectonic plate boundaries.

Due to the continuous nature of the geothermal energy source and the conventional turbine-generator conversion technology, geothermal power will have a high capacity factor, can be supplied on a continuous basis, and is considered dispatchable. Capacity factor of existing geothermal installations in the US is 69% [4].

The most attractive geothermal sites are those where a high temperature can be accessed relatively close to the surface, where wastewater can be conveniently discharged, and (for EGS) a supply of water is available for injection. Thus the extent to which geothermal energy is ultimately deployed will be determined by the availability and viability of sites that result in a higher return in investment than competing electricity sources, after consideration of the costs to transmit power from those sites to consumers.

Figure 19 – "Sonoma Calpine 3" at "The Geysers", the world's largest geothermal field, 22 geothermal power plants, 350 wells, 725MW, located in the Mayacamas Mountains, California, USA

Figure 20 – "Hellisheiði" Power Station, 50 wells, 7 generators, 300MW (2006), located in Hengill, Iceland

2.5. Hydroelectric energy

Hydroelectric power (*hydropower*) is generated from water moving through the hydrological cycle, driven by solar radiation. Power generated is proportional to flow x "head" (elevation drop). Two configurations are typically used, namely traditional *reservoir* (Figure 21) and *run-of-river* (Figure 22).

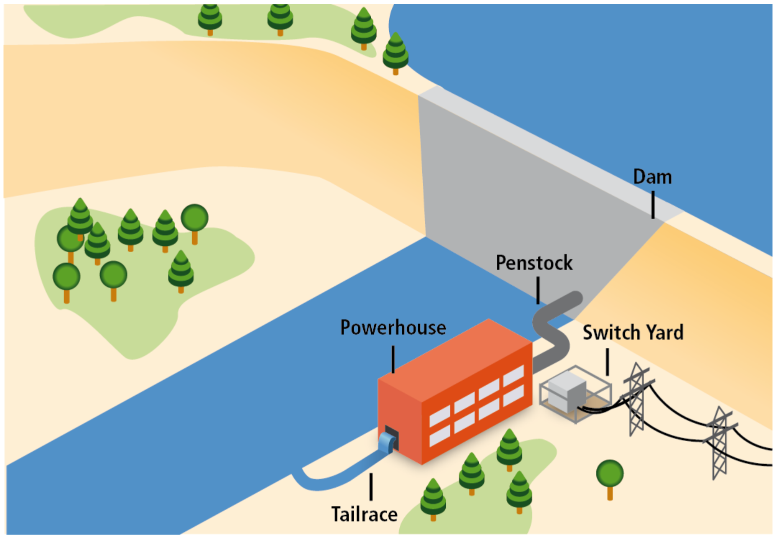

Figure 21 – Hydroelectric Power Plant (reservoir type)

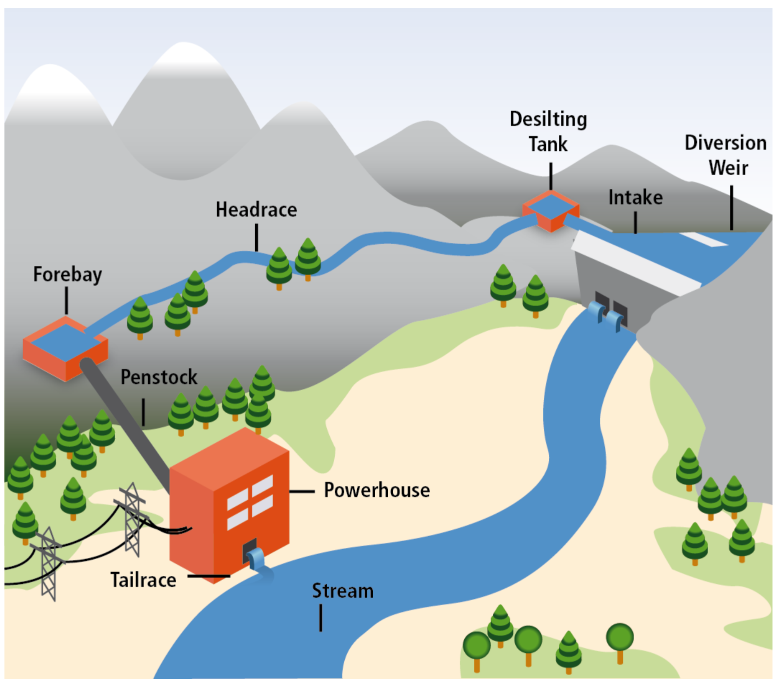

Figure 22 – Hydroelectric Power Plant (run-of-river type)

Hydropower is a mature (> 100 year old) technology with most of untapped potential residing in smaller run-of-river sites. The largest individual generator units have rated power ~ 800 MVA, with as many as 10 – 20 units installed at one facility.

Hydroelectric power is available as a continuous power source but plants are often operated intermittently below nameplate capacity to provide an energy storage function and to provide flood control. In fact *pumped storage*, based on hydropower technology, in use for many decades, is the most effective means of large scale energy storage in terms of power, energy, efficiency, and number of cycles.

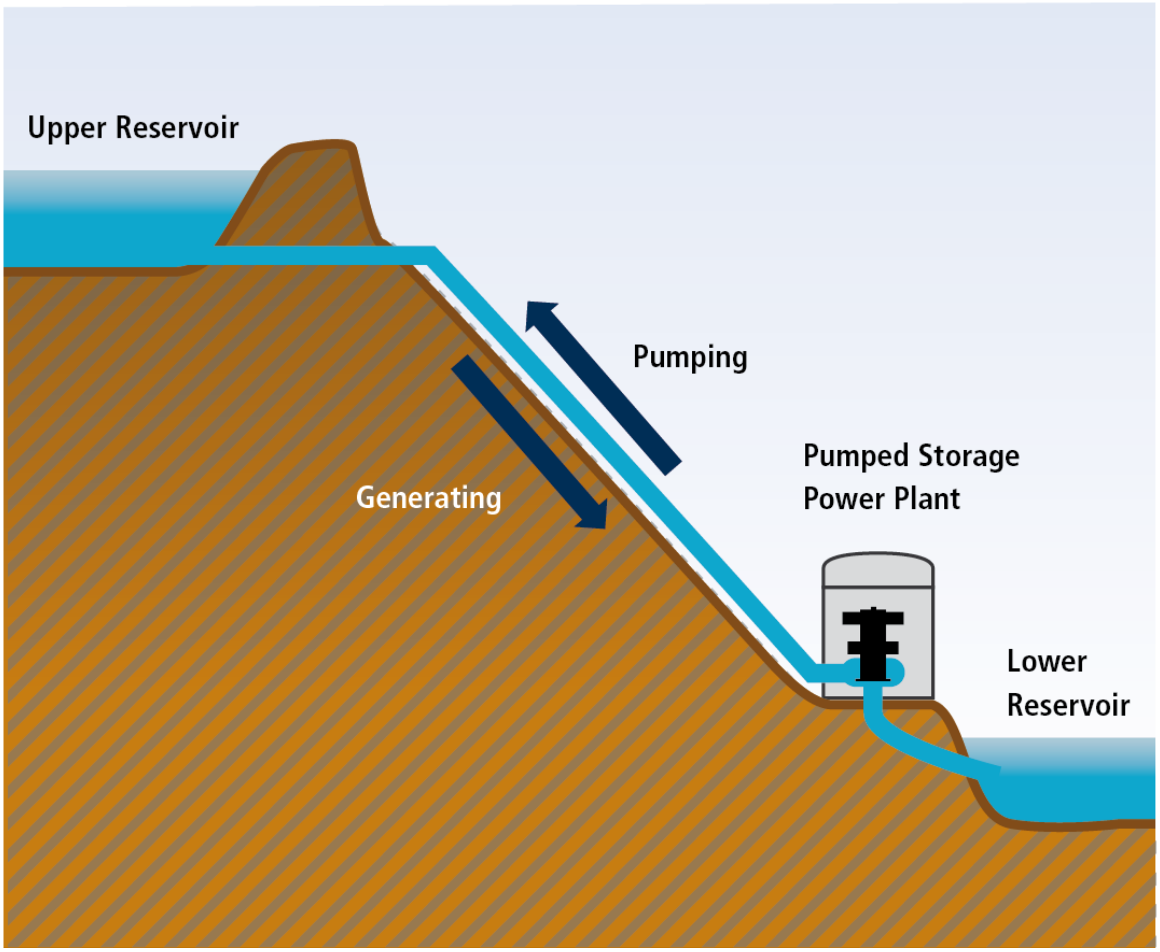

Figure 23 – Pumped Storage Concept Based on Hydroelectric Technology

Due to the continuous supply of hydrological energy, hydroelectric power has the potential for high capacity factor, can be supplied on a continuous basis, and is considered dispatchable. However, in practice, due to its use for energy storage and flood control, the capacity factor of existing hydropower installations in the US is only 38% [4].

Figure 24 – "Three Gorges", World's Largest Reservoir Hydroelectric Power Plant, 32 generators @ 700MW, total 22.5 GW (2012), Yangtze River, China

Figure 25 - "Chief Joseph Dam", World's Largest Run-of-River Hydroelectric Power Plant,

26 generators @ 100MW, total 2.6 GW (1979), Columbia River, Washington, USA

3. Comparison of Key Metrics

Comparison of key metrics is a difficult but important exercise in understanding the potential benefits, issues, and constraints of the various renewable sources. The difficulty arises because, across the database of available information:

- within each category there is a wide range of site conditions, technologies, and other aspects that become blurred in the process of averaging and generalization;
- studies performed do not always follow the same terminology and methodology;
- as technologies mature, their characteristics change, so at any given time a snapshot of existing data may be misleading, as a measurement of present performance, if it includes old data;
- use of existing data as a prediction of future performance does not account for technological improvement, or reduction in availability of prime sites, or other factors that may improve or diminish performance.

Despite the above shortcomings we have collected data from numerous sources over the range of renewable sources and have attempted to present an unbiased, apples-to-apples comparison. We have included data from nuclear fission power in order to contrast the differences between renewables and another option for carbon-free electricity generation.

3.1. List of metrics with definitions and references

Theoretical Potential (EJ/yr) [2]

Base resource potential "derived from natural and climatic parameters" that "represents the upper limit based on physical principles and current scientific knowledge", not accounting for conversion losses; less than the total global energy flow in some cases where constraints are imposed (e.g. solar energy over oceans not included, wind energy in upper atmosphere not included, etc.).

Technical Potential (EJ/yr) [2],[11-12]

Resource potential for electricity production "obtainable by full implementation of demonstrated technologies" without regard to cost but with various practical constraints imposed (in some studies subdivided into geographic potential that factors in land suitability, and technical potential that factors in conversion efficiency).

Economic Potential (EJ/yr) [11-12]

Resource potential obtainable with consideration of price at < 3, 5, 10, 15, 20, 30 cents/kW-h.

Resource Distribution (%)[11-12]

Fraction of the total resource potential available in N. America, W. Europe, E. Europe + Russia, Africa + Middle East, Asia, Latin America, Pacific.

Power Utilization (GW) [3],[13]

Installed peak power capacity worldwide as of 2014.

Capacity Factor (%) [4]

Capacity factor for utilization in the US based on annual average in 2014, assumed to be representative of the global capacity factor.

Energy Utilization (EJ/yr)

Estimate of present global energy delivery, calculated as product of *Power Utilization x Capacity Factor.*

Capital Cost ($/kW) [14]

Cost per unit of installed peak power in the US as of 2012. Note that additional costs would be incurred for wind and solar sources to the extent required for grid integration (energy storage and expanded transmission grid to connect remote sources to load centers).

Levelized Cost of Electricity (LCOE, $/kW-hr)

Calculated from *Capital Cost* along with *Capacity Factor,* 10% discount rate, and various other parameters. Again, note that additional costs would be incurred for wind and solar sources to the extent required for grid integration.

Output power density (W/m^2) [15-18]

Peak output power per unit area.

Output energy density (MJ/m^2-yr)

Calculated as product of *Output Power Density x Capacity Factor.*

Area Requirement for 1GWe-yr (km^2) [21]

Scaled from Output Power Density

Energy Return on Investment (EROI)[2],[19-21]

Ratio of input energy (primary thermal energy) to fabricate, install, operate, and decommission, divided by lifetime output energy (electrical energy).

Carbon emission (g CO_2eq/kWh)[22-23]

Total lifetime carbon emission.

Dispatchability

Sources that produce steady, controllable output that can be turned on or off at the request of grid operators are considered to be dispatchable, whereas intermittent sources are not.

3.2. Comparison

A comparison of the key metrics is given in Table 1. Note that, for ocean energy, only a total summary of resources is given, without subdivision into the numerous forms (waves, tides, currents, thermal gradients, and salinity gradients), each of which tends to have unique characteristics and none of which are expected to play a major role in the energy supply of the 21st century

Table 1 – Key Metrics

	SOLAR			**OCEAN**	**WIND**			**GEO-THERMAL**	**HYDRO**	**NUCLEAR**
	Solar: Overall	**Solar: CSP**	**Solar: PV**	**Ocean**	**Wind: Overall**	**Wind: On-Shore**	**Wind: Off-Shore**	**Geothermal**	**Hydro**	**Nuclear**
Theoretical Potential (EJ/yr)	3,831,139	-	-	7,400	6,000	-	-	1,400	147	-
Technical Potential (EJ/yr)	2,685	-	-	222	401	379	22	45	50	-
Economic Potential @ < 3c/kW-h (EJ/yr)	0	0	0	-	6	5	0	0	0	-
Economic Potential @ < 5c/kW-h (EJ/yr)	158	158	0	-	91	87	4	5	9	-
Economic Potential @ < 10c/kW-h (EJ/yr)	2,372	803	1,570	-	366	344	22	45	31	-
Economic Potential @ < 15c/kW-h (EJ/yr)	2,614	992	1,622	-	401	379	22	45	43	-
Economic Potential @ < 20c/kW-h (EJ/yr)	2,685	992	1,693	-	401	379	22	45	50	-
Economic Potential @ < 30c/kW-h (EJ/yr)	2,685	992	1,693	-	401	379	22	45	50	-
Distribution (% North America)	3.5%	-	-	20.7%	39.4%	-	-	11.1%	10.0%	-
Distribution (% W. Europe)	0.5%	-	-	6.1%	5.2%	-	-	4.4%	14.0%	-
Distribution (% E. Europe + Russia)	5.4%	-	-	8.2%	17.7%	-	-	13.3%	10.0%	-
Distribution (% Africa + Middle East)	57.4%	-	-	5.8%	8.5%	-	-	11.1%	16.0%	-
Distribution (% Asia)	10.3%	-	-	31.3%	3.2%	-	-	26.7%	28.0%	-
Distribution (% Latin America)	7.1%	-	-	9.7%	11.2%	-	-	24.4%	20.0%	-
Distribution (% Pacific)	15.9%	-	-	15.5%	15.0%	-	-	8.9%	2.0%	-
Power Utilization (GW)	142	3	139	-	318	-	-	12	1,310	372
Capacity Factor (%)	22%	20%	24%	-	34%	34%	34%	69%	38%	92%
Energy Utilization (EJ/yr)	1.1	0.0	1.1	-	3.4	-	-	0.3	15.5	10.7
Capital Cost ($/kW)	$4,470	$5,067	$3,873	-	$4,222	$2,213	$6,230	$6,243	$2,936	$5,530
Levelized Cost of Electricty ($/kW-hr)	$0.28	$0.37	$0.19	-	$0.18	$0.10	$0.26	$0.13	$0.09	$0.09
Output power density (W/m2)	28	25	31	-	3	-	-	19	12	404
Output energy density (MJ/m2-yr)	196	152	241	-	31	-	-	422	143	11696
Area Requirement for 1GWe-yr (km2)	169	208	131	-	1018	-	-	75	221	3
EROI	8	6	10	-	23	-	-	8	143	9
Carbon emission (g CO_2 eq/kWh)	40	29	50	-	13	13	12	39	20	18
Dispatchability (1 = Dispatchable)	0	0	0	-	0	0	0	1	1	1

Some key points are as follows.

- Compared to the present world annual electricity consumption of 73 EJ/yr, and the projected consumption of ~ 375 EJ/yr in 2100:

    - the technical potential of solar (2685 EJ/yr) is enormous;
    - the technical potential of wind and ocean, individually, are of the same order as the total global consumption in 2100;
    - technical potential of geothermal and hydro are each of the same order as the present level of total global consumption.

- Energy density of solar and wind are relatively low. Land area requirements to supply total global electricity of 375EJ/yr in 2100 using solar would be ~ 180 Mha, and using wind would be ~ 1200 Mha. For comparison, the land area of the contiguous US is 925 Mha.

- Distribution of resources is quite uneven with, most notably, Africa and the Middle East the largest for solar, and North America the largest for wind.

- Present utilization of technical potential is a small fraction of total available, with the exception of hydro, which presently utilizes ~ 1/3 of its potential.

- Amongst the non-traditional sources (solar, ocean, wind, geothermal) only wind is economically competitive, in terms of LCOE, with the traditional sources (hydro, nuclear) at the present time. In this assessment, additional costs due to grid integration (energy storage, expanded transmission grid, etc.) that are necessary for the intermittent, geographically dependant sources, are not included.

- The capacity factor of the intermitted non-dispatchable sources (wind and solar) is much lower than the traditional dispatchable sources (hydro, nuclear).

- Energy return on investment is similar for all of the sources except for hydro which is ~ 10x higher than the others.

- Since wind and solar are rapidly evolving we anticipate the following future trends:

    - Capacity factor may begin to decrease as the availability of prime sites (high irradiance, high mean wind speed) begins to decrease;
    - Efficiency, EROI, and cost per unit of installed power of solar should decrease with technological advancements (but not so much for wind which is a relatively mature technology).

4. Benefits and challenges

4.1. Benefits

Benefits of the renewable sources of electricity generation include the following.

- Lifetime CO_2 emission for a renewable electricity source is typically less than 5% of fossil fuel sources for the same energy output, based on energy input during fabrication and construction using today's industrial infrastructure. The emission per unit of energy output will tend to decrease further in the future as industrial infrastructure (that supplies energy during fabrication and implementation) transitions to a higher fraction of renewable sources.

- General environmental pollution from renewable electricity sources is less than traditional fossil fuel sources since ash, smog, acid rain, sludge, waste heat, and other products of combustion are avoided.

- Use of water is reduced compared to traditional fossil and nuclear fission powerplants that use water to dissipate heat in the condensers of steam turbine generators.

- Issues related to nuclear fission such as weapons proliferation, waste disposal, and accidents are avoided.

- Sources of renewable energy and its conversion to electricity are easy to understand and have widespread public acceptance.

- Renewable sources are inexhaustible on a human time scale.

4.2. Challenges

Challenges of the renewable sources of electricity generation include the following.

- The low power density, low capacity factor, and hence low energy density of the sources creates several challenges:

    - High relative cost due to large total mass of components used to convert energy, along with extensive network required to convert, collect and concentrate and transmit electric power, all operating at a low duty factor;

    - Large land area requirements, typically 50x (solar) to 350x (wind) compared to traditional sources per unit of energy generated.

- The intermittent nature of the sources complicates the operation of the electrical grid and creates the need for large-scale electrical energy storage.

- The geographic dependence of the sources limits their convenient deployment and creates the need for expansion of the electric grid to connect to load consumers not located near the sources.

- Renewable sources tend to disrupt the local ecology where they are deployed (e.g. blocking sunlight from reaching the ground, creating a hazard for birds, impeding the migration of fish, etc.)

5. Technical issues

5.1. Technical feasibility

The basic technical feasibility of the renewable energy sources and their conversion to electricity is not in question since:

- All of the sources offer technical potential that exceeds or approaches the entire world's present electricity consumption;

- A wide range of energy conversion technologies have been demonstrated on a large scale (with the exception of some of the ocean energy technologies)

    - Basic functionality and (perhaps to a lesser degree) reliability and maintainability;
    - Production of more energy than was input to construct, operate, maintain, and decommission (EROI).

5.2. Grid integration

Grid integration refers to the incorporation of renewable electricity sources, in some fractional amount, into the electric power grid along with other traditional sources of electricity. To do so successfully requires that the grid be able to supply the load as it varies throughout the day, season and year, and to maintain power flow and stability during unplanned outages of generators and/or transmission lines.

Traditional power sources have facilitated the successful operation of the grid for over a century owing to their dispatchable characteristics. Grid operators are able to schedule the delivery of a specified amount of power well in advance with a high probability that power will be delivered as specified, on schedule. In addition they are able to maintain specified power reserves as contingency for unplanned outages of generation and transmission facilities that can be called upon when needed to stabilize the grid.

Because of the inherent variability of their output on multiple time scales, the primary new renewable technologies (solar and wind) are not dispatchable and present a major operational challenge.

The higher the fraction of integration of renewables, the more complex the problem becomes. Worldwide, the integration of new renewables is at a very low fraction, with wind at ~ 3% and solar ~ 1% [3]. The highest levels of integration have taken place in European countries (e.g. Denmark wind ~ 40%), but these figures are misleading because they are based on the individual countries base consumption, not the full capacity of the European grid into which the sources have been integrated. In the US, renewable energy contributed about 10% of total electricity in 2010 (6.4% from hydropower, 2.4% from wind energy, 0.7% from biopower, 0.4% from geothermal energy, and 0.05% from solar energy), but ambitions exist for a much higher level ~ 80% that is presently under study [24].

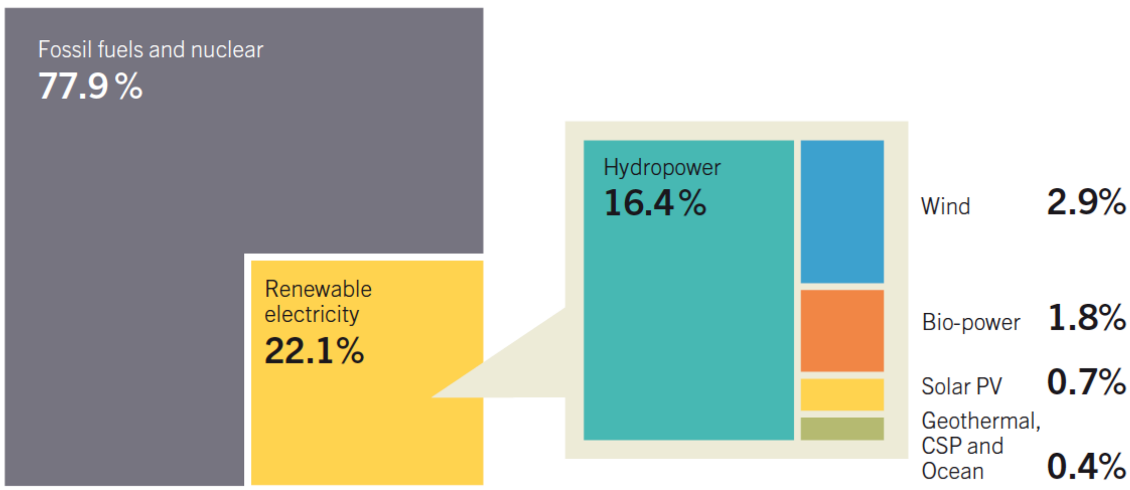

Figure 26 – Global Sources of Electricity Production in 2014

Grid integration of intermittent renewables can be facilitated by two measures, namely energy storage and enhanced control (control of distributed resources, demand side management, etc.) via a "smart grid". To the extent that electrical energy can be placed in, or withdrawn from, storage, the use of storage in conjunction with an intermittent renewable leads to dispatchable conditions. To the extent that demand side management can be used to shift the time of day of electrical loads, or to constrain electrical loads, the issue of intermittency is lessened. We consider the time shifting of loads in a manner consistent with load consumers needs to be an acceptable mode, but the constraint of loads such that consumers' demand is not met to be an unacceptable mode.

Ideally, the temporal pattern of power available from an intermittent renewable source would match the pattern of demand. This is actually the case for air conditioning loads which tend to coincide with the pattern of solar irradiance and do in fact comprise a large fraction of electricity demand in some regions. It may also facilitate the expanded use of electric vehicles considering the scenario where commuters partially discharge their batteries on the way to work, charge their batteries during peak irradiance while at work, and partially discharge then on the way home.

Depending on the relative location of geographically dependent renewable sources, and regions of electrical load consumption, integration may require an expansion of the system of transmission lines in order to deliver the power where it is needed. The value of transmission line expansion tends to be lessened by the fact that the low capacity factor of intermittent renewables implies a low duty factor on the transmission and substation components.

The use of energy storage and the expansion of the grid to account for the intermittency and geographic dependence of renewables both tend to diminish the EROI and increase the cost.

In developing nations where existing grids are weak, the ability to integrate large amounts of new intermittent sources is limited. If most growth in global electricity consumption will occur in developing nations as their citizens adopt the life style of developed nations then the feasibility of supplying this increased demand using intermittent sources is questionable. This could in theory be mitigated with energy storage but the added cost, on top of the already high cost of renewable sources, would not be affordable to developing nations.

5.2.1. Dispatchability

Dispatchable generation refers to sources of electricity that can be dispatched at the request of power grid operators; that is, generating plants that can be turned on or off, or can adjust their power output on demand. Dispatchability is actually a multifaceted attribute that involves:

- Availability
- Predictability
- Set-point accuracy
- Range of adjustment
- Time response

Availability refers to the readiness of a power source to provide power when called upon, ideally 24 hours per day, 7 days per week. This attribute is important to grid operators so that they can reserve a power source as a contingency to overcome unplanned outages of generators and/or transmission lines.

Predictability refers to the likelihood that a given amount of power will be available from a power source when called upon some time in the future (hours, days ahead). Predictability is important to grid operators so that they can schedule the future use of a power source in the near term (hours, days ahead), to meet demand in a planned and optimal way.

Set-point accuracy refers to ability of a power source to generate a constant set-point power output when called upon. Set-point accuracy is important to grid operators so that they can balance supply and demand without the need to dispatch other sources of power to overcome set-point errors, so they can reserve a set amount of additional power to be called upon to overcome balance supply with demand (regulating reserve), so they can reserve a set amount of additional power to be called upon to overcome unplanned outages of generators and/or transmission lines (spinning reserve).

Range of adjustment refers to ability of a power source to produce power over a range of set-point values. Range of adjustment is important to grid operators so that they can establish set-point values that optimize the overall mix of power sources as they balance supply and demand. Range of adjustment can be achieved by adjustment of input power and/or by adjustment of power flow controllers, depending on the generation and conversion technology.

Time response refers to ability of a power source to track time-varying changes in set-point values. Time response is important to grid operators so that they can increase or decrease power output on a time scales suitable to match supply and demand (10's of minutes), to damp power oscillations (10's of seconds), to maintain power flow and stability during unplanned outages of generators and/or transmission lines (seconds or less). Time response depends upon time required to adjust input power and/or power flow controllers, depending on the generation and conversion technology.

5.2.2. Energy storage

Numerous energy storage [23-24] technologies exist or are under development with various characteristics and constraints. However, at the present time pumped hydro and compressed air energy storage (CAES) are the only viable utility-scale technologies. Both of these technologies can be implemented at an appropriate scale (~ 100's of MW power level and ~ GW-hr energy) and exhibit adequate cycle life (> 10,000 cycles corresponds to ~ 30 years for diurnal storage). Round-trip efficiency is in the range 70-85%. However, the deployment of these technologies is limited to geographic locations with appropriate characteristics.

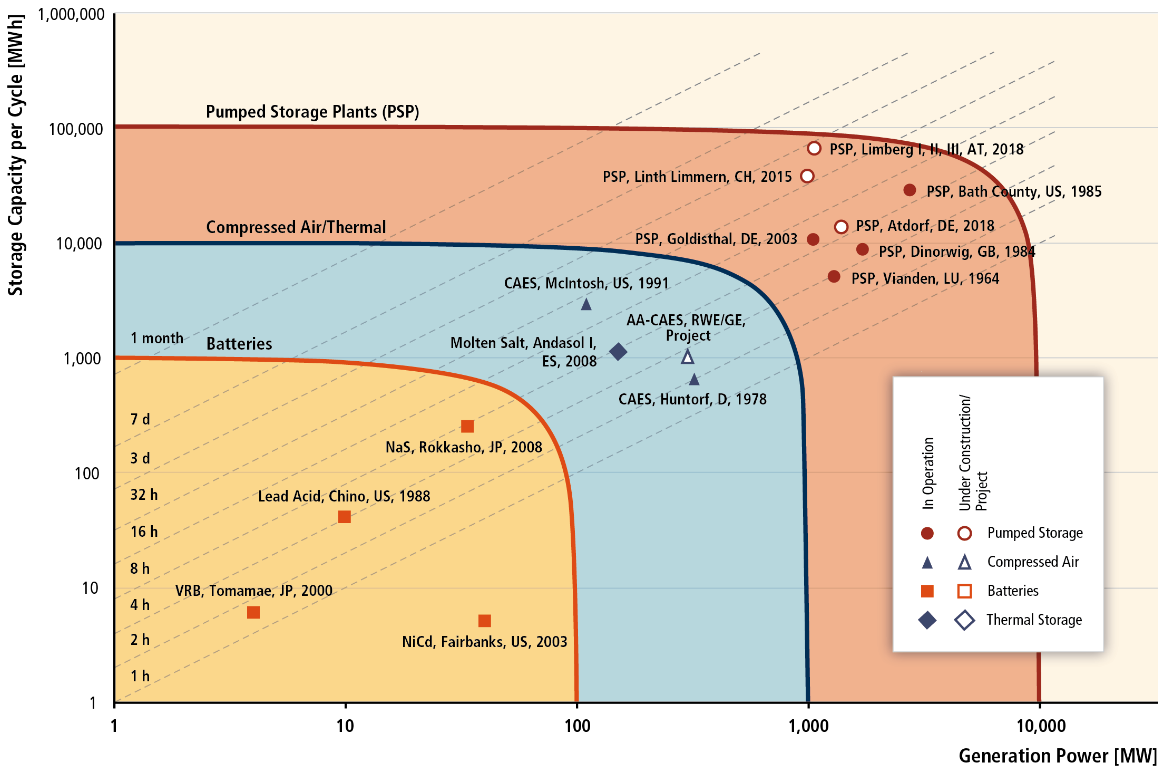

Figure 27 - Storage and installed capacity of selected large electricity storage sites

Large-scale battery-based energy storage is a nascent phase but could become significant, via utility-scale arrays or perhaps based on a very large number of small installations used in conjunction with rooftop PV systems[4].

Large-scale storage[5] using H_2, by itself or mixed with methane[6], or Synthetic (or Substitute) Natural Gas (SNG) generated by "methanation" [27] reaction between H_2 and CO_2 are also under investigation but are in a nascent phase. The round-trip efficiency of these systems tends to be very low, e.g. 38%. But these technologies do offer the possibility of very large-scale storage as depicted in Figure 28.

[4] For example the Tesla 100kWh battery blocks based on lithium ion technology developed for electric vehicles http://www.teslamotors.com/presskit/teslaenergy

[5] H_2 storage http://www.siemens.com/innovation/en/home/pictures-of-the-future/energy-and-efficiency/smart-grids-and-energy-storage-electrolyzers-energy-storage-for-the-future.html

[6] Methantion http://breakingenergy.com/2014/12/02/power-to-gas-enables-massive-energy-storage/

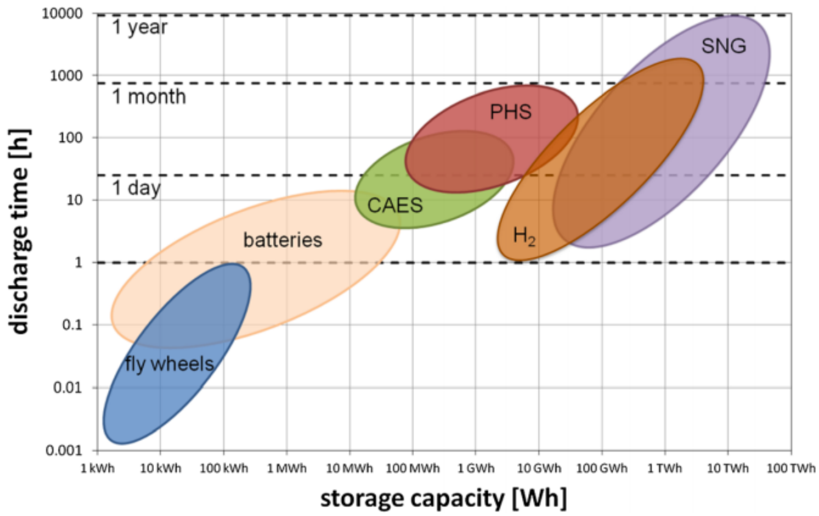

Figure 28 - Charge/discharge period and storage capacity of different electricity storage systems (CAES, compressed air energy storage; PHS, pumped hydro storage; SNG, substitute natural gas)

As depicted in Figure 29 the deployment of energy storage will increase the investment cost of intermittent renewables both in terms of money and energy input to fabricate, construct, and operate, depending on the round-trip efficiency as well as the fraction of energy generated that has to be stored.

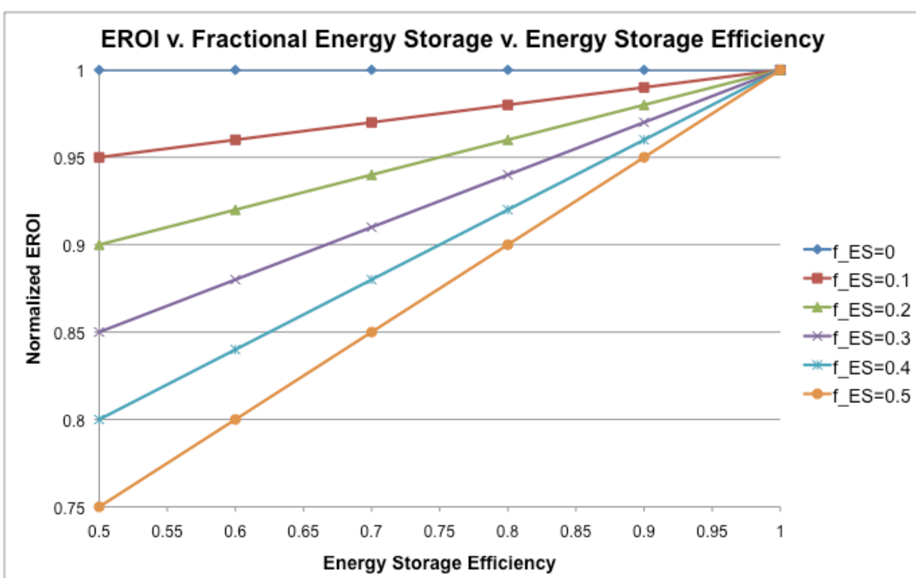

Figure 29 – Effect of energy storage round-trip efficiency on EROI at various storage fractions

5.2.3. Integration assessment

We performed an assessment of integration of the traditional and renewable sources as summarized in the following table. Note that these findings assume that energy storage is not integral with the technology under consideration.

Table 2 – Assessment of Integration Issues for various electricity sources

Attribute	**Attribute Weighting**	**Gas Turbine**	**Hydro**	**Nuclear/ Coal Steam Turbine**	**Geo-thermal**	**Utility Scale Solar PV**	**Con-centrated Solar Power (CSP)**	**Wind**	**Rooftop PV**
Availability	3	3	3	3	3	0	0	0	0
Predictability	3	3	3	3	3	1	1	0	1
Setpoint accuracy	3	3	3	3	3	3	3	3	0
Adjustability	2	3	3	1	2	3	3	3	0
Time response	1	2	2	1	2	3	2	3	3
Location independance	2	3	0	2	0	1	1	1	2
Overall Integration Score	-	98%	83%	81%	79%	55%	52%	48%	24%

	Weighting
Critical	3
Valuable	2
Limited Value	1

	Scoring
Very good	3
Good	2
Poor	1
Very poor	0

All forms of solar received the lowest score on availability owing to the diurnal cycle of solar radiation. We consider that predictability is poor but not very poor because diurnal and season irradiance are very predictable but weather (cloudiness) is not. Assuming that the output of a large solar array can be rapidly controlled from zero to full available power via its power electronics interface to the grid, all of its control attributes are very good. CSP is similar to solar PV except that, with a conventional turbine-generator system, its time response is not as good. For rooftop PV we assume that it's power production is not controlled by grid operators so it scores very poor in all categories except location since it is presumably located coincident with the load that it is intended to supply.

For wind we consider that availability and predictability is very poor because it is highly weather-dependant. However, similar to solar PV, we assume that the output of an individual wind turbine power converter can be rapidly controlled from zero to full available power via its power electronics. In the case of wind farms, control over the turbines within the farm needs to be coordinated by an overall controller that adjusts the power output of the entire farm [28].

Overall grid controllability depends on the centralized grid operators' ability to control the power sources within their control area. They must do so in order to balance supply and demand while operating transmission and distribution equipment within ratings, maintaining voltage and frequency within limits and responding to unplanned outages of generators and/or transmission lines. In general, controllability decreases as the number of individual power sources increases and as the individual power source autonomy increases. Note that, although high scores for control attributes have been given in the assessment of solar and wind sources based on their ability to be controlled, that is not to say that centralized control has been implemented on a widespread basis at present. In fact it has not, and to a large degree grid operators are now dispatching traditional sources so as to accommodate variations in output of variable and intermittent renewables that are not under their control. The development of a smart grid is expected to facilitate centralized control over a large number of individual, distributed power sources.

6. Evaluation of future energy portfolio studies

6.1. NREL RE Futures

6.1.1. Description of study

The National Renewable Energy Laboratory (NREL) study entitled "Renewable Electricity Futures" (RE Futures) [24] is an in-depth, comprehensive study that explores grid integration issues using models that resolve the contiguous United States into eleven regions and perform hourly calculations that simulate integrated engineering and economic performance of the grid as envisioned in 2050. It assesses a variety of scenarios with prescribed levels of renewable electricity generation in 2050, from 30% to 90%, with a focus on 80% (with nearly 50% from variable wind and solar photovoltaic generation) and identifies the characteristics of the system that would be needed to same.

The study accounts for the regional differences in renewable resource availability (e.g. solar in the southwest, wind in the Great Plains, etc.) as well as regional and seasonal variations in electricity demand. It factors in the need for expansion of the transmission grid to deliver power from source regions to load regions.

The study considered several dozen scenarios with varying levels of electricity demand, varying fractions of renewable integration, and variations in other boundary conditions. In the low demand (baseline) scenario, improvements in energy efficiency offset increases in the use of electric vehicles such that the overall demand growth between 2010 and 2050 is minimal. Most results are presented for the low demand scenario with an intermediate level of renewable technology improvement.

The study finds that:

- Supply and demand can be balanced in every hour of the year in each region with nearly 80% of electricity from renewable resources, including nearly 50% from variable renewable generation.

- Measures needed to improve system flexibility include:

    - Increase in energy storage from ~20 GW in 2010 to 100–152 GW in 2050 (factor of 5-8x);

  - Increase in demand-side interruptible load from 15.6 GW in 2009 to 28–48 GW in 2050 (factor of 2-3x);

  - Expansion of transmission infrastructure by ~ 120 million MW-miles above existing 150-200 million MW-miles) to smooth electricity demand profiles and connect load with remote generation (factor of 1.6–1.8x);

  - Reliance on conventional plant dispatch flexibility, including daily ramping of fossil generators;

  - Reliance on demand-side interruptible load, conventional natural gas generators, and storage to manage operating reserve requirements;

  - Implement controlled charging of electric vehicles.

- Gross land-use impacts associated with renewable generation, energy storage, and transmission expansion in total amount to ~ 3% of the land area of the contiguous US.

- A combination of technology advances, new operating procedures, evolved business models, and new market rules will be required.

- Greenhouse gas emissions would be reduced by ~ 80% and water use reduced by ~ 50%.

- Incremental cost associated with high renewable generation would add $25-$50 per MWh retail electricity ~ $98 per MWh (factor of 1.25–1.5x) based on 2009 pricing.

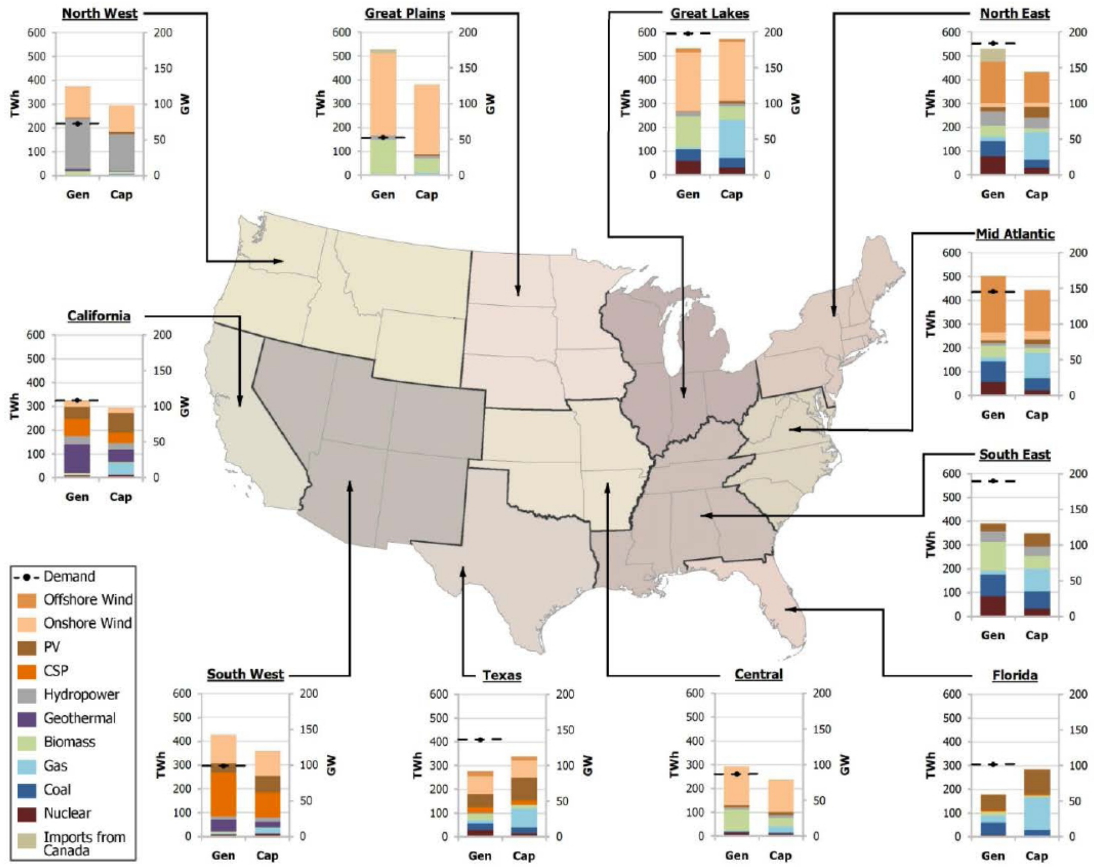

Figure 30 - Renewable generation and capacity in 2050 by region under 80% RE-ITI scenario

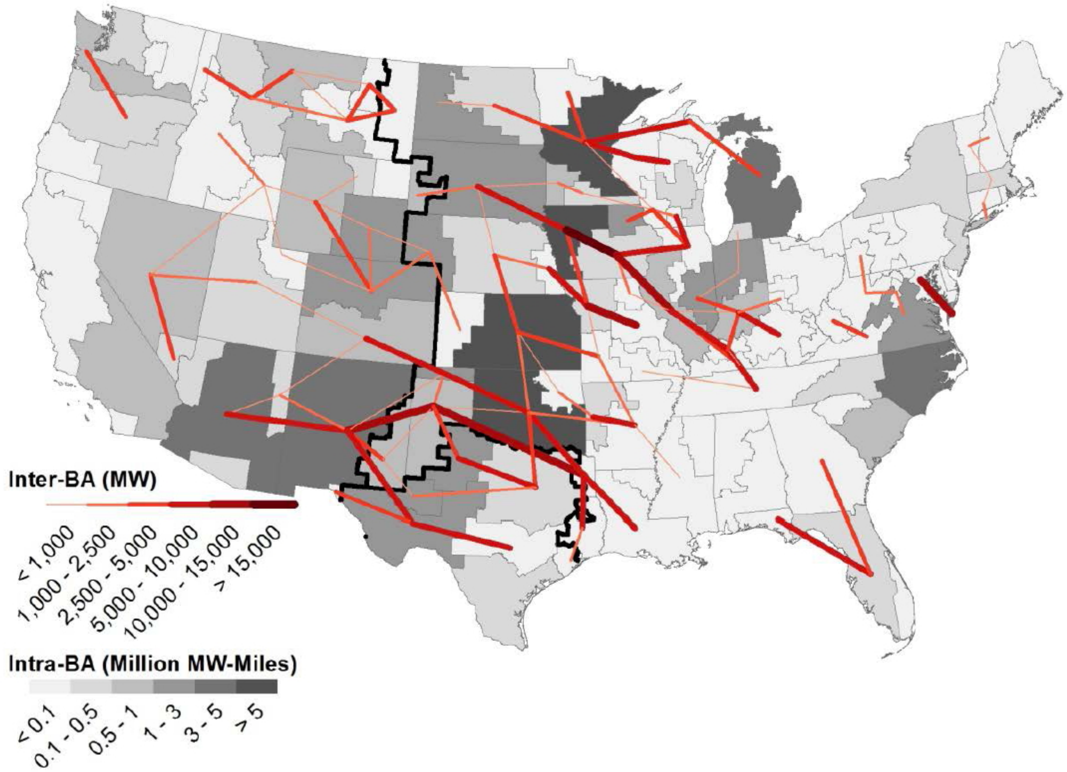

Figure 31 - New transmission capacity additions and conceptual location in the 80% RE-ITI scenario

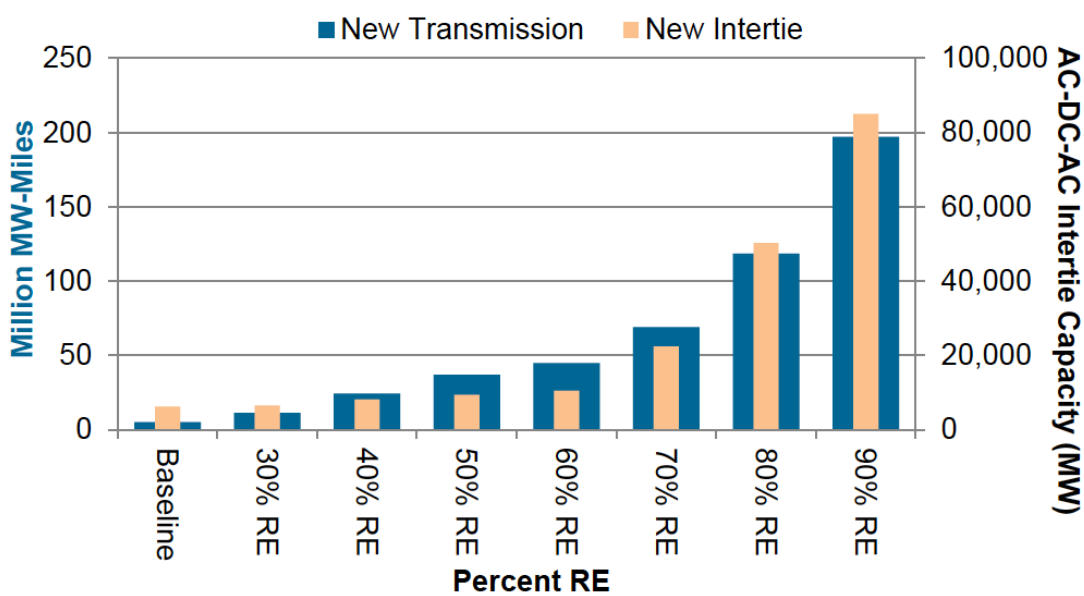

Figure 32 - New transmission capacity requirements at different Renewable Energy (RE) integration fractions

(Note: existing total transmission capacity in the contiguous US is ~ 150–200 million MW-mile)

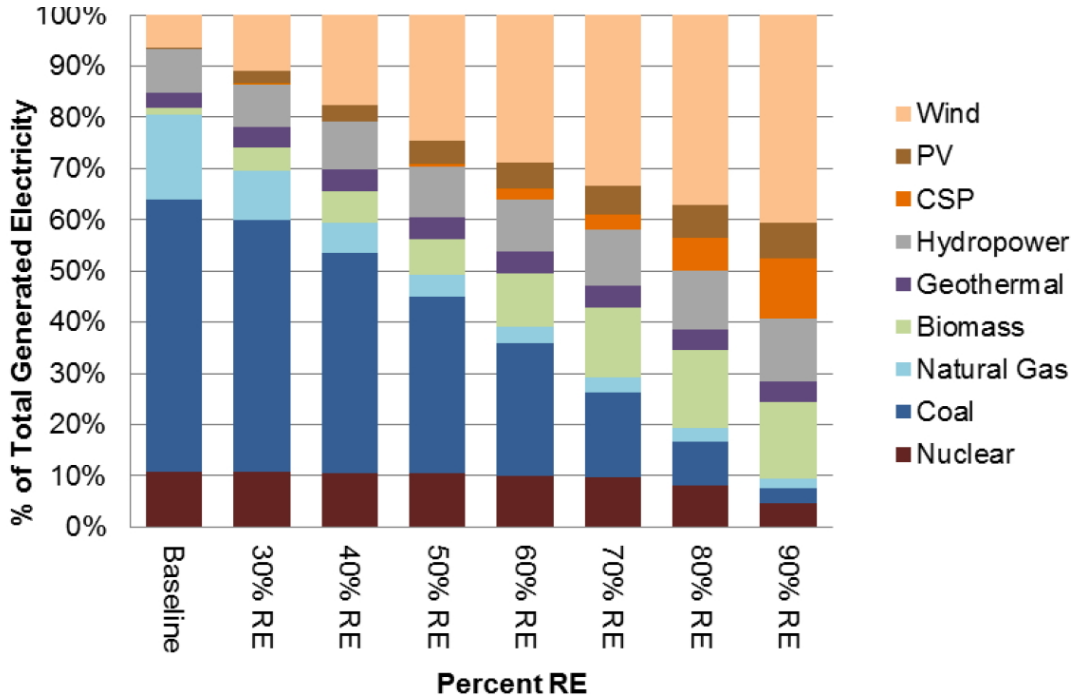

Figure 33 – Mix of sources at different Renewable Energy (RE) integration fractions

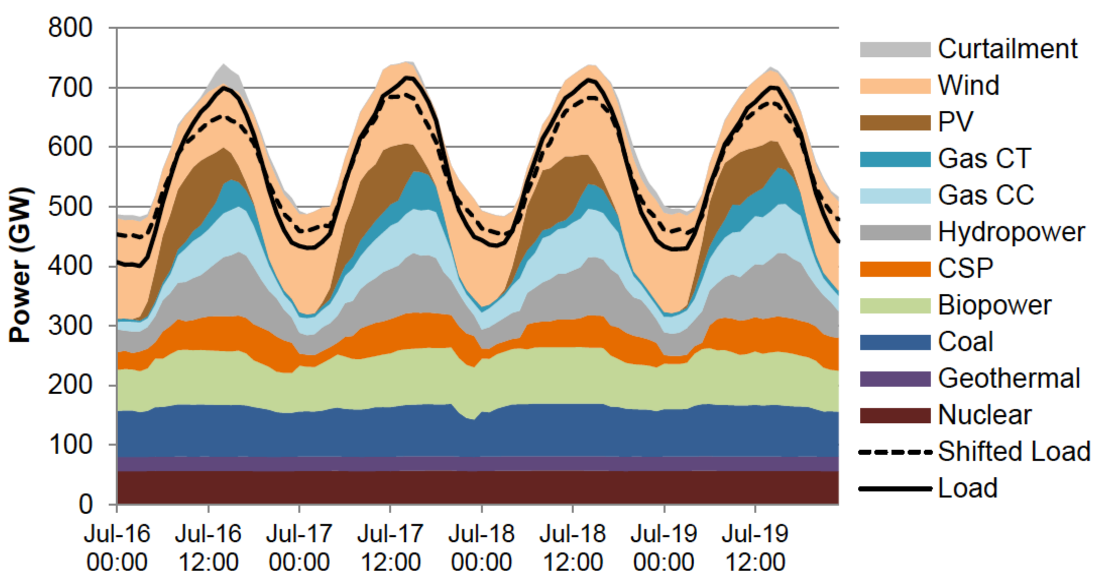

Figure 34 – Summer Peak Load Scenario in 2050

6.1.2. Evaluation of study

The results of the NREL RE Futures study reinforce the nature of the issues that arise from the integration of a high fraction of intermittent renewables that are geographically dependent. Basically, the generation of electricity by coal is replaced by solar and (predominantly) wind, accompanied by various changes (energy storage, demand side curtailment, transmission system expansion) that are necessary to accommodate the change. Greenhouse gas emissions and water usage are beneficially reduced, at the expense of greater cost, land use, and system complexity.

The study is strictly applicable to conditions in the US since the geographic distribution of resources and load centers is unique to the US, and since it represents integration of renewables on to an already strong and mature grid, with no growth in electricity consumption.

In our evaluation the following risks have been identified.

- Assumed levels of energy storage may not be realizable due to limitations in available sites for pumped hydro and CAES, and technical/economic barriers that prevent the implementation of utility-scale battery energy storage

- Assumed levels of interruptible load, and/or smart grid capability to effect same, may not be realized due to load consumer objections and/or technical/economic barriers

- Assumed extent of transmission expansion may not be realized due to right-of-way issues and/or economic barriers (sensitivity to this constraint was one of the scenario variations studied in the report)

- Daily ramping of fossil generators may not be realized due to technical/economic/market barriers

- Reliance on fossil generators for contingency reserves may not be realized due to economic/market barriers

- Projections of cost of electricity after integration of renewables may be unrealistic.

6.2. EMF-27

6.2.1. Description of study

The Intergovernmental Panel on Climate Change (IPCC) is evaluating means for limiting the atmospheric greenhouse gas concentration to 450 or 550 ppm CO_2 equivalent by

2100. The Fifth Assessment Report (AR5) of Working Group III of the IPCC has amassed a scenario database[7] comprised of 31 models and 1,184 scenarios. The Stanford Energy Modeling Forum Study 27[8] (EMF-27) is one of the sources that fed into the AR5 scenario database.

We have evaluated one particular global electricity supply and consumption scenario from the AR5 database called "EMF27-450-Full_Tech" that is associated with one of the more aggressive cases based on a 450 ppm CO_2 limit with mitigating using the full set of available technologies [29]. The AR5 database contains the results of 10 different integrated assessment models as they apply to the EMF-27 scenario. In our work we take the mean of these 10 scenarios as the basis for evaluation.

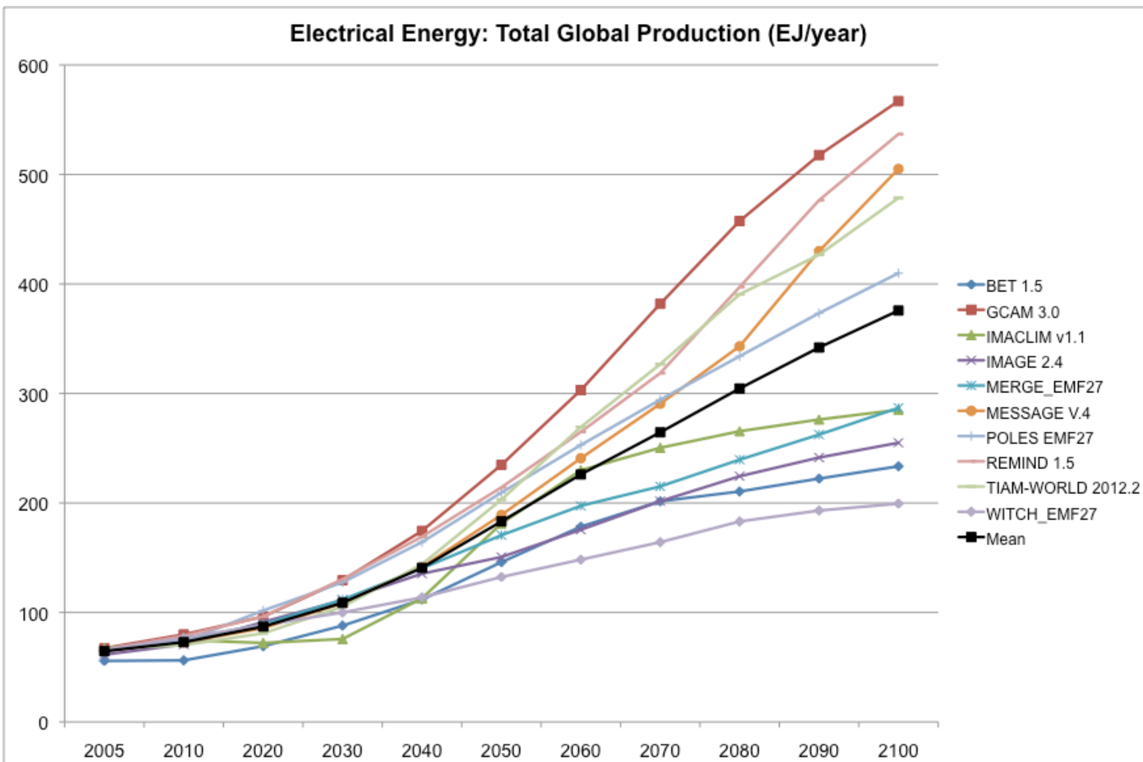

Figure 35 – Global electricity production from EMF27-450-Full Tech scenario models (Mean value is used in analysis, 73 EJ/year in 2010, 375 EJ/year in 2100)

[7] AR5 Database https://secure.iiasa.ac.at/web-apps/ene/AR5DB/dsd?Action=htmlpage&page=about

[8] EMF-27 https://emf.stanford.edu/projects/emf-27-global-model-comparison-exercise

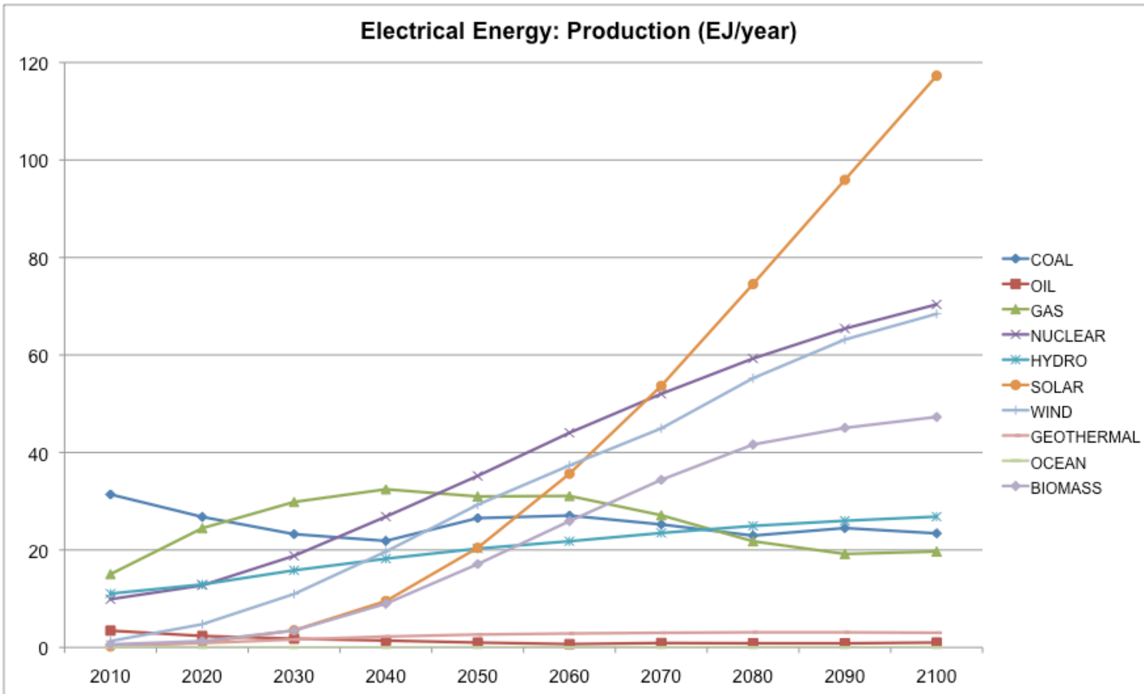

Figure 36 - Global electricity production from various sources based on mean of EMF27-450-Full Tech scenario models

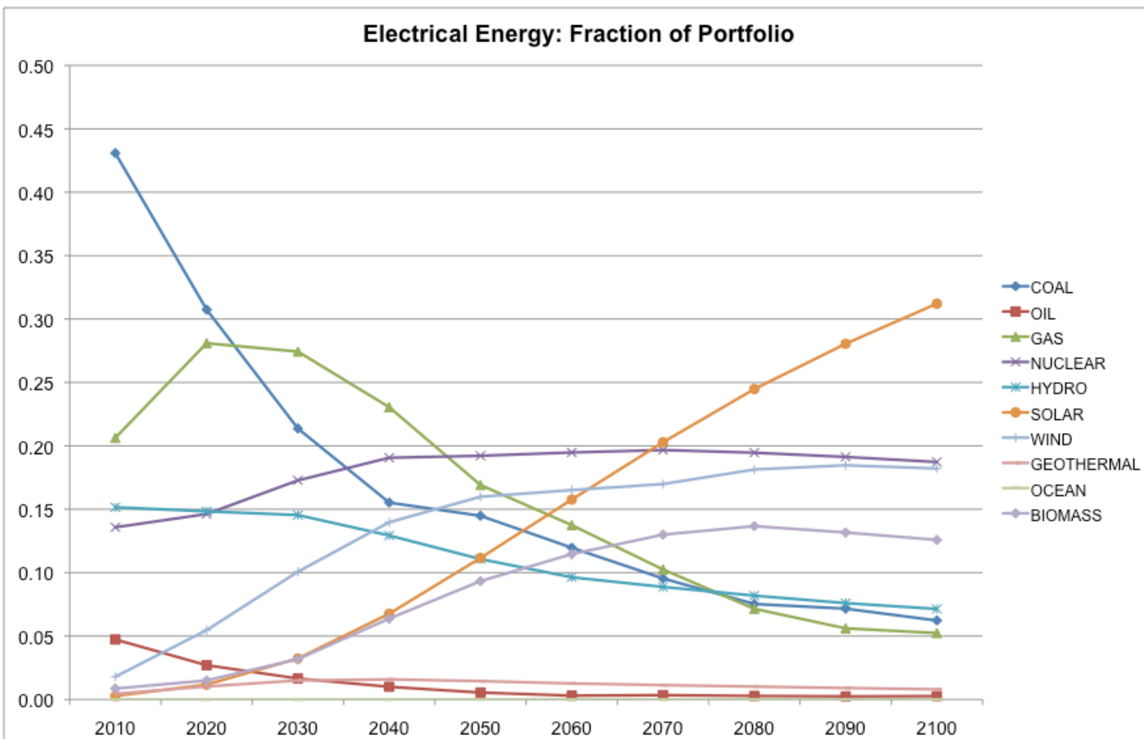

Figure 37 – Fraction of global electricity production from various sources based on mean of EMF27-450-Full Tech scenario models

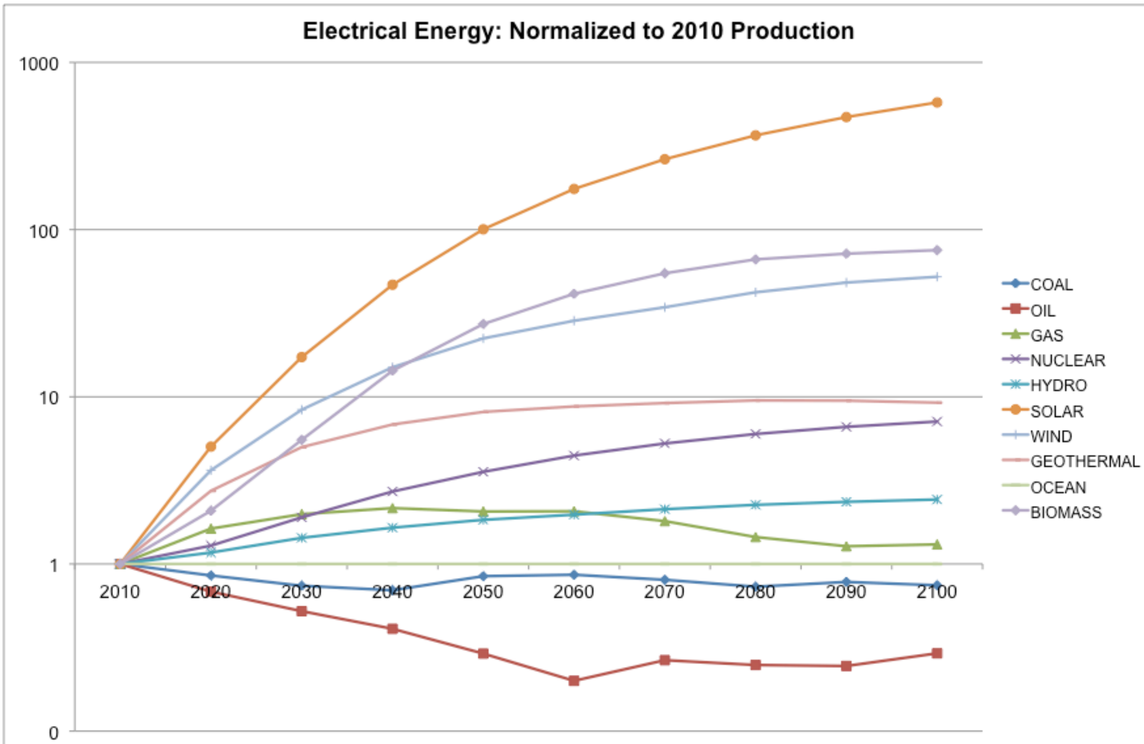

Figure 38 – Expansion of electricity production from various sources based on mean of EMF27-450-Full Tech scenario models

Several aspects of the scenario are noteworthy:

- It covers global electricity production, and the portfolio fractions may be markedly different in individual regions.
- Solar (117 EJ/yr), Nuclear (70 EJ/yr), Wind (68 EJ/yr) and Biomass (47 EJ/yr), become the dominant sources at end of century.
- Growth in solar over present levels is a prominent feature
  - Solar 580x
  - Biomass 75x
  - Wind 52x
  - Nuclear 7x
- The fraction of intermittent sources (solar + wind) is ~ 50% at the end of the century on a global basis, higher in some regions and lower in others.

6.2.2. Evaluation of study

Considering the dramatic expansion in the use of solar energy we decided to evaluate the ramifications. We followed a modeling scheme that simulates the "dynamic EROI" as exhibited by a collection of electrical generating facilities, of a common technology (e.g.

solar, wind, etc.), over an extended period of time as old units are retired and new units are added [30]. The modeling is based on two coupled first order differential equations, one covering the mobilization of construction activities, the other covering the construction of new units and the retirement of old units.

$$\frac{d}{dt}P_r(t) = -\frac{1}{T_l}P_r(t) + \frac{C(t)}{T_c}$$
$$\frac{d}{dt}C(t) = \frac{(1-f_o)f_d f_p P_r(t)}{f_c} - \frac{C(t)}{T_c}$$

$P_r(t)$ is the total rated nameplate capacity
T_l is the individual plant lifetime
T_c is the individual plant construction time
$C(t)$ is the rated generating capacity under construction
f_o is the fraction of generated power required to operate and maintain an individual plant
f_d is the duty cycle (capacity factor)
f_p is the amount of generated output power that is plowed back to construct new plants
f_c is the amount of primary (thermal) energy expended to emplace a unit of nameplate capacity

A block diagram representation is given in Figure 39, where P_d is the demand, P_g is the generated power, P_o is the power used for operation and maintenance, P_c is the plowback power used for construction, and P_e is the imbalance (error) power. A "construction planning" process is applied to the error to stimulate new construction.

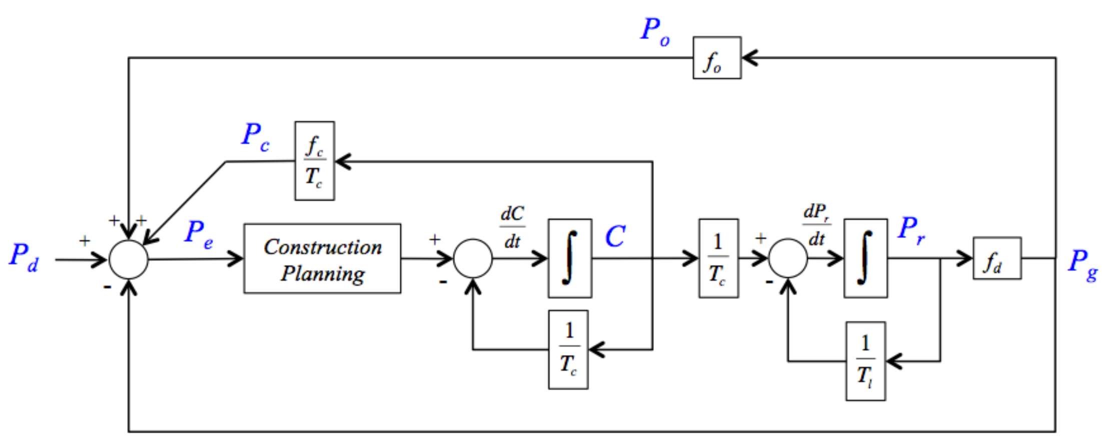

Figure 39 – Block Diagram of powerplant construction process

We developed a construction planning scheme as incorporated in Figure 40. Here we use the plowback fraction f_p to enforce a limit on plowback power P_p, and introduce supplemental power P_s when necessary to achieve the desired level of construction power Pc. The supplemental power would come from some other source, and the collection of plants being modeled would only supply the plowback power P_p. This allows for the simulation of situations where another source is "cannibalized" [9] to provide the energy

[9] Energy cannibalization https://en.wikipedia.org/wiki/Energy_cannibalism

necessary to deploy the source in question. We deploy a PID controller with settings chosen to minimize sum of squares error over the period of simulation.

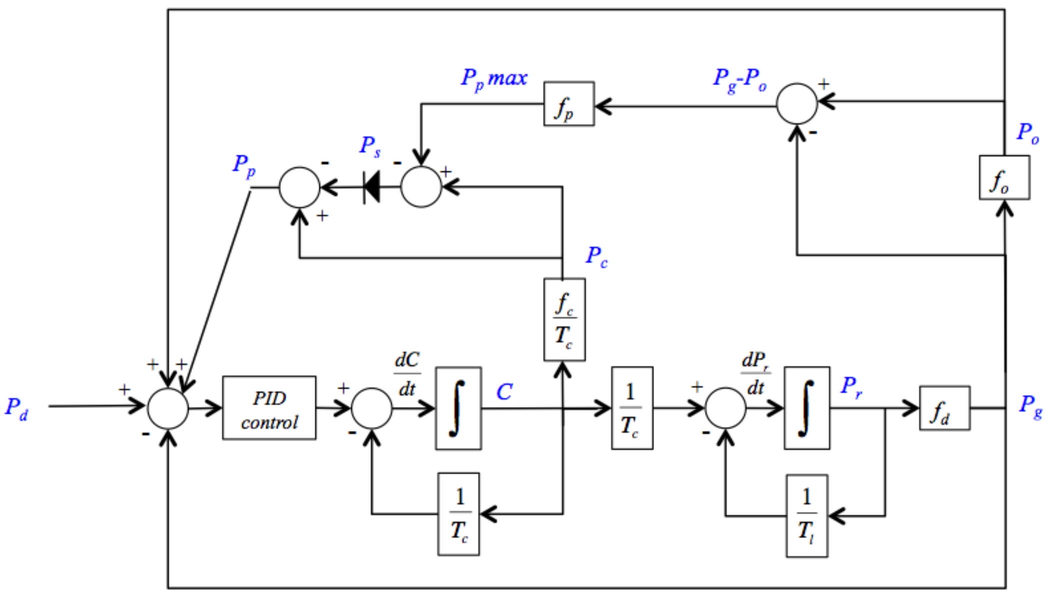

Figure 40 - Block Diagram of powerplant construction process including construction planning scheme

Derivation of input parameters used to simulate the EMF27-450-Full_Tech solar energy expansion scenario are given in Table 3 – Input parameters related to EROI calculations. Note that these results do not factor in the energy required for grid integration (e.g. energy storage, transmission expansion, etc.) or the reduction in efficiency due to energy storage.

Table 3 – Input parameters related to EROI calculations

Parameter	**Minimum**	**Mean**	**Maximum**
T_p (years) [21]	1.6	2.3	3.0
EROI	6.1	9.7	13.4
f_d	-	0.19	-
T_c (years) [31]	-	2	-
T_l (years) [2]	-	25	-
f_o	0.01	0.025	0.05
f_c	0.31	0.45	0.56

The values for f_o were taken as assumptions. The values of EROI and f_c were calculated based on the other parameters. The value of 0.19 for f_d is based on the normalized irradiance of 1700 kWh/m^2 that was used in the reference [21] which corresponds to 19% of a full year of irradiance at 1kW/m^2. In the simulation we used a value of 0.17 which corresponds to the world's average across regions where the average exceeds 1000 kWh/m^2, considered to be the cut-off for economic viability. It is, admittedly, difficult to assign EROI parameters that provide a representative global simulation model across the range of solar technologies and site characteristics. Nevertheless the exercise is useful to develop an understanding of underlying trends and sensitivities.

Results of a simulation of the EMF27-450-Full_Tech solar energy expansion scenario from 2010 to 2100 using the mean parameters and a plowback limit of 0.5 is given in Figure 41.

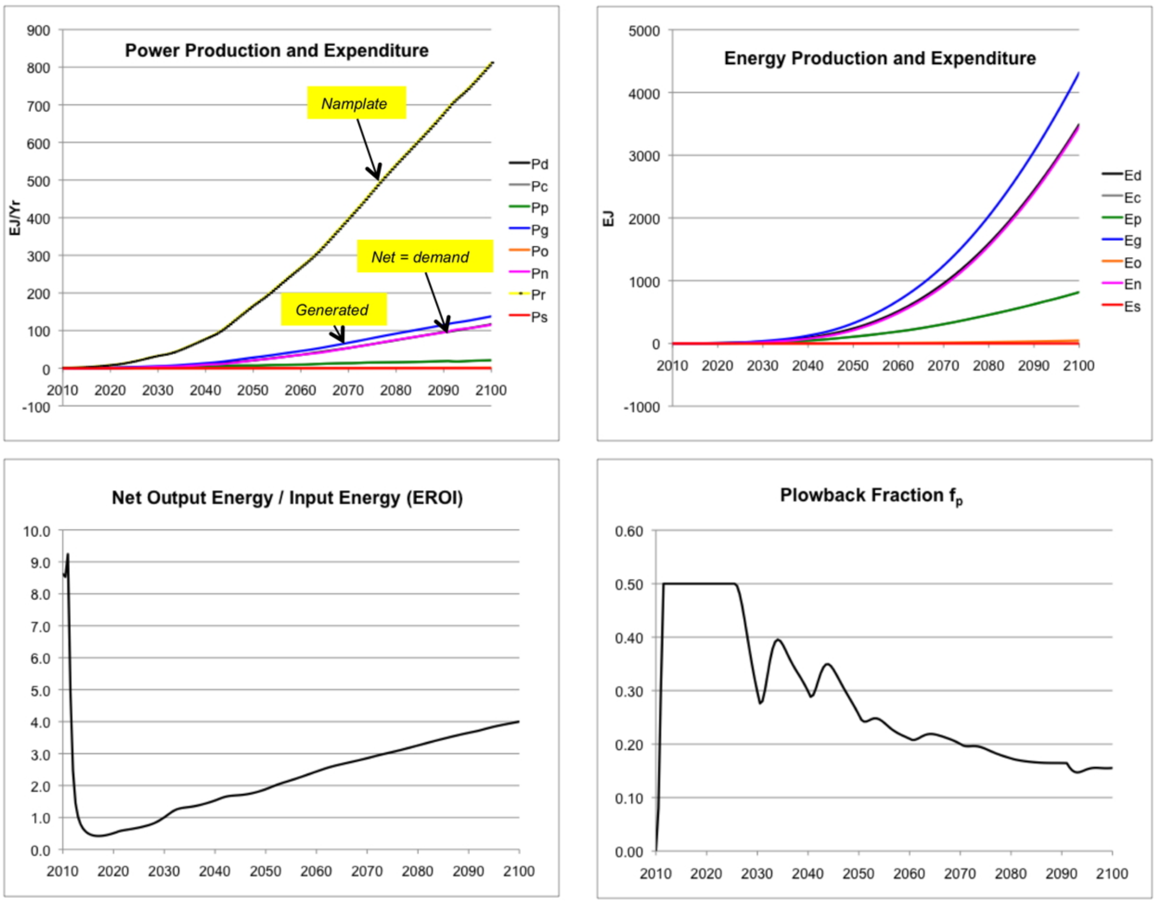

Figure 41 – Expansion of solar power generating capacity per EMF27-450-Full_Tech scenario

The simulation results show that the plowback power and energy lead that arise from capacity expansion tend to increase the installed power requirement and diminish the EROI compared to a static situation. The total generated energy must exceed the energy supplied to consumers by ~ 25% in order to emplace the infrastructure. With a plowback limit of 0.5 the capacity expansion has to draw on supplemental power during the first 15 years of expansion.

In order to evaluate the sensitivity to input assumptions we ran additional cases with the input energy (the denominator of the EROI ratio) at minimum and maximum values, and with an efficiency reduction of 20% to account for loss of efficiency due to energy storage. This would arise, for example, if round-trip efficiency is 60% and 50% of the energy produced is passed into and out of storage.

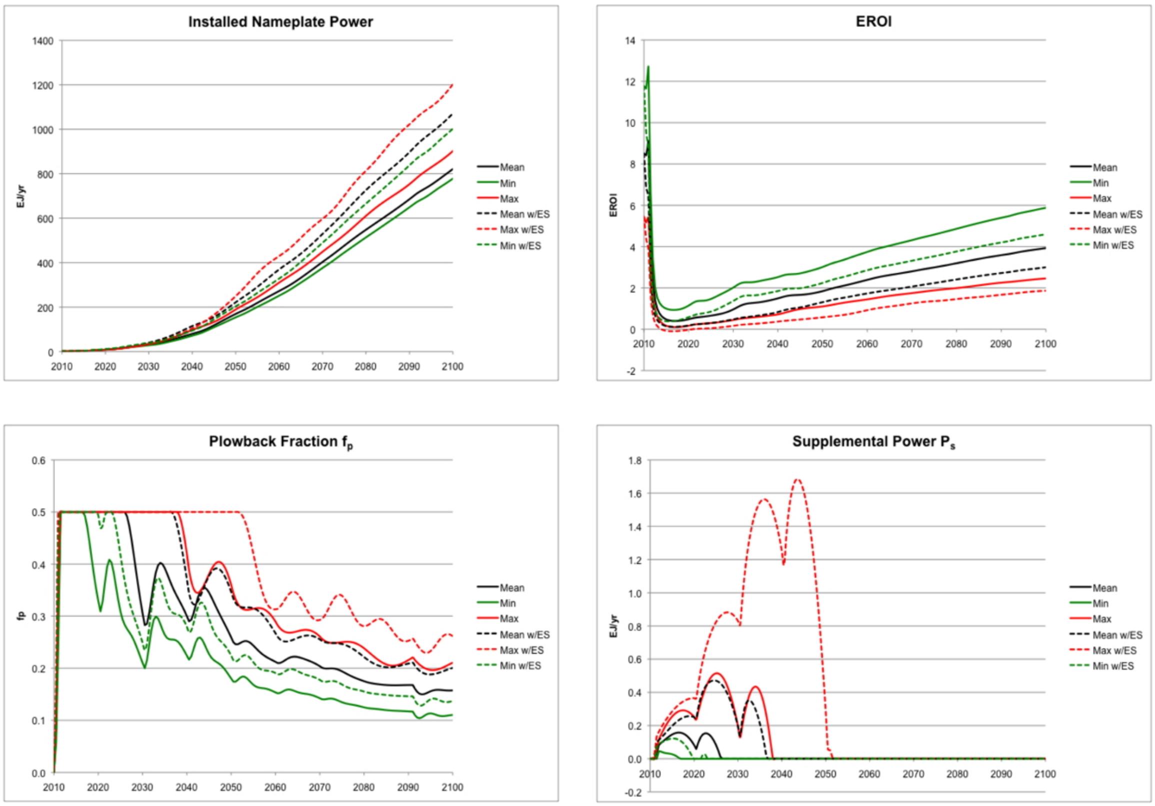

Figure 42 – Sensitivity of simulation to range of EROI data and inclusion of losses due to energy storage

In our evaluation the following risks have been identified.

- From the simulation results:

    - Energy required to emplace the infrastructure can be significant, especially at high rates of expansion, and has probably not been included in the overall scenario assessment;

    - Due to significant uncertainty in the input energy (the denominator of the EROI ratio), there is a significant error bar in the results;

    - The energy to emplace features necessary for integration (energy storage, transmission expansion, etc.) along with loss of efficiency due to energy storage, will tend to degrade the overall performance.

- Considering the findings of the NREL study which stretched the technology and economics in order to allow for a high fraction of renewables in 2050 in the US grid, the combination of wind + solar amounting to ~ 50% of the global EMF27-450-Full_Tech portfolio seems unrealistic as a global possibility since some regions would have to significantly exceed 50%.

- Regions with strong solar resources (Figure 1) do tend to coincide with regions where population growth, increase in standard of living, and electricity consumption, are expected to drive the global electricity demand in the 21st century. However, these regions:

    - Do not presently possess a strong grid that can accommodate an intermittent source;

    - As developing regions, will be unlikely to select the most expensive power source (with possible exception of oil-rich Middle East countries);

    - As arid regions, do not have sites amenable to pumped hydro energy storage.

7. Summary

In this report we have provided a brief review of renewable sources, their energy capture and conversion systems, and a comparative summary of key metrics. We have discussed the benefits and challenges including issues related to integration into the power grid.

We have considered plans for future expansion of renewables in the US as embodied in a study by the National Renewable Energy Laboratory (NREL) along with scenarios developed under the auspices of the Intergovernmental Panel on Climate Change (IPCC) covering the global supply of electricity, indentifying risks that could impede the plans.

Summary findings include the following.

- The technical potential of the renewables is more than adequate to supply global electricity demand though the 21st century. In fact solar energy alone could in principle suffice. Since they do not rely on the combustion of organic materials, and are not exhaustible on a human time scale, the renewables offer the potential to provide an ideal sustainable, carbon-free energy future.

- The intermittent nature of solar and wind energy, the most potent renewable sources, is not consistent with the need to supply power to consumers on a steady basis day and night, throughout the year. The development of large-scale energy storage that would fully stabilize the supply to consumers is problematic. In some instances the coincidence of solar radiation with air conditioning loads will mitigate the need for energy storage but the use of solar and wind energy in combination with other dispatchable sources that can compensate for their intermittency will always remain a practical necessity. The optimum mixture of solar and wind with dispatchable sources is a complex issue that depends on the characteristics of any particular region.

- The inherent low power density, low capacity factor, and low energy density of the renewable sources leads to a relatively high cost due to the total mass of components used to convert energy, along with extensive network required to convert, collect and concentrate and transmit electric power, all operating at a low duty factor. In addition, land area requirements are relatively large compared to traditional sources per unit of energy generated.

- The geographic dependence of solar and wind energy limits their deployment to regions where the resources are potent and in reasonable proximity to load centers. Regions with strong solar resources do tend to coincide with regions where population growth, increase in standard of living, and electricity consumption, are expected to drive the global electricity demand in the 21st century. However, these regions do not presently possess a strong grid that can accommodate intermittent renewable sources. As developing regions, they will be unlikely to select the most expensive power sources. And as arid regions, they do not have sites amenable to pumped hydroelectric energy storage. These aspects are not congruent with the IPCC scenarios for the 21^{st} century energy portfolio which indicates wind + solar providing ~ 50% of the worlds total electricity by 2100.

- Not accounting for energy storage and other integration features, the EROI of solar is comparable to other traditional sources including nuclear fission, and wind is superior. However, with the rapid expansion of solar in the IPCC scenarios the dynamic effect will reduce the net energy returned and will require that a significant fraction of the energy produced be plowed back to feed the infrastructure expansion.

- Hydroelectric power stands out as a superior renewable source in terms of EROI, CO_2 emission, cost of electricity, and dispatchability. Unfortunately the resource is relatively limited with ~ 1/3 of technical potential already exploited. Still, its deployment should be prioritized and when possible used in conjunction with solar and wind so as to provide compensation for intermittency.

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