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Comparison of Resource Intensities and Operational Parameters of Renewable, Fossil Fuel, and Nuclear Power Systems

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Abstract

Depletion of fossil, their associated thermal emission, and fear of global warming, have been exerting unparallel momentum to tap on naturalenergy resources. At the current state however some of these resources are associated with large capital, low capacity, large overall carbon footprint that we need to be aware off to make a judicial decision. A comparison study between renewable, fossil fuel and nuclear powersystems is presented in this work. The comparison includes the resource intensity, operational parameters and current status. The results show that the renewable power systems such as hydro power, tidal power (barrage), offshore wind power, and wave power utilizemore materials during the construction than the conventional (coal, natural gas) and nuclear power systems; the renewable energy systems require greater surface area reaches 50 to 150 times the conventional and nuclear power systems except geothermal power plant; the renewable hydro-power system has the highest energy and CO_2 intensities during the construction of the power plant; solar power system has the highest capital intensity compared to all power systemsas itrequiresmore capital and energy to construct the same nominal generating capacity; the system efficiency of solar power is only 10% to 18% compared to 30-50 % for conventional and nuclear power systems; and the capacity factor for solar power is as low as 10% compared to 80% for conventional power system. Still,- most of the renewable power systems have low capacity factor except the geothermal power that offers up to 95%.

Keywords:
Renewable Energy, Fossil Fuel Energy, Nuclear Energy, Carbon Foot Print, Capital Intensity, Energy Intensity, Area Intensity, Material Intensity, Capacity Factor, System Efficiency, Life Time, Current Installed Capacity

1. Introduction

Energy, water and food security and climate change are among the challenges facing the wellbeing. Population growth (9 billion by 2050), economic growth, environmental stress(severe climate conditions), excessive consumption patterns, limited natural resources (land, water, materials, and fuels), urbanization, and governance failure (no integrated solution planning based on water, energy and food sectors) are the drivers for imminent food, water and energy shortages(see Fig. 1). This can lead to social tensions and geopolitical conflicts at the local and global levels.New approach is needed for future planning that will use an integrated solution based on the interconnections of all these sectors - energy, water, food and climate change as shown in Figure 1.

The water, food, and energy demands are projected to increase by 30%, 50%, and 40%, respectively, by 2030 [1]. There have been interconnection between, energy, water, food and climate change. For example the energy is used for water extraction, distribution and treatment [2-3]. Likewise, water is used for electricity generation inpower systems (steam turbine engines) and renewable power systems (i.e. concentrated solar panels and hydro power). Furthermore, energy is used for food production (equipment used in the agriculture sector) and the food prices is also sensitive to transportation cost [4-5]. New biomass based crops are also used for the production of alternative and renewable fuels (biodiesel and ethanol). The emissions from the combustion of coal and gas has left a noticeable and undebatable effects of the climate (temperature increase, flood, hurricanes, and other natural disasters). In turns,the environmental pressure iseffecting the future energy will be produced (move from fossil fuel energy to clean energy

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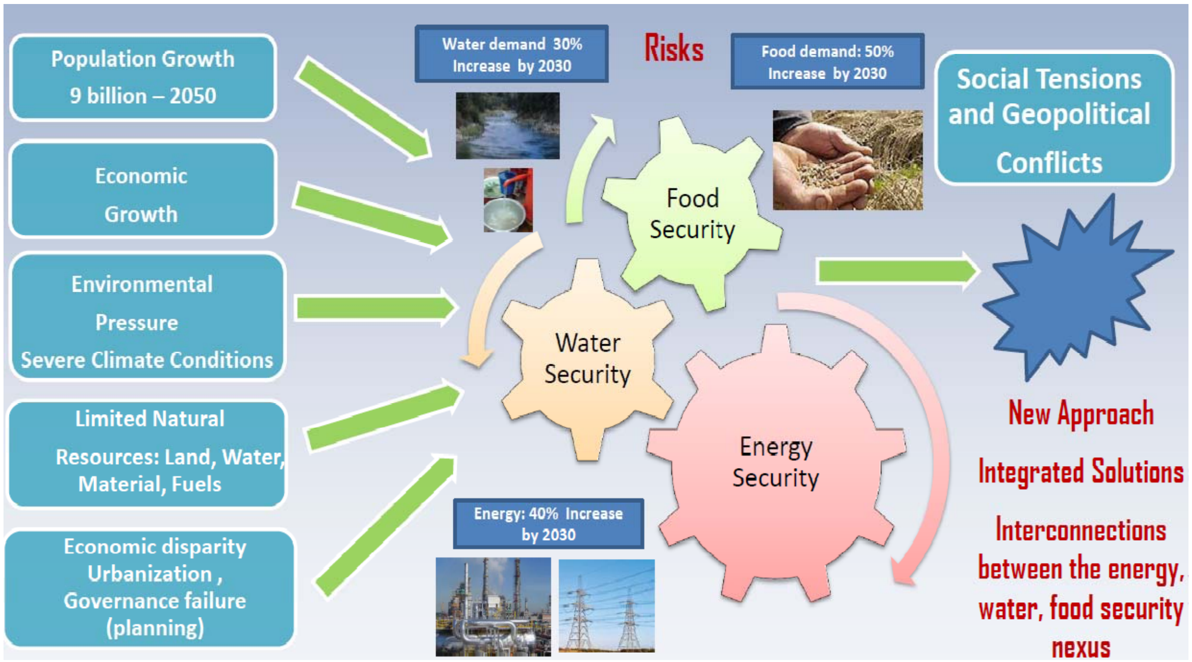

Figure 1 Energy, water, and food inter connections

systems such as nuclear and renewable energy systems). There are also inter-linkages between water and food [6], climate change and water [7], and climate and food. This work,however, will embark more on energy. The type of power systems (conventional power systems, nuclear and renewable power systems) will play an important role in these inter linkages.

Today most of the global energy demand is derived from the combustion of gas, oil and coal. The reliance on fossil fuels will diminish in the coming years due to (1) the new emissions regulations – reduction of carbon dioxide and other greenhouse gases (NOx, SOx…), (2) the reduction of the coal, oil and natural gas reserves, and (3) the need to reduce the dependence on foreign imports (use local resources). At the same time the world energy demand is projected to tripleby 2050[8]. How this energy will be generated when the oil, gas and coal reserves become depleted. Nuclear and renewable energies are two alternatives to conventional power generation using fossil fuels [9].The conventional power systems include coal, natural gas and fuel oil power plants. The nuclear power systems use uranium and plutonium as fuels. The renewable power systems use solar, wind, hydro (water), ocean (wave, tidal, ocean energy thermal system), geothermal and biomass natural sources.

The fossil fuel power systems have high energy-density, easy to transport and allows a large amount of power to be generated in a compact plant taking up relatively smallland area. Today they are the principal source of power but they are also the source of political and social tensions as the limits to their supply become more apparent[10]. There is also a concern about the emissions during the use of fossil power systems. Most of the power systems used to generate electricity use either coal or natural gas (fuel oil is mostly used in transportation and heating). The first conventional power system is coal plant - the coal is injected and burned inside the furnace to generate heat. The combustion products at hightemperature are used to heat water to generate steam whichdrives a steam turbine connected to a generator to generate electricity. Typical thermal efficiency of coal plant is 37%.Coal contains carbon, hydrogen, nitrogen, sulfur and many other elements. There are four type of coal: anthracite, bituminous, sub-bituminous and lignite. The anthracite contains 86-98% carbon and has a calorific value of 30 – 36 MJ/kg. It provides a clean-burning, making it attractive for heating and electricity generation. The bituminous coal, the most common type, has a carbon content of 46 – 86% and calorific value of 26 – 30 MJ/kg. It is used for power generation and to make blast-furnace coke for iron-making. Sub-bituminous and lignite, both have a carbon content of 46 – 60% but sub-bituminous coal has a calorific value of 20 – 26 MJ/kg compared to 14 – 20 MJ/kg for lignite [10]. Coal combustion releases not only carbon dioxide (CO_2) but also the oxides of sulfur (SOx) and nitrogen oxides (NOx). Several pre-combustion and post-combustion technologies are used to reduce the emission from coal combustion: for example washing coal reduces the nitrogen (N_2) in the coal; scrubbing, spraying a lime-water mix into the smoke removes acidic oxides of sulfur; carbon capture and storage (CCS) is an emerging technology used to capture the carbon dioxide, compressand store it in spent oil and gas reservoirs.

The second conventional power system is natural gas power plant. Natural gas combustion provides the cleanest-burning compared to the other fossil fuels (coal and oil). It is used for both heating and electricity generations. Natural gas is primarily methane, with small amount of ethane, propane, butane, hydrogen sulfide and other impurities which are removed in the refining process.For electricity generation, gas is either burnt in a furnace to produce steam (steam turbine is connected to a generator to generate electricity), or combusted in a gas turbine (gas turbine is connected to a generator to generate electricity).The thermal efficiency of gas turbine based plant is higher than the one using steam turbine. In combined cycle units, a gas turbine produces electricity and itswaste heat runs secondary steam turbine, reaching an overallefficiencybeyond50%.

The first alternative power system is nuclear power plant. Nuclear technologies are designed to extract usable energy from atomic nuclei via controlled nuclear reactions. Nuclear methods include nuclear fission (most used today), nuclear fusion and radioactive decay. In Nuclear power plant, the energy from the nuclear reactor is used to heat a working fluid such as water, which is then converted into mechanical work for the purpose of generating electricity or propulsion. Nuclear power plant generates no emissions (clean power system) but there are a severalissues in nuclear waste management that generated during the process, and safety (accident and terrorist threats). The uranium used in the nuclear power plant is not renewable and is also available only in some parts of the world (example: Canada, Australia, and Ukraine).

The second alternative power system is using renewable energy. Renewable energy could supply most of the energy demand (80%) by 2050[8]. Renewable energy technologies that can be integrated in the present and future energy systems include solar, wind, hydro, bioenergy, geothermal, and ocean (wave, current, temperature gradients) as source of renewable energy (see Fig.2):

- Onshore and offshore wind power plants convert the energy from the wind (kinetic energy) to electricity (wind generators are used to harness the kinetic energy in the wind).
- Solar power plant converts the sunlight to electricity directly (Photovoltaics) or indirectly (Concentrated Solar Plant).
- Hydro power is generated by using electricity generators to extract energy from moving water.
- Bioenergy when tapping on biomass and bioresources (agriculture, animal, forest, and municipal waste such as wood, wood waste, straw, sugarcane, etc…) through different processes: (1) direct combustion - thermal(2) gasification - conversion of biomass solid to syngas (CO and H_2) (3) pyrolysis – thermal decomposition of biomass solid fuels into liquid fuels in the absence of oxygen.
- Wave power (ocean power) is the transport and the capture of the energy by ocean surface waves and conversion of this energy to electricity via wave energy converters.
- Marine current power is a marine energy obtained by harnessing the kinetic energy of marine currents such as the Gulf Stream. Marine current turbines convert the energy from the marine current (kinetic energy) to electricity (marine generators are used to harness the kinetic energy in the marine current).
- Ocean thermal energy conversion system (OETC) uses the temperature difference between cooler deep and warmer shallow or surface ocean waters to run a heat engine and produce useful work, usually in the form of electricity. However, the temperature differential is small (low thermal efficiency) and this impacts the economic feasibility of ocean thermal energy for electricity generation.
- Geothermal power is the electricity generated from geothermal energy (thermal energy generated and stored in the earth). This include dry steam power plants, flash steam power plants and binary cycle power plants.

Figure 2 Renewable Energy Systems

A comparison of the total electricity net generation by source (fossil fuel, nuclear, renewable), regions, countries and type of renewables (hydro, wind/biomass, and solar/tides/waves) are shown in Figures 3- 5. Figure 3 shows the total electricity net generation by source (fossil fuel, renewables and nuclear) for different regions in the world for the year 2010[11]. The data are presented in the triangular plot with the range for each axis from 0 – 100%. The data shows that the Central and South America regionsare performing very well with respect of the development and the use of alternative and clean power systems. More than two third of the total electricity is produced from renewable power systems (67% renewables, 2% nuclear and 31% fossil fuel). Europe is coming next with 26% renewables, 25% nuclear, and 49% fossil fuels (half of the total electricity is generated from clean energy systems – renewables and nuclear). For North America and Eurasia, 18% of the total electricity is produced from renewables, 17% from nuclear and 65%from fossil fuels. For Africa, 17.5% of the total electricity is produced from renewables, 2% from nuclear and 84% from fossil fuels. For Asia and Oceania region, 7% renewables, 16% nuclear and 77% fossil fuels. For the Middle East region, 2% of the total electricity generated was produced from renewables, 0% from nuclear and 98% from fossil fuels. The Middle Eastern countries rely heavily on fossil fuels especially natural gas for the production of electricity.

Figure 4 shows the total electricity net generation by source (fossil, renewables and nuclear) for different countries during 2010 [11]. The countries in the top corner of the triangle use mostly renewables sources to generate electricity where neither nuclear nor fossil fuels were used to generate electricity. The countries in the bottom right corner of the triangle is nuclear energy dependent whereas the countries in the bottom left corner of the triangle is fossil fuels (coal or natural gas) dependent. France and Belgium used more nuclear energy to generate electricity in 2010. For France, 76% of the total electricity is generated from nuclear, 14% from renewables and 10% from fossil fuels. For Belgium, 51% of the total electricity is generated from nuclear, 9% from renewables and 40% from fossil fuels. Norway and Canada are examples of countries where more renewable energy was used to produce electricity. For Norway, 96% of the total electricity is generated from renewables, 0% nuclear and 4% from fossil fuel. For Brazil, 85% of the total electricity is generated from renewables, 3% nuclear from and 12% from fossil fuel. Other countries such as Algeria, Saudi Arabia, United Arab Emirates, Qatar, Jordan 97% to 100% of their total electricity in 2010 was generated from fossil fuels.

Figure 5 shows the total electricity net generation by renewable sources (hydro, wind/biomass and solar/tides/waves) for different countries during 2010 [11]. The data are presented in the triangular plot to demonstrate the type of renewable energy system that is developed for each country. The countries in the top corner of the triangle in Figure 5 use mostly wind and biomass sources to generate electricity (no hydro and solar/tides/waves sources were used to generate electricity). The countries in the bottom right corner of the triangle rely more on solar/tides/waves energy to produce electricity (no hydro and wind/biomass sources were used to produce electricity). Finally the countries in the bottom left corner of the triangle use mostly hydro power to generate electricity (no solar/tides/waves and wind/biomass sources). The data in Figure 4 shows for example for Norway, 96% of the total electricity is generated from renewables, 0% nuclear from and 4% from fossil fuel. From this total renewables power produced in Norway in 2010, 99% is from hydro and 1% wind/biomass sources. For Algeria, only 1-2 % of the total electricity generated in 2010 was from renewables. All the power generated from renewables is attributed to hydro power (100%). In Germany, 19% of the total electricity generated in 2010 was from renewables. From this total renewable energy, 71% is from wind and biomass, 11% is from solar/tides/waves and 18% from hydro power. Germany and Spain are two examples of countries where more than 50% of the total renewable energy is coming from wind/biomass and solar/tides/waves.

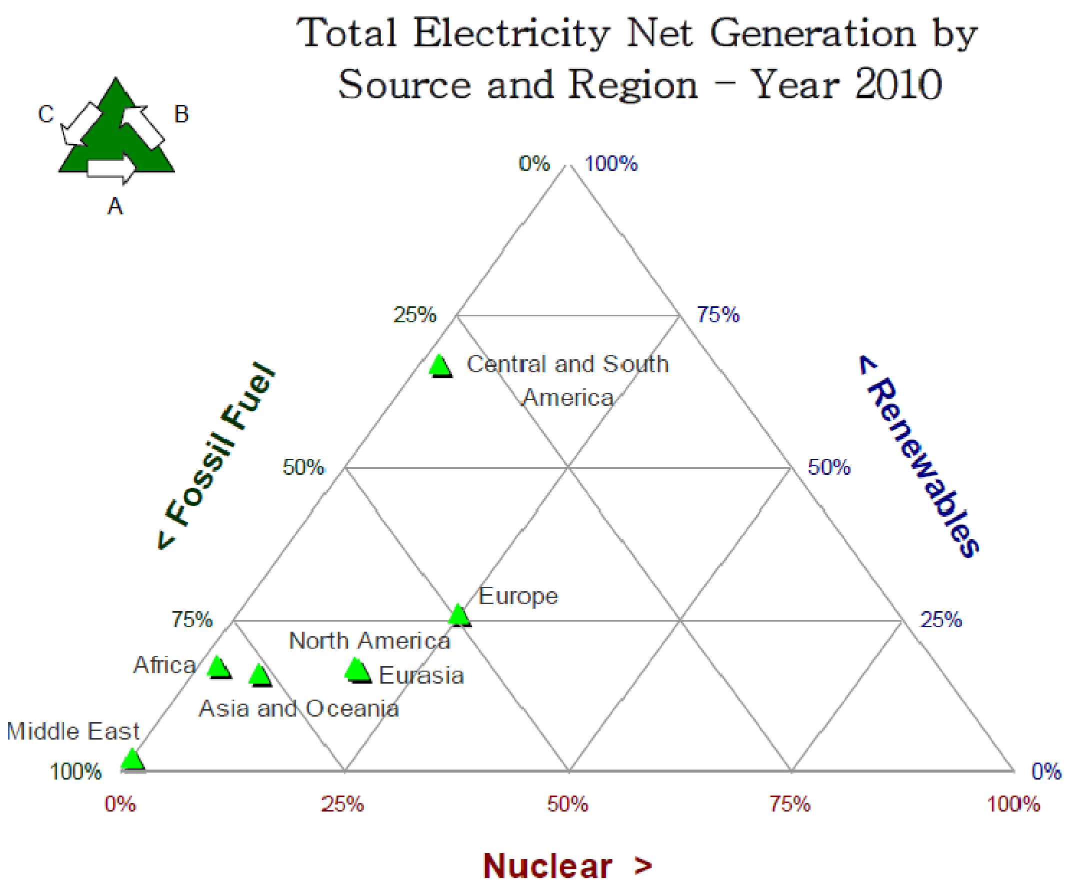

Figure 3 Total Electricity Net Generation by source and by regions in 2010

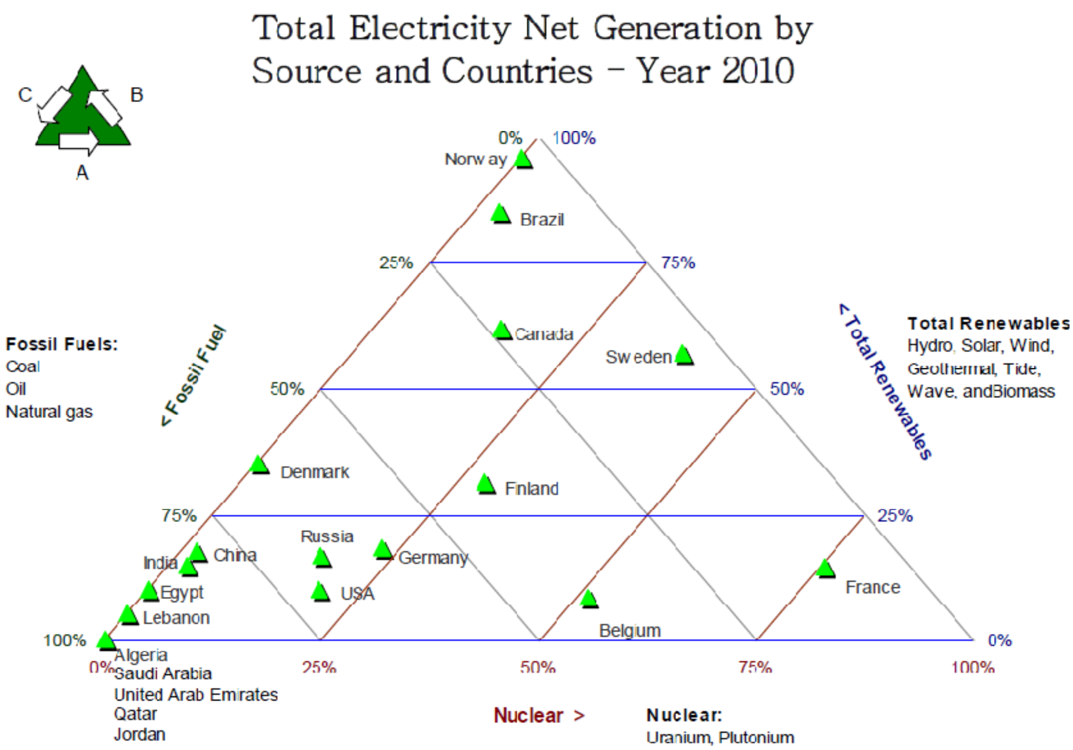

Figure 4 Total Electricity Net Generation by source (fossil fuels, nuclear, renewables) and by countries in 2010

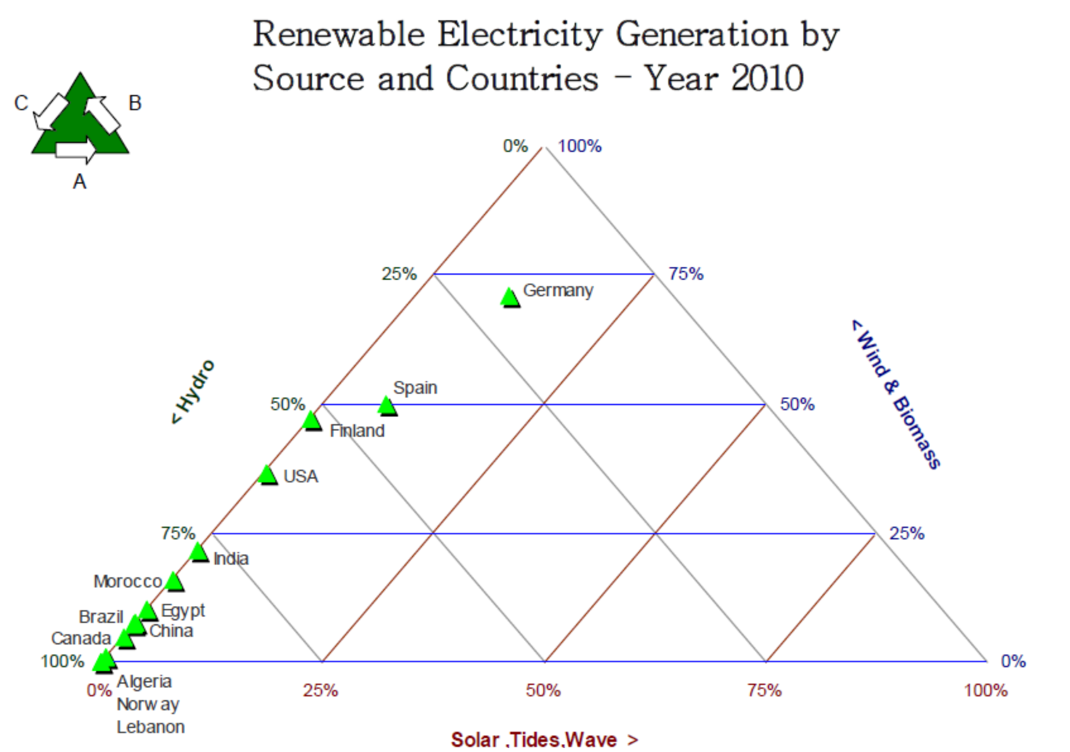

Figure 5 Total Electricity Net Generation by renewable source (hydro, wind/biomass, and solar/tides/wave) and by countries in 2010

2. Comparison of the Resource Intensity, Operational Parameters and Status of Power Systems

Renewable Power Systems draw their energy from natural sources: sun, wind, wave, tidal, geothermal, and biomass. Their construction incurs a capital cost which can be large. They occupy land area [10]. Materials and energy are consumed to construct and maintain them. Construction and operation have associated carbon footprint (emissions associated with the construction, operation and maintenance of the renewable power plants) [10]. A comparison between renewable, fossil fuel and nuclear power systems is performed in this study. The comparison includes (1) the resource intensity, (2) operational parameters and (3) status of the current power systems:

2.1 Resource Intensity:

- Capacity intensity – Construction: This is the capital used for the construction of power system per unit rated power ($/kW). The rated or nominal power output is the power the system delivers under optimal conditions. Coal, oil, and natural gas (fossil fuels) fired power plants operate much of the time at optimal conditions [10]. Renewable power systems do not operate most of the time at optimum conditions because the minimum level of energy (solar radiation for solar power, wind and current velocity for wind and marine current power, wave height for wave power, etc.) needed to operate at optimum conditions is not met all the time.
- Capital intensity – Fuel: This is the cost of fuel per kW of power generated ($/kW).
- Area Intensity: This is the land area used for the power system per unit rated power (m^2/kW)
- Materials intensities: This is the total materials used for the construction of the power plant (Kg/kW)
- Energy intensity - construction: This is the total energy used during the construction of the power plant (MJ/kW)
- Energy intensity - fuel: This is the total energy from the combustion of fuel used to generated electricity (MJ/kW)
- CO_2 Intensities –This is the total carbon dioxide (kg of CO_2) released to the atmosphere during the construction (equipment used during the construction of the power plant) and the combustion of fossil fuel (kg/kW)

2.2 Operational Metrics:

- Capacity factor (%): this is the fraction of time the power system operates at maximum power (or rated power). The power system does not operate at maximum power because the natural resource is not available all the time or due to maintenance.
- System efficiency (%): this is the efficiency of which the fuel or resources is converted to electricity.
- Life time – The expected time the power system will remain fully operational (years). Current installed capacity: The total global rated capacity of a given power system (GW).
- Growth rate (%): the rate at which the installed capacity grows each year.
- Delivered cost: The cost to generate one kilowatt-hour of electrical energy ($/kW).

3. Results

A comparison between the resource intensities, operational parameters and the status (current installed capacity, growth rate and delivered cost) of fossil fuel (coal and natural gas), nuclear and renewable power systems is presented in this paper. The renewable energy systems include offshore or land based wind power, offshore wind power, bioenergy or biomass based power, hydro power (earth dam and steel reinforced concrete), tidal power (barrage), wave power, tidal power (current), solar energy (PV poly-silicon and PV single crystal), and geothermal power (shallow and deep) [12-13]. Figure 6 shows the material intensity (materials used for the construction of the power plant) versus the area intensity for conventional (coal and natural gas) and alternative power systems (nuclear and renewables). The results show that some of the renewable power system such as hydro power (steel reinforced concrete and earth dam), tidal power – barrage and wind power – offshore and wave power use more materials during the construction of the power plant compared to conventional (coal, natural gas) and nuclear power systems. The tidal power – barrage has the highest material intensity. The material intensity for tidal power –barrage is 8 times than coal and natural gas power plants. Solar power systems have the lowest material intensities compared to the other renewables, fossil and nuclear power systems. Figure 6 shows also that most of the renewable energy systems use more area: 50 to 150 times than conventional (coal and natural gas) and nuclear power systems except geothermal power.

The energy (MJ/kW) and capital ($/kW) intensities for the construction of the power plants are presented in Figure 7. Natural gas power plant show the lowest energy and capital intensities compared to all power systems. Renewable power systems such as hydro power – steel reinforced concrete, tidal power – barrage, geothermal power – deep, wave power, and solar power show high energy intensities with the highest for geothermal power - deep. Solar power systems not only use more energy during the construction of the power plant (high energy intensity) but also present the highest capital intensity compared to all power systems. The capital intensity for solar plant (PV) is 20 times than the natural gas power plant.

The energy (MJ/kW) and CO_2 (Kg/kW) intensities during the construction of the power plants are shown in Figure 8. The results show a linear variation of the energy with CO_2 emissions. The more equipment or energy is used during the construction of the power plant the more CO_2 will be produced. The results also show the renewable power systems are not carbon free – emissions are released to the atmosphere during the construction of the renewable power plants and also during the maintenance of the systems. The results in Figure 8 show that the natural gas power plant has the lowest energy and CO2 intensities. In the other hand, hydro power – steel reinforced concrete plant has the highest energy and CO2 intensities. It is also noted that conventional (coal and natural gas power systems) and nuclear power systems have lower energy and CO2 intensities during the construction of these plants compared to all the renewable power systems except geothermal power – shallow and wind power – land based.

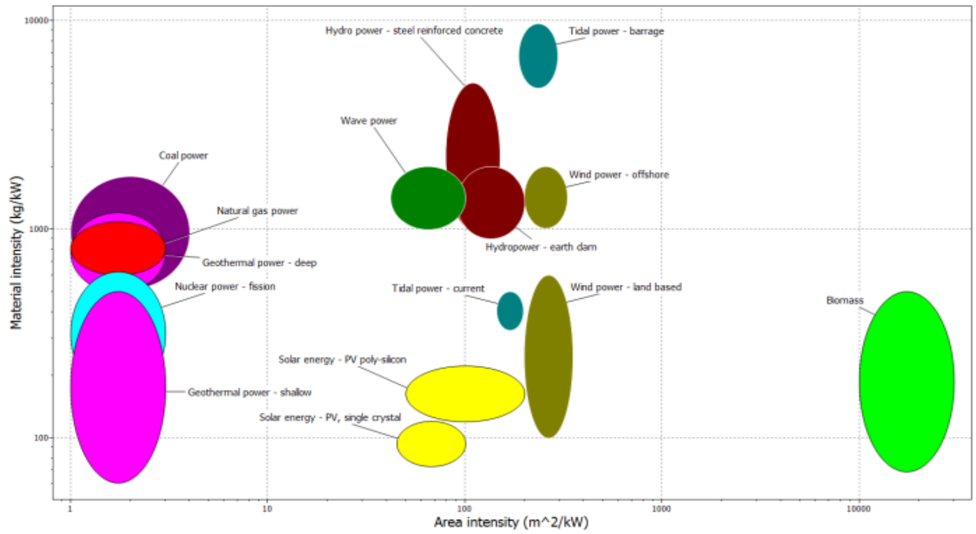

Figure 6 Material and Area Intensities of Renewable, Fossil and Nuclear Power Systems

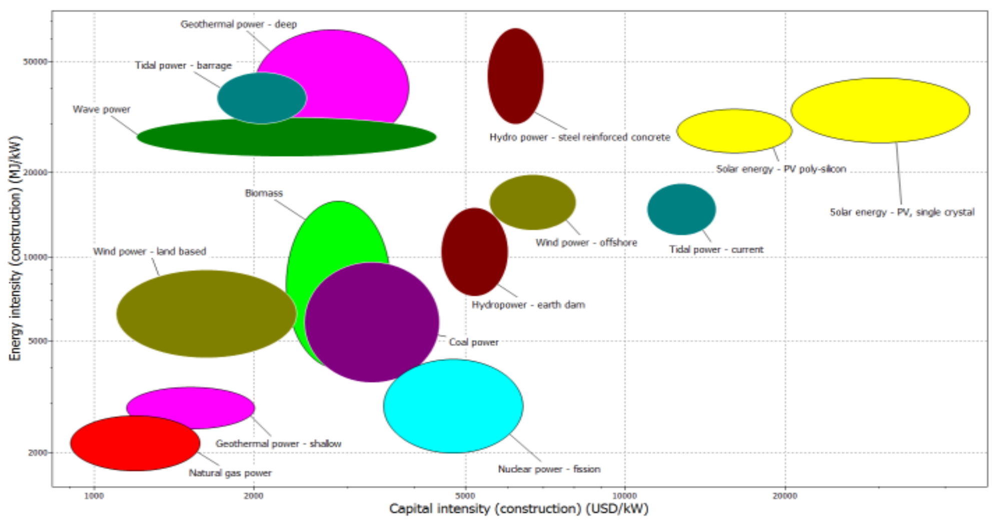

Figure 7 Energy and Capital (Construction) Intensities of Renewable, Fossil and Nuclear Power Systems

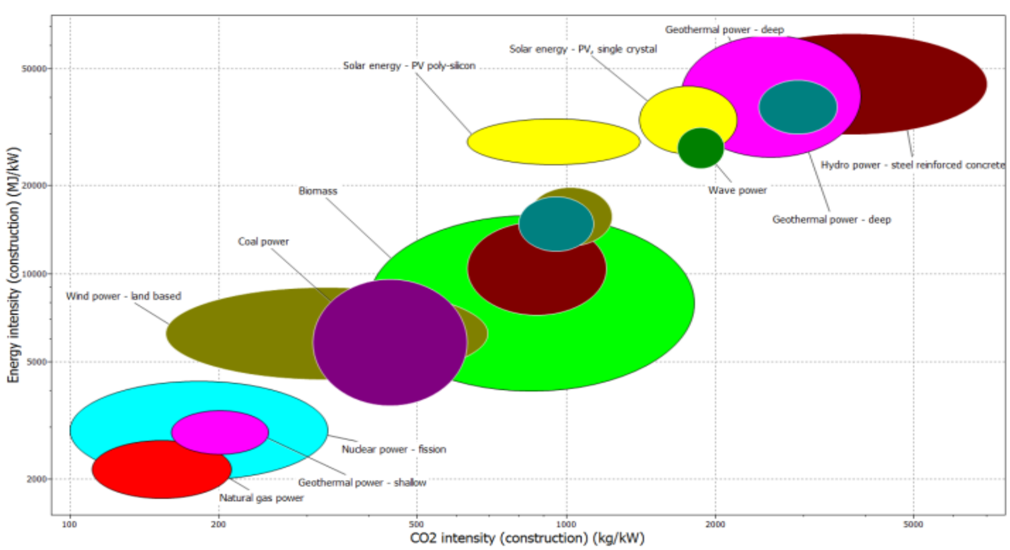

Figure 8 Energy and CO2 intensities (Construction) of Renewable, Fossil and Nuclear Power Systems

Figure 9 shows the operational parameters of the conventional and alternative power systems. The results presented in Figure 9 shows the system efficiency versus the capacity factor. The results show low system efficiency for some of the renewable power systems such as solar power, wave power, and geothermal power – shallow. For example the system efficiency of solar power is only 10% to 20% compared to 30-50 % for conventional (coal, natural gas, combined cycle) and nuclear power systems. Other renewable power systems such as wind power – offshore, wind power – onshore, tidal power – barrage, tidal power – current, hydro power show the same of better system efficiency than the conventional power systems. The hydro power has the highest system efficiency (75-80%). Figure 9 shows also an important operational parameter – capacity factor. This the fraction of time the power system operates at maximum power. Solar power not only has the lowest system efficiency (10 to 20%) but also the lowest capacity factor. The capacity factor for solar power is 10% compared to 80% for conventional power system (coal and natural gas power systems). All the renewable and nuclear power systems show lower capacity factor compared to fossil fuel power systems except geothermal power – shallow.

The expected time the power system will remain fully operational (life time)versus the capacity factor are presented in Figure 10. Some of the renewable power systems such as solar power, wind power, wave power and tidal power – current show lower life time (20 - 25 years) compared to conventional and nuclear power systems (35 years). The hydro power, and tidal power (barrage) plants show the highest life time (~ 80 years).

The current installed capacity and the delivered cost of the power systems are presented in Figure 11. The coal power plant has the highest current installed capacity with 2000 GW, followed with natural gas power plants (1000 GW) and hydro and nuclear power plants (~ 400 GW). Some of the renewable power systems such as wave power and tidal power – current have very low installed capacity since they are still is the research and development and testing phases. For the delivered cost, renewable power systems such as geothermal power – shallow, wind power – land based and hydro power – earth dam show same or better delivered cost compared to conventional (coal, natural gas) ad nuclear power plants. In the other hand, other renewable power systems such as tidal power – current, wind power – offshore and solar power show high delivered cost (10 – 20 times more) compared to conventional and nuclear power systems.

5. Conclusion

Energy, water, food and climate change are the key challenges facing the world in the future and are interconnected. A new approach is needed for an integrated solutions which takes into account the inter connections of all these sectors. The energy sector plays an important role in this inter-connection. What type of energy needs to be used to generate electricity: (a) fossil fuel power systems but with the incorporation of new clean combustion technologies, (b) nuclear power systems, and (c) renewable power systems? What type of renewable energy systems: wind, solar, hydro, biomass, geothermal, ocean energy? Beside the availability of the natural resources and the cost of the power systems, what are the other criteria or the parameters (resource intensities and operational parameters) that can be used for the selection of the renewable power systems?

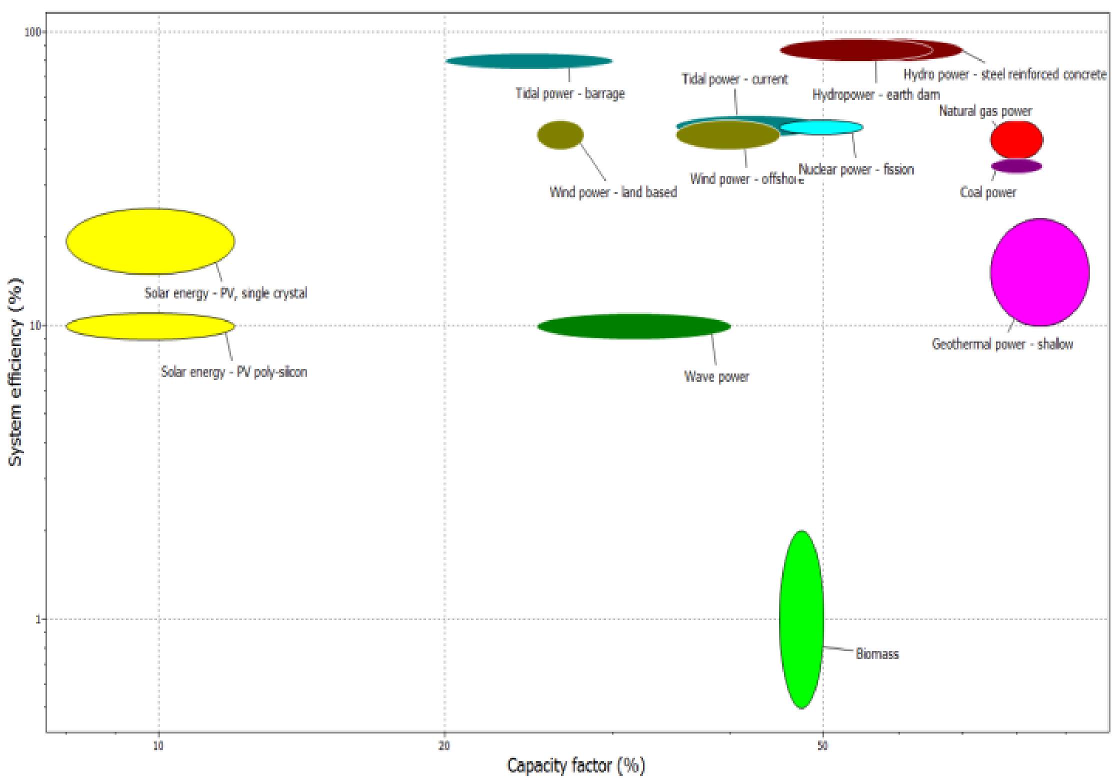

Figure 9 Operational Parameters (System efficiency and Capacity Factor) of Renewable, Fossil and Nuclear Power Systems

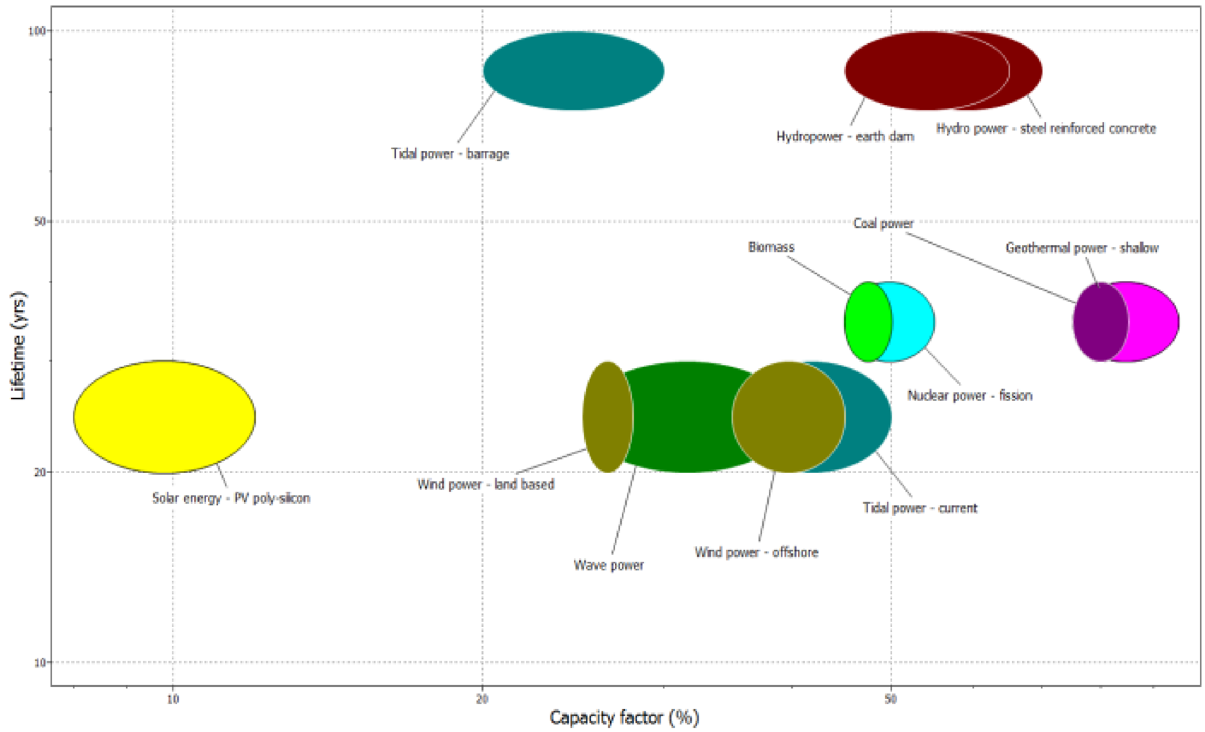

Figure 10 Life Time and Capacity Factors of Renewable, Fossil and Nuclear Power Systems

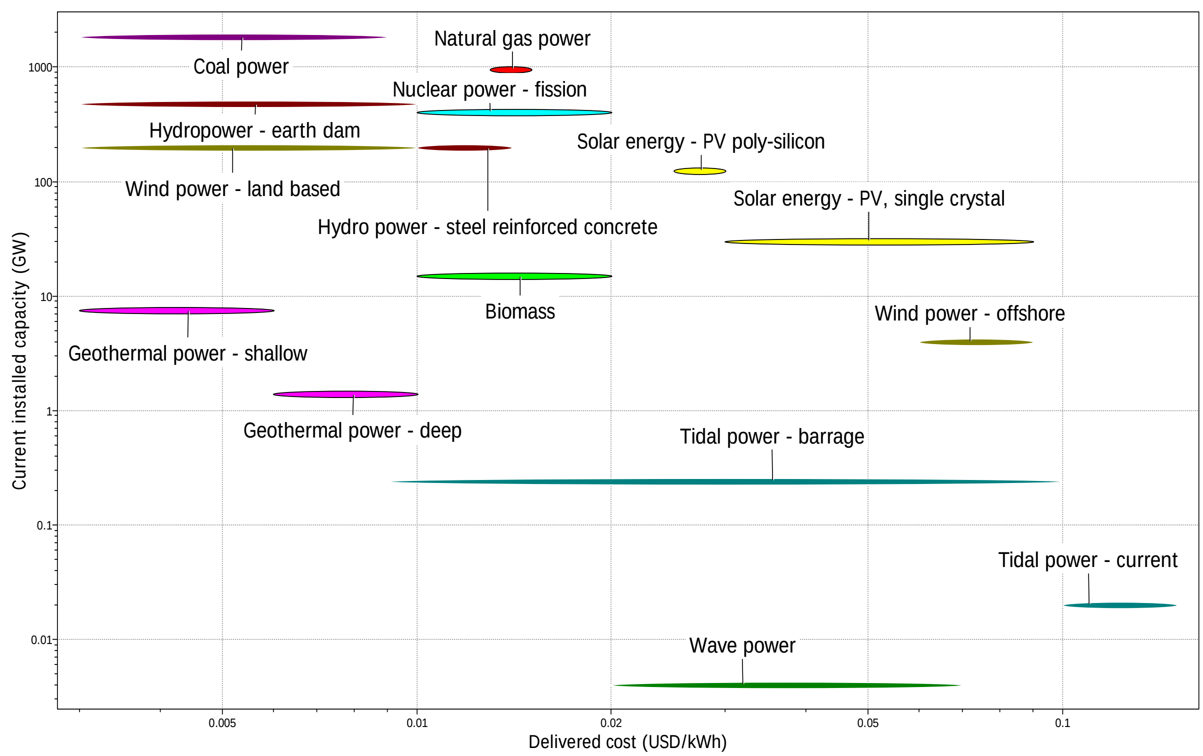

Figure 11 Current Installed Capacity and Delivered Cost of Renewable, Fossil and Nuclear Power Systems

This paper presents a comparison of the resource intensity, operational parameters and the status of renewable, fossil and nuclear power systems. The results show:

- Materials intensity: the renewable power system including hydro power, tidal power (barrage), offshore wind power, and wave power use more materials during the construction of the plant compared to conventional (coal, natural gas) and nuclear power systems.
- Area intensity: renewable energy systems use more area reaching 50 to 150 times theconventional (coal and natural gas) and nuclear power systems except geothermal power plant.
- The energy and CO_2 intensities – construction of the power plants: emissions are released to the atmosphere during the construction of the renewable power plants. The conventional (coal and natural gas power systems) and nuclear power systems have lower energy and CO_2 intensities during the construction of these plants compared to all the renewable power systems except geothermal power (shallow) and onshore wind power plants. Hydro-power system has the highest energy and CO_2 intensities during the construction of the power plant.
- Capital intensity – Construction: solar power system has the highest capital intensity compared to all power systems. It takes more capital and energy to construct the same nominal generating capacity
- Operational parameters - systems efficiency and capacity factor: the system efficiency of solar power is only 10% to 18% compared to 30-50 % for conventional and nuclear power systems. Solar power has also the lowest capacity factor. The capacity factor for solar power is 10% compared to 80% for conventional power system (coal and natural gas power systems). Geothermal power has the highest capacity factor 75-95%.
- Life time: Some of the renewable power systems such as solar power, wind power, wave power and tidal power (current) show lower life time (20 - 25 years) compared to conventional and nuclear power systems (35 years). The hydro power, and tidal power (barrage) plants show the highest life time (~ 80 years).

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