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Energy-Water-Carbon Interconnection: Challenges and Sustainable Solutions Methods and Strategies

Chaouki Ghenai

Ocean and Mechanical Engineering Department, College of Engineering and Computer Science, Florida Atlantic University, 777 Glades Road, 36-177, Boca Raton, Florida, 33431 U.S.A.

Abstract

This paper presents information on the interconnections or linkages between the energy, water and carbon foot prints. The concerns, issues and challenges regarding the energy production, water consumption and climate change for the Middle Eastern and North African (MENA) countries will be discussed. The population and economic growth will drive the MENA energy demand. The energy demand is expected to double by 2030. The MENA electrical power generation sector relies on fossil fuels (natural gas and oil) and it is producing high greenhouse gas (GHG) emissions per capita. MENA countries have the lowest per capita water resources but the water consumption is very high. Sustainable solution methods and strategies with respect to water use and management, electrical power generation and CO2 emissions are needed. Water is a key element in energy resource (coal, natural gas, oil, and uranium) extraction, refining and processing; electric power generation using conventional and alternative energy systems (fossil fuel and nuclear power plants using steam turbines, concentrated solar power CSP and hydro power); cooling of power plants; and CO2 emission control technology (CO2 scrubbing process – remove of CO2 from power plant gas stream). Sustainable energy systems for power generation (solar PV and wind power or water free electrical power generation), and new alternative cooling systems for fossil and nuclear power plants are needed to reduce water consumption and CO2 emissions. A large amount of energy is also used and high CO2 emissions are produced to extract, supply, treat and use fresh water and for desalination plants. A water oriented strategies (conservation, efficiency, reuse, smart fresh water use and renewable energy systems for desalination plants) can significantly reduce the energy consumption and CO2 emissions. The development of sustainable and water free electrical power generation systems and smart water management strategies will contribute to the mitigation of the climate change caused by increasing greenhouse gas (GHG) emissions.

Keywords: *Water-Energy-Carbon Nexus, MENA Countries, Water for Energy, Energy for Water, Sustainable Solutions and Strategies, Renewable Energy, Energy Efficiency, Water Management, Climate Change*

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 (See Figure 2). For example the energy is used for water extraction, distribution and treatment [2-3]. Likewise, water is used for electricity generation in power systems (steam turbine engines) and renewable power systems (i.e. concentrated solar panels and hydro power). Furthermore,

* Corresponding author. Tel.: +5612973943
Fax: +5612972825; E-mail: cghenai@fau.edu
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energy is used for food production (equipment used in the agriculture sector) and the food price 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 have left measurable and undebatable effects of the climate (temperature increase, flood, hurricanes, and other natural disasters). Consequently, the environmental stress is noticeably changing the resources of energy (move from fossil fuel energy to clean energy 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 as shown in Figure 2. The type of power systems (conventional power systems, nuclear and renewable power systems) will play an important role in these inter linkages.

Figure 1 Energy, water, and food inter connections

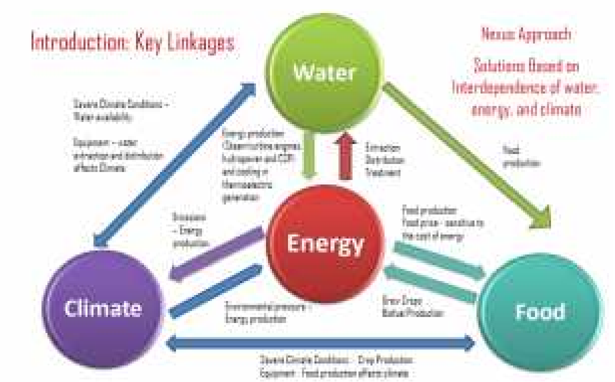

Figure 2 Key Linkages: Energy/Water, Energy/Climate, Energy and Water/Food

Today most of the global energy demand is derived from the combustion of gas, oil and coal. The reliance on fossil fuels is expected to diminish in the coming decades due to (1) the new emissions regulations – reduction of carbon dioxide and other greenhouse gases (NOx and Sox for example), (2) the reduction of the coal, oil and natural gas reserves, (3) the need to reduce the dependence on foreign imports (use local resources), and (4) the projected triple increase in the energy demands by 2050 [8]. How this energy will be generated when the oil, gas and coal reserves become depleted. Nuclear and renewable energies are the 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 small land 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. 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 high temperature are used to heat up water into steam which drives a steam turbine connected to a generator that produces 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 in the blast-furnace coke for smelting iron. 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. 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, compress and 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 plant is higher than the one using steam turbine according to Carnot. In combined cycle, a gas turbine produces electricity and its waste heat runs secondary steam turbine, reaching an overall efficiency beyond 50%.

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 several issues 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 demands (80%) by 2050 [8]. Renewable energy technologies that can be integrated in the present and future energy systems includes solar, wind, hydro, bioenergy, geothermal, and ocean (wave, current, temperature gradients) as source of renewable energy [10].

1.1 Water for Energy

Energy industry is water intensive [11-14]. Water is used for the energy extraction and fuel production, electrical power generation, energy transportation and energy storage a shown in Figure 3. Water is used for the production of coal, oil (conventional oil, oil sands, gas to liquid, coal to liquid) , natural gas (conventional and shale gas: fracking is water intensive) and biofuels (growing and refining: ethanol production from sugar corn; biodiesel production from soybean and palm oil; and syngas fuels and hydrogen). Water is also used for electrical power generation. Thermal fossil fuel, nuclear, biomass plants and concentrated solar power use water in the boiler feed for steam generation and the cooling process (steam condensing). Hydropower uses water for electricity generation. Water is also used for energy transportation (coal slurry pipelines) and energy storage (pumped storage hydroelectric).

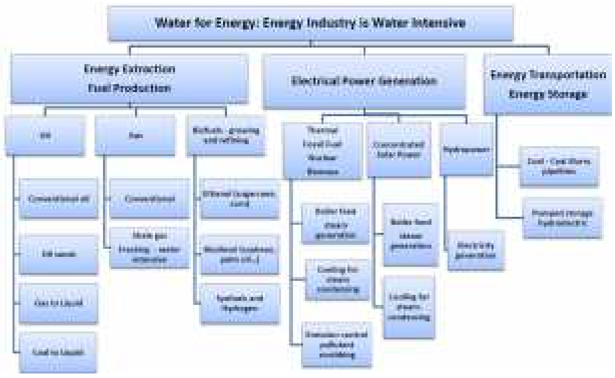

Figure 3 Water for Energy

1.2 Energy for Water

Water industry is energy intensive [11-12]. Energy is used for water supply, distribution, water purification; wastewater treatment and water use (see Figure 4). Energy is used for pumping water: ground water is more energy intensive than surface water. Energy is also used for the distribution and collection of water, water purification (surface water needs more treatments and is more energy intensive than ground water), pumping and treatment of waste water, and water desalination (energy intensive compared to fresh water treatments).

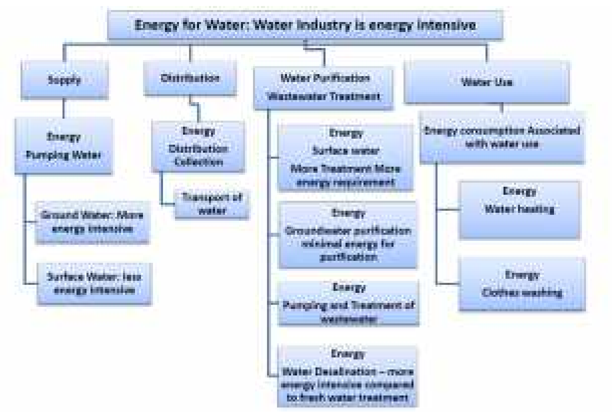

Figure 4 Energy for Water

2. Concerns, Issues and Challenges

The energy demand is expected to increase due to population growth and the decrease of the fossil fuel resources (See Figure 5). The projected world energy consumption using conventional fossil fuels (coal, oil and natural gas), renewable resources and nuclear will continue to grow for the next two decades. How this energy will be generated when the oil, gas and coal reserves become depleted.

Issue # 1: Energy

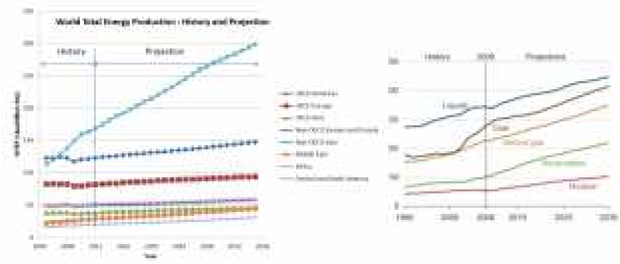

Figure 5 World Total Energy Productions and World Energy Consumption by Fuel

The second issue is related to the carbon foot print and climate change. The projected world energy related carbon dioxide is expected to increase as shown in Figure 6. The atmospheric changes caused by both natural process and energy production activities (increased green-house gas (GHG) emission and particulates matter PM) are responsible for climate change. The development of advanced technologies for pollution-free energy is needed for the reductions of the carbon foot print and climate change mitigation. The climate change will affect the way energy will be produced in the future and is the most significant driver affecting the world's supply of water.

Issue # 2: Carbon Foot Print

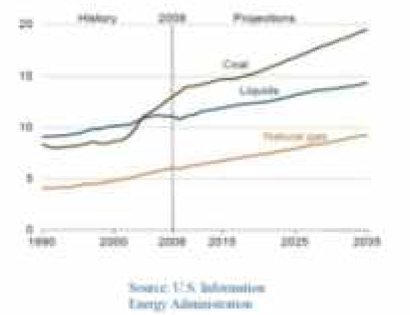

Figure 6 World Energy Related Carbon Dioxide by Fuel Type in Billions Tons

The third issue is related to the availability of water resource. Figure 7 shows the total available world water resources: 97% is sea water (non-drinkable), 2.5% is fresh water but frozen and 0.5% fresh water (aquifer, rainfall, natural lakes, reservoirs, and rivers. The 0.5% available fresh water is used for domestic, industrial, and agriculture applications. Figure 8 shows the percentage of water use for domestic, industrial and agriculture in the world, low and medium income countries and high income countries. For low and medium income countries 82% of the total water is used for agriculture. This water is removed from the source without return to the source (see Fig.8). For high income countries 59% of the water is used for industrial application (thermoelectric power generation, hydroelectric, manufacturing and food processing for example). Most of this water is used for thermoelectric and hydroelectric power generation. This water returns to the source after the use during the cooling of the power plants (non-consumptive) as shown in Fig.8.

Figure 7 Water Resources

Figure 8 Water Use: Domestic, Agriculture and Industry

3. Statistical Data: Water, Energy and Carbon

The total available renewable water resource per capita, the total water withdrawal and use, the total electricity generation, the total renewable electricity generation and the total amount of carbon dioxide (CO2) per capita for the Middle Eastern and North African (MENA) countries and a comparison with high income countries will be discussed in this paper.

3.1 Water Statistics: Total Renewable Water Resources and Water Withdrawals

Figure 9 shows the total renewable water resources per capita for the MENA and high income countries. The data shows a small amount of renewable water is available for most countries in the MENA region with the exception of Iraq and Iran. Countries such as Saudi Arabia, United Arab Emirates, Bahrain, Qatar, Kuwait and Libya have little or almost no renewable water resources. The total renewable water resource that is available per year for each MENA countries is negligible compared to the high income countries such as USA, France and China as shown in Fig.9. In the other hand the water withdrawals (m^3/person) for the Middle Eastern and North Africa countries is among the highest in the world. The Middle East and North Africa are respectively second and third in water withdrawals and use after North America as shown in Figure 10. The MENA countries have low renewable water resources but the water consumption and use for these countries is high.

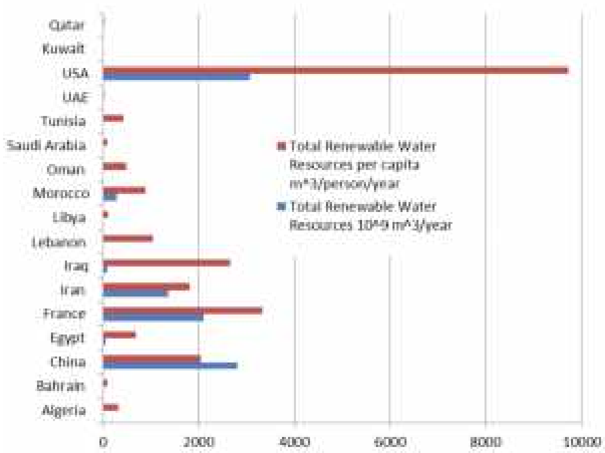

Figure 9: Total Renewable Water Resources: MENA and High Income Countries

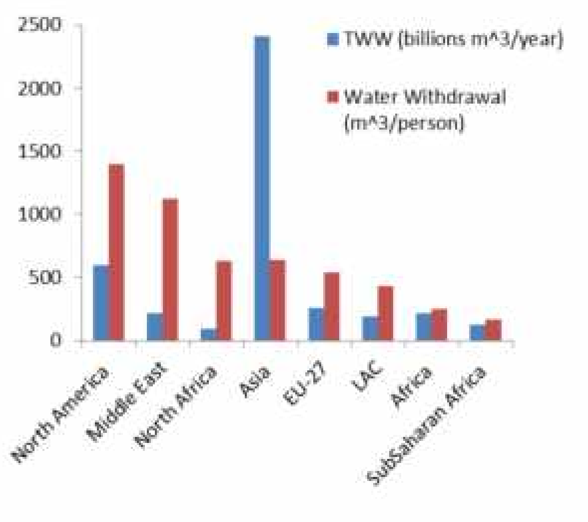

Figure 10 Water Withdrawals by Region

Water withdrawals and use by sectors (agriculture, industrial and domestic), regions (North America, Latin America and Caribbean, Europe, Asia, Middle East, and North Africa) and countries are shown in Figure 11 and 12. Figure 11 shows that most (80 - 85%) of the water withdrawals for Middle East and North Africa is used for agriculture and small percentage (<10%) is used for industrial applications. The water used for agriculture is removed without return to the source (consumptive water). In addition high percentage of this water is lost in the distribution pipes and during the use of non-efficient irrigation systems in the MENA countries. Compared to other regions in the world, Europe and North America for example more than 55% and 45% respectively of water is used for industrial applications. Most of this water is used for thermoelectric and hydroelectric power generation. This water returns to the source after being used for the cooling of the power plants for thermoelectric power plants and electricity generation for hydroelectric power plants (non-consumptive water). Figure 12 shows that for all the MENA countries, less than 10 % of the total available water are used for industrial applications.

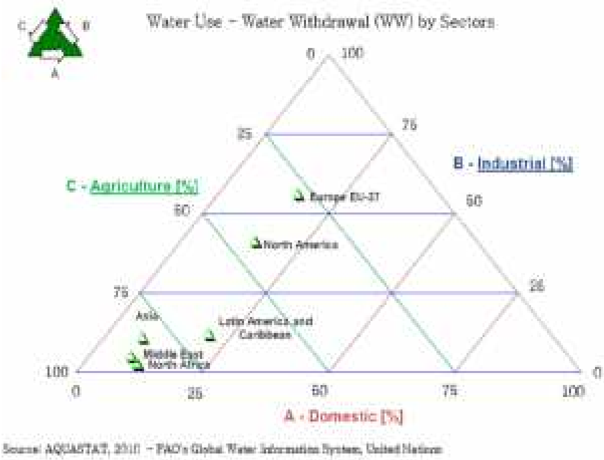

Figure 11 Water Withdrawals by Sectors and Regions

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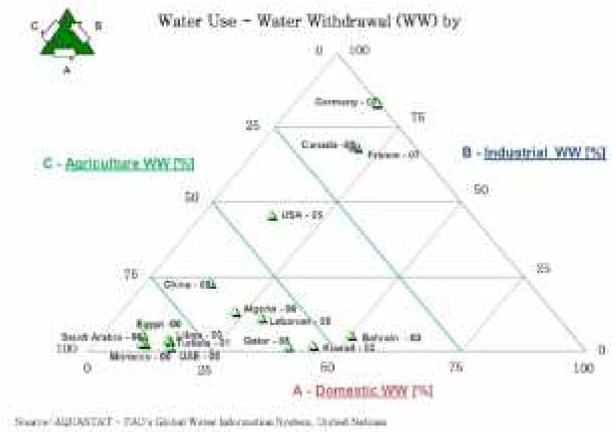

Figure 12 Water Withdrawals by Sectors: MENA versus High Income Countries

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 13-15. Figure 13 shows the total electricity net generation by source (fossil fuel, renewables and nuclear) for different regions in the world for the year 2010 [15]. The data shows that the Central and South America regions are 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.

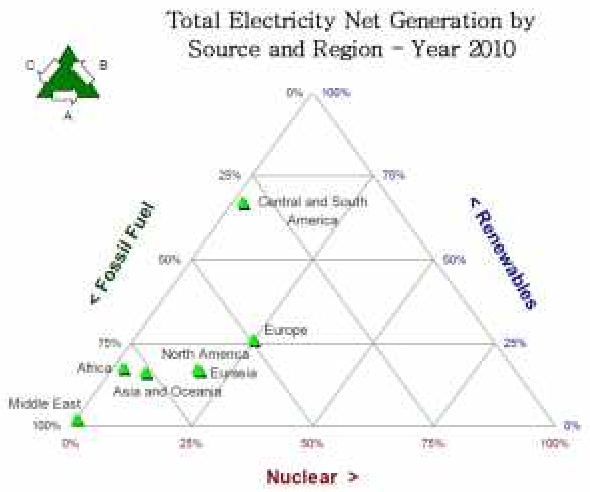

Figure 13 Total Electricity Net Generation by Source and Region

Figure 14 shows the total electricity net generation by source (fossil, renewables and nuclear) for different countries during 2010 [15]. 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 are 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.

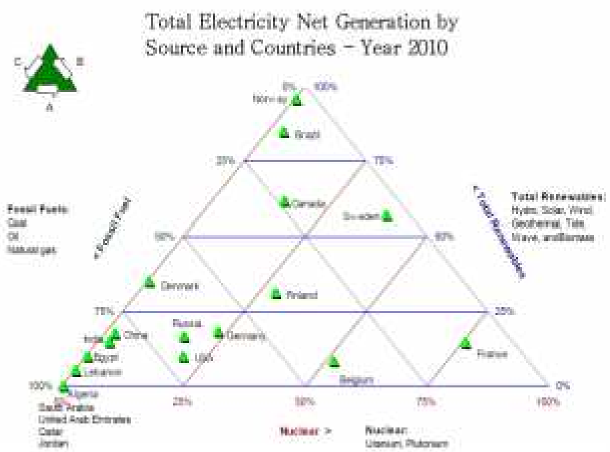

Figure 14 Total Electricity Net Generation by Sources and Countries, 2010

Figure 15 shows the total electricity net generation by renewable sources (hydro, wind/biomass and solar/tides/waves) for different countries during 2010 [15]. 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 15 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 14 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.

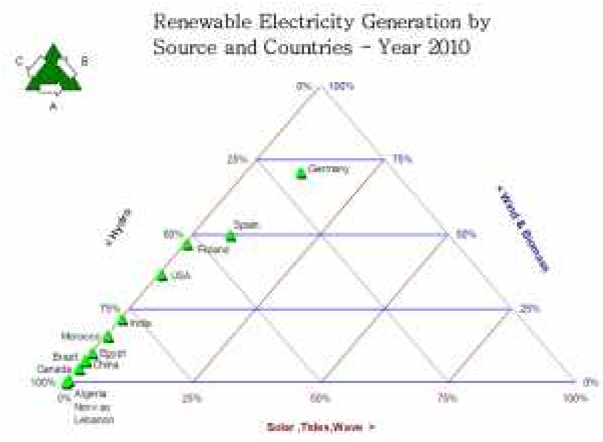

Figure 15 Renewable Energy Net Generation by Sources and Countries

Figure 16 shows the 2011 energy related carbon dioxide (CO2) per capita for different countries [15]. The MENA countries such as Qatar, Kuwait, Oman, UAE, Bahrain, and Saudi Arabia have the highest CO2 per capita that exceed by far the world average and some of the industrial and high income countries such as USA, Canada, Germany, and France. More sustainable energy systems (renewable and energy efficiency power systems) are needed in the MENA countries to control the high amount of CO2 emissions in these countries and for the mitigation of the climate change.

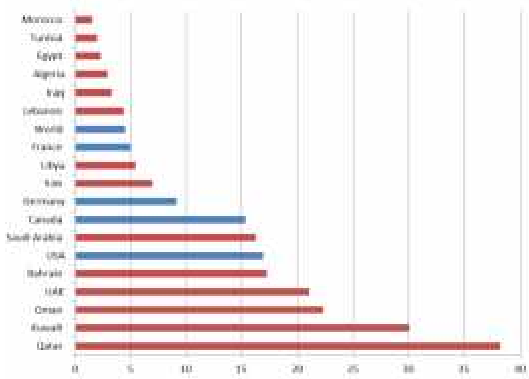

Figure 16 Tons of CO2 per Capita by Countries in 2011

4. Sustainable Solution Methods and Strategies

4.1 Sustainable Solutions for Energy and Carbon

Renewable energy, alternative fuels (Biodiesel, Syngas Fuels, Biogas, Hydrogen) and energy efficiency are sustainable solutions for power generation, transportation, building and industrial applications. Renewable energy technologies that can be integrated in the present and future energy systems includes solar, wind, hydro, bioenergy, geothermal, and ocean (wave, current, temperature gradients) as source of renewable energy. Renewable energy such as solar and wind energy can help to supply part of the energy demand in the MENA countries and reduce the greenhouse gas and particulate matter from the combustion of fossil fuels.

4.2 Sustainable Solutions for Energy, Water and Carbon

The development of solar and wind energy in the MENA countries will help not only to produce clean energy from renewable resources but eliminate also the use of water during thermoelectric power generation (production of steam for fossil fuel power plants and cooling of the power plants).

Solar PV system uses renewable resources, produce clean energy (no greenhouse gas emissions during the use of the system) and no (or little) water is used during the electricity generation. The PV system has low efficiency (10-20%), low capacity factor (10-20%), relatively high cost (Levelized Cost of Energy LCoE) and produce intermittent power (need energy storage systems). New PV solar energy systems (new generation photovoltaic cells and the use of single axis and dual axis trackers) are needed to increase the efficiency and reduce the cost of the PV systems. The integration of single and dual axis trackers with the PV systems can increase the efficiency of the PV system by 30-40%.

Wind energy system uses also renewable resources, produce clean energy (no greenhouse gas emissions during the use of the system) and no (or little) water is used during electricity generation. The efficiency of the wind energy system and the capacity factors are between 20-40%. Wind power systems produce also intermittent power (need energy storage systems).

4.3 Solution Methods and Strategies for Water Management

In addition to the development of solar and wind energy systems that will eliminate the use of water during electricty genertaion from fossil fuel power plants, water management (water conservation, water efficiency and water reuse) strategies are also needed [16-17].

Water conservation will help the reduction of water use. Water efficiency consists of conserving water with water saving technologies (showerheads and weather based irrigation controllers for examples), developing water loss metering (reduce water losses in the pipes), water audits, leak detection, repair and replacement. Clean and more efficient technologies need to be used for waste water treatments and for desalination systems. For desalination systems, distillation (use heat) and reverse osmosis (use pressure to force seawater through polymer membrane) are used to separate salt from water. Both distillation and reverse osmosis are energy intensive with high cost ($0.40/$m^3$ to $1.50/$m^3$). Saudi Arabia uses 1.5 millions barrels of oil daily at its desalination plants to produce fresh water but generate high GHGs emissions from the combustion of fossil fuel. Clean energy sytems such as solar power desalination plants with more efficient PV cells and more efficient membranes are needed to reduce the cost of deslaination and reduce the GHGs emissions from the combustion of fossil fule in desalination plants.

4.4 Integrated Modeling Approach for Energy Planning, Water Management and Climate Change Mitigation Assessment

The use of integrated modeling tools for energy planning, GHGs reduction, water management and their effects on the societal stability and change are needed for the MENA countries. For example the long range energy alternatives planning (LEAP) software can be used for energy planning and climate change mitigation assessment. This will help to evaluate current energy demand and supply pattern and explore alternative long range energy scenarios in the MENA countries. Water evaluation and planning (WEAP) software can be used to evaluate sustainability of current water demand and supply patterns and explore alternative long range water scenarios.

5. Conclusion

Climate change caused by greenhouse gases and particulate matters from fossil fuel combustion is the most significant driver affecting the water supply. The power sector is highly vulnerable to changes in water resources. Thermo electric power generation: Fossil fuel (coal, natural gas), nuclear and renewable (Concentrated Solar Power and biomass) require water as working fluid to generate steam and for the cooling process (condensing the steam). Sustainable energy systems are needed to supply the energy demand, produce clean energy (reduce the carbon foot print) and reduce or eliminate the use of water for electricity generation. Solar PV and wind energy systems use renewable resources, produce clean energy (no GHGs emissions during the use of the systems) and no (or little) water is used during electricity generation.

The MENA Countries rely mainly on fossil fuels to generate electricity, the GHGs emission per capita is high, the renewable water in these countries is not available and the water consumption per capita is high. The solution methods and strategies for the MENA countries consist of: (1) development of solar and wind renewable energy systems, (2) development of energy efficiency systems for power generation, buildings, transportation, and industry, (3) diversification of energy systems (fossil fuel, renewable and nuclear power systems), (4) water management: water conservation, efficiency, reuse and development of sustainable solar desalination systems, and (5) effective integration of energy and water policy planning and climate change mitigation assessment (impacts of energy production on GHGs emissions and water resources and vulnerability of power plants to changes of water resources).

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