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Opinion

Electricity without Fuel

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Abstract

Most power plants produce electricity by converting a mechanical motion into alternating current (AC). Photovoltaic solar panels convert an electromagnetic flux of light into direct current (DC). In general, electric energy can be harvested from a flux in the environment or from a change of the environment itself. One can produce electricity from mechanical, chemical, thermal, electromagnetic (light), or another physical flux, or from a change of temperature, chemical composition, or a physical field: gravitational, magnetic, electric, mechanical stress and strain, etc. Flux examples are mechanical motions of air and water, surface waves and tides, heat fluxes due to a temperature gradient, solar light, and a chemical flux (such as humidity propagation in the atmospheric air or diffusion of salt in water due to a gradient of salinity at the mouth of a fresh-water river flowing into an ocean). Environmental changes are under-used in energy production, although people are exposed to daily and seasonal changes of the environment, which include changing air temperature, pressure, humidity, and composition, tidal changes of the gravitational field, and less periodic changes of the geo-magnetic and electric fields. Production of electricity without fuel from the environmental changes and fluxes requires a durable infrastructure for a cost-effective utilization of the "semi-perpetual" energy resources.

Keywords

Fuelless; renewable electric power generation; semi-perpetual energy; sustainability

1. Introduction

The semi-perpetual rotation of the Earth around itself and around the Sun, motion of the Moon around the Earth, the sunlight, the heat from the Sun, the warm interior of the Earth, and the cold deep space generate energy fluxes and environmental changes on our planet and provide numerous possibilities for a fuelless generation of electric energy, only a tiny fraction of which is currently used by people. While burning the fossil fuels (coal, oil, and natural gas) requires a cheaper energy infrastructure, the accumulation of carbon dioxide and other "greenhouse" gasses in the atmosphere poses a threat for life on the whole planet. Use of the nuclear power unavoidably results in a nuclear waste and radioactive pollution. On the long timescale, fuelless energetics (Figure 1) is anticipated to be the most sustainable source of electricity [1, 2]. Thus, building a long-lasting infrastructure for producing electricity without fuel is a prudent investment [2, 3].

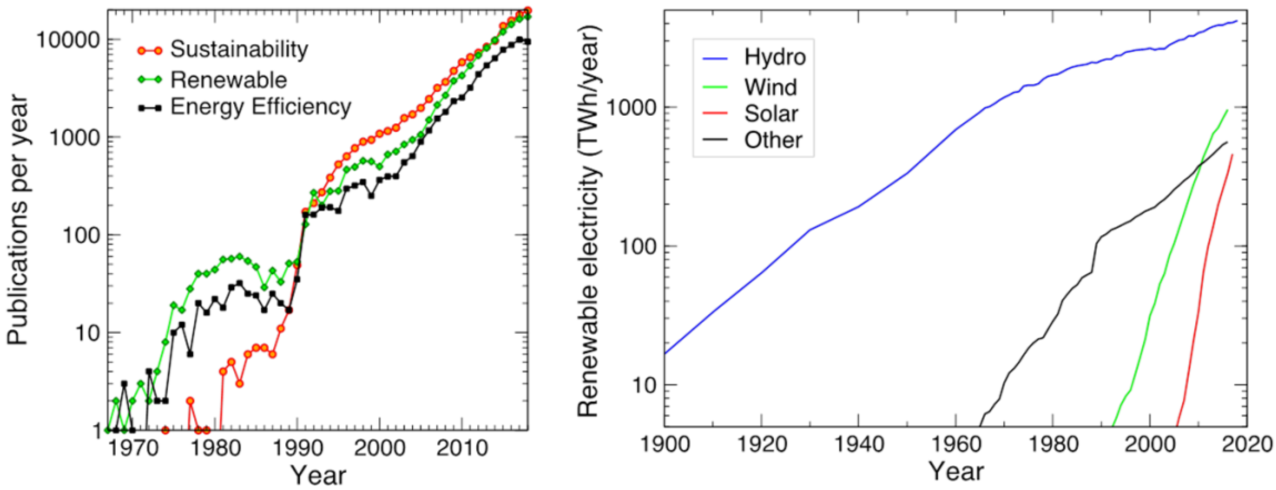

Figure 1 Left: The number of publications per year on sustainability, renewables, and energy efficiency (retrieved 12.12.2019 from Web of Science, https://clarivate.com). Right: global annual electricity production (terawatt-hours per year) by hydro, wind, solar, and other renewable (biofuel, geothermal, wave and tidal) power plants [1, 3].

One can compare the levelized cost of electricity (LCOE) with fuel and operating costs. For example, the average LCOE for new hydroelectric power plants is 4 to 5 cents per kilowatt-hour (kWh), while the operating cost for existing hydro-plants is around 1 cent/kWh, see Figure 2. The cost of fuel for fuelless power plants is zero. With reduction of the construction and capital costs of wind and solar plants, their construction becomes economically profitable, see Figure 2.

The main obstacle for the fuelless energetics is the cost of infrastructure. Indeed, the capital cost of fuelless power plants is typically higher than that of a dispatchable generation using fossil fuels, see Table 1. Nevertheless, due to the governmental incentives, the number of fuelless power plants is increasing (Figure 3) and their total power is growing [1, 3]. Recently, the installed cost of solar photovoltaic (PV) power plants became lower than that of wind generators, see Figure 2.

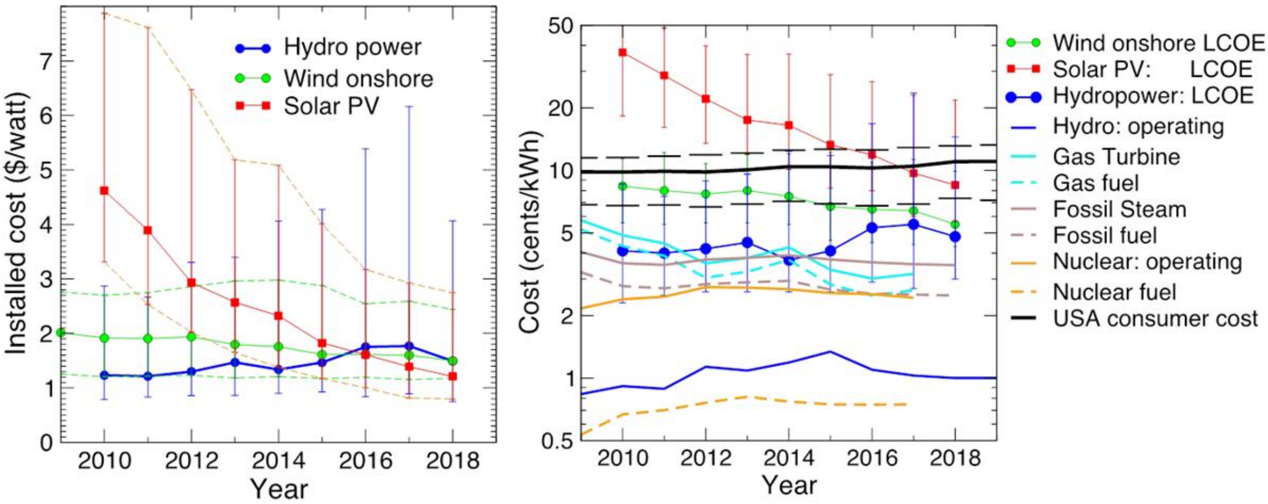

Figure 2 Left: Global weighted average and spread (5% to 95%) of installed cost (2018 USD per watt) [3]. Right: The levelized cost of electricity (2018 cents per kWh) [3], operating and fuel cost for various types of fuelless and fueled power plants [1, 2] compared to the electricity price for the U.S. consumers: average, residential (upper), industrial (lower) [1].

Table 1 The average construction cost (2018 USD per Watt) [1, 2, 3]; estimated capital cost (cents/kWh), operation and maintenance (O&M), fuel cost, average operating expenses (Σ=O&M+Fuel+Transmission), levelized cost of electricity (LCOE) for new electric power plants entering service in the USA in 2023 (2018 cents per kilowatt-hour) [1], and global electricity cost (cents/kWh) per source in 2018: average (spread 5%-95%) [3]. Cost of electricity from conventional fuels is estimated for the USA [1, 2], and can be compared to the price of electricity for average (11 cents/kWh), residential (13), commercial (11), and industrial (7 cents/kWh) consumers in July 2019 [1]. Construction cost of hydro- and geothermal power plants strongly depends on location and resource availability.

Cost	**Construction**	**Capital**	**O&M**	**Fuel**	**Σ**	**2023**	**2018**
	$/W		**2018 U.S. cents/kWh**				**cents/kWh**
Hydro	1 – 7	3.0	0.76	0	0.9	3.91	4.7 (3-13.6)
Wind onshore	1.647	2.78	1.26	0	1.5	4.28	5.6 (4.4-10)
Solar PV	2.343	3.71	0.88	0	1.17	4.88	8.5 (5.8-22)
Geothermal	2.5	2.46	1.33	0	1.47	3.94	7.2 (6-14.3)
Biomass	4.116	3.73	1.57	3.75	5.48	9.21	6.1 (4.8-24)
Coal steam	0.82	0.71	1.014	2.527	3.54	4.02–4.28	4 – 10
Gas turbine	0.92	1.72	0.528	2.648	3.176	4.9 – 7.75	5 – 9
Nuclear	5.945	3-6	1.69	0.747	2.44	5.4	6 – 11

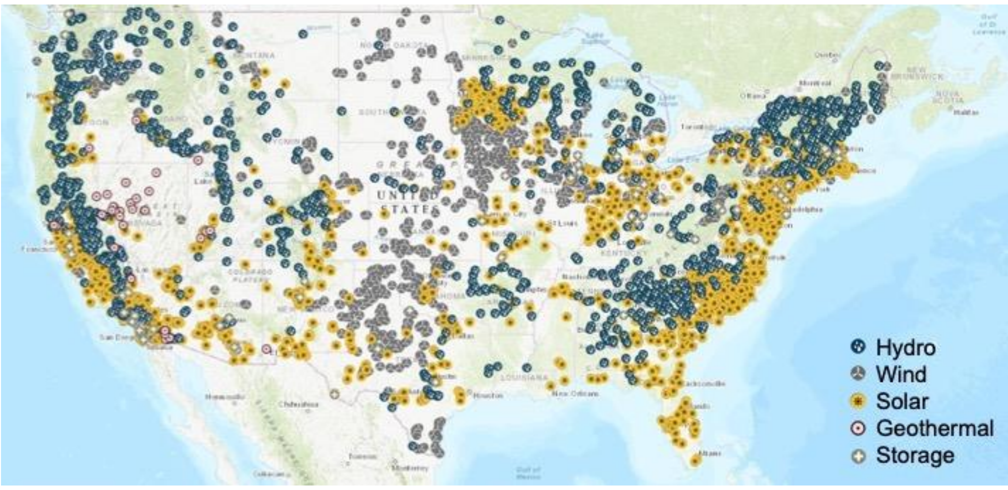

Figure 3 Hydroelectric, wind, solar, geothermal, and battery storage power plants in the continental USA in 2019. Source: U.S. Energy Information Administration [1].

Most of operating fuelless electric generators use an available flux of a mechanical, thermal, or solar light energy. However, there are many kinds of environmental energy fluxes, and not all of them are used. In addition, one can generate electricity from a change of the environment.

Energy sources (section 2.1), transformations (2.2), transmission and storage (2.3), cost and price (2.4) are considered in section 2. Fuelless generators and complex energy solutions are discussed in section 3. Consumption and future directions are in sections 4 and 5. Summary is in section 6.

2. Energy

2.1 Sources of Energy

The Solar system has plenty of energy. The effective temperature of the photosphere of the Sun is T_s=5778 K; its total luminosity is 3.846×10^{26} watt [4]. The cosmic microwave background radiation temperature (of the deep space) is only T_b=2.725 K. A hypothetical Carnot heat engine utilizing the temperature difference between T_s and T_b would have an efficiency $\eta=1-T_b/T_s=0.9995$ and produce 3.844×10^{26} watt of energy.

In addition to light, the Sun produces a solar wind (a flux of ions) and generates a changing magnetic field. Moving planets with warm interiors have mechanical (kinetic), gravitational, and thermal energy. These are additional sources of energy in the Solar system.

An average surface temperature of the Earth is around T_e= 288 K (15C), with extremes from 184 K (–89.2 C) in Antarctica to 343.8 K (+70.7 C) in Iranian Lut Desert [4, 5]. Available temperature differences (including T_s-T_e and T_e-T_b) can be used for power generation.

The Earth has a vertical gradient of temperature. Due to the primordial and radiogenic heat, interior of the Earth is warm (several thousand kelvins inside the core). There is a heat flow from interior to the surface, estimated at 4.7×10^{13} watt [6]. Partially used by geothermal power plants, this heat flux is small compared to 1.73×10^{17} watt of solar radiation received by the Earth [4].

Mechanical motion of the planets (the Earth and the Moon) changes of the surface acceleration and produces tidal waves, which are sources of energy. Rotation of the Earth and its motion around the Sun produces daily and annual changes of surface illumination and variations of surface temperature. The Earth has an atmosphere and is partially covered by water; winds and currents are fluxes of mechanical energy in the environment.

The Earth is not chemically homogeneous, it contains chemical and nuclear fuels. People burn fuels to produce heat, boil water to produce steam, and use steam to produce mechanical motion and generate electricity. However, evaporation of water into a dry air is also a source of energy. In general, energy can be harvested from a difference in composition or from a change of composition of a liquid or a gas. Thus, a fresh water flowing into a salty lake or an ocean is a source of energy, see Figure 4. Large rivers with a significant discharge (in 10^3 m^3/s) include Amazon (209), Congo (41), Orinoco (40), Rio de la Plata (22) with an outflow to the Atlantic Ocean, Padma/Ganges (38) to the Indian Ocean, Yangtze (30) to East China Sea, Yenisei (19.6), Lena (16.9), Ob' (12.4) to the Arctic ocean, Saint Lawrence river (16.8) and Mississippi (16.79×10^3 m^3/s) to the Atlantic Ocean.

A seasonal change of salinity of an ocean due to accumulation and melting of ice is also an energy source. One can generate electricity from a changing humidity of the atmospheric air. Nearly any increase of entropy can be converted to electricity. Unfortunately, a spread of pollution also results in an entropy increase, but generating electricity by polluting the environment is not recommended, although it is technically possible.

The Earth has a magnetic field, which is not constant. This field is weak. However, an electric loop surrounding a large area can generate a significant voltage from a changing geomagnetic field.

The Earth generates an electric field. Usually, a charge of the upper atmosphere is positive and the surface is negative [4]. If not harvested, atmospheric electricity produces thunderstorms.

Oceans cover approximately 71% of the surface of the Earth [4]. On water, electricity can be generated mostly from sunlight, wind, waves, tides, and currents [7]. Other resources include the temperature differences between water and air, water and clear sky (T_b=2.725 K in deep space), and the vertical gradient of temperature in water and air. Rain, water evaporation, changing weather and changing environment are energy sources.

In general, electricity can be produced from a flux or from a change of the environment. One can harvest solar light, thermal, mechanical, gravitational, chemical, magnetic, and electric energy. Fuelless power plants do not use nuclear and fossil fuels, but can indirectly harvest thermonuclear energy from the Sun and the heat flux from nuclear reactions in the Earth interior.

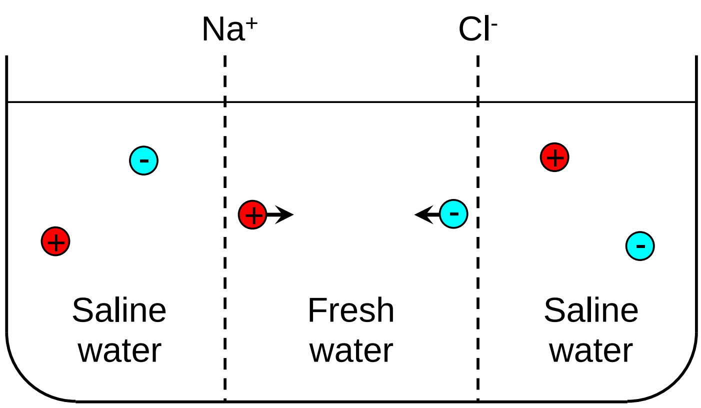

Figure 4 Electricity from a difference of water salinity is generated using two conductive ion-exchange membranes, one of which is transparent for Na^+ (but not Cl^-), the other – for Cl^- ions.

2.2 Energy Transformations

According to the energy conservation law, the total energy of an isolated system remains constant, although energy can transform from one form to another. A fuelless power plant transforms a fraction of the environmental energy into electricity. Technologies for the thermal energy conversion are quite old [8, 9, 10]; there is a rapid development of novel materials [11, 12] for renewable energy and sustainability [13], and particularly photovoltaics [14].

The Earth is not an isolated system: it receives a flux of energy from the Sun and emits energy into space. For as long as the Sun shines and the planets move (and have warm interiors), there will be some energy for fuelless electric generators.

2.3 Energy Transmission and Storage

Discovery of novel materials results in technological development. New technologies change economic models. Before the large-scale electrical power grids, fuel was transported to power plants that generated electricity where and when it was needed. Fuel was used to produce heat, temperature difference was transformed into mechanical motion, which was converted into electric current, which was delivered to consumers.

Electrical grid is a conducting network for delivering electricity from producers to consumers. High-voltage power lines are used to transport electricity over large distances. A high-voltage direct current (DC) power line has fewer losses than an alternating current (AC) line.

Fuelless energetics fundamentally differs from a dispatchable use of fossil fuels. Although a dispatchable renewable energy exists (examples are hydroelectric, geothermal and ocean thermal energy conversion power plants), many fuelless power plants (including solar and wind generators) produce electricity when environmental energy is available, and it should be stored until needed.

Energy storage is used to accumulate energy when it is available (and cheap), and release it when it is demanded (and more expensive). Hydroelectric energy storage using pumped-storage hydro-power accounts for 95% of all utility-scale energy storage in the United States in 2019 [2]. Battery storage is more compact and more feasible on a smaller scale; it can be mobile (as well as storage of hydrogen and renewable fuels). However, cost of batteries remains an economic factor.

Environment itself is an energy storage, if a change of the environment is used to generate electricity. One can encapsulate and insulate a fraction of the environment, so that its property does not change as quickly [15]. Next, electricity is generated from a difference between the encapsulation and the free environment. The larger is the encapsulation, the more energy can be extracted on demand. Such fuelless power plant reminds a pumped hydroelectric energy storage, in which the changing environment acts as a pump, and instead of water one can use thermal, mechanical (pressure, stress, or strain), gravitational (tidal), chemical (water salinity, air humidity and vapor partial pressure), magnetic, or electrostatic energy.

Phase transitions inside a storage medium are useful for a compact storage of energy in a changing environment. Phase transitions can release heat [16] or mechanical energy [17]. A magnetic phase transition alters a magnetic flux. A phase transition can alter a surface electric charge, similarly to a piezoelectric response to an applies mechanical stress. Electro-, magneto-, elasto-, and baro-caloric materials and effects can be used for energy storage and generation.

2.4 Cost and Price of Energy for Various Purposes

In general, price of electricity depends on a balance between an instant supply and demand. An acceptable cost of energy depends on place, time, and application. Cost of electricity is typically higher in energy-deficient and lower in energy-redundant places (although there are exceptions). Price can vary during daytime and at night. Some small-scale applications (like an electronic watch or a radio) require little energy, while factories and large consumers need more. Various sources of energy are appropriate for various purposes, and there is no single universal price per kilowatt-hour that fits them all.

The cheapest electricity typically comes from large hydroelectric power plants, with operating cost around 1 cent per kWh. However, hydropower is not ubiquitous and not available everywhere.

Size does matter. Electricity from larger power plants is usually cheaper than from smaller ones. When the cheapest hydro-power is already used, construction of new smaller-scale hydro-plants increases an average cost of hydro-electricity. In contrast, new wind generators are typically larger than the old ones, and an average cost of wind energy is decreasing with time [2, 3], see Figure 2.

With technological development, wind and solar power is becoming cheaper [13]. Figure 2 allows to anticipate that in the future the solar PV electricity [14] will become cheaper than wind power, while the difference in LCOE from offshore and onshore wind generators will become smaller. There is a reduction of cost of a battery storage [13], and one can reasonably expect a reduction of cost of electricity from unconventional and non-dispatchable sources with time.

Large solar power plants not only generate electricity, but also create temperature gradients and convection fluxes in the environment, which are additional sources of energy. There is a hope that in the future single-source power plants will be replaced by fuelless electric complexes, similar to that in Figure 5 (without underwater part, this electric complex can be constructed onshore).

Fueled power plants remain the major economic competitors of fuelless energetics. Penalties for the air pollution [18] make them less competitive. The long-term cost of altering composition of the atmosphere is our ability to breath and live on this planet [19]. Climate changes impact not only humans and living organisms, but also renewable energy generation [20].

Nuclear industry produces radioactive waste; annually up to 15 tones of beta-radioactive technetium-99 with a half-life of 211,000 years is added to the biosphere. There is an ongoing debate about cost and safety of nuclear power [21]. If one ignores safety, then the operating cost of a large nuclear power plant is relatively low, around 2.5 cents/kWh [2]. Nuclear safety is expensive, and it works similar to contraception, which reduces the probability of undesired events, but does not completely exclude them. Safety regulations are tightened after each major nuclear disaster, such as those on Chernobyl nuclear power plant in Ukraine on 26 April 1986 or on Fukushima Daiichi Nuclear Power Plant in Japan on 11-15 March 2011. In general, nuclear plants are not safe in places endangered by earthquakes, tsunami, flooding, avalanches, volcanoes, or a human factor.

3. Fuelless Generators

3.1 Conventional Fuelless Power

The hydro-, wind, solar, and geo-thermal generators account for the majority of fuelless power. They are flux generators: they convert into electricity the fluxes of water, air, sunlight, and heat.

3.2 Underused Flux Power

For low-cost electricity, a flux should have a sufficient power density in space during a substantial fraction of time. Currently, it is not economically feasible to utilize such short-term fluxes as avalanches, earthquakes, tsunami, volcano eruptions, or lightnings during thunderstorms. Although hydro-electricity is among the cheapest [1, 2, 3] and can be dispatchable, construction of small-scale hydro-plants on rivers with high seasonal variations of water discharge has a marginal profitability. Similarly, underused are short-term winds and hurricanes.

Other fluxes are steady but weak. An example is a heat flux due to temperature difference between the Earth surface and deep space. By using a filter, reflective for visible light but transparent in infrared, under a clear sky one can cool a fraction of the surface and use the temperature difference to generate electricity. A clear sky radiative cooling is also considered as a passive cooling technology for buildings [2, 22].

Ocean water has a vertical gradient of temperature, suitable for thermoelectric power [2, 7, 13, 23]. An underwater power grid would increase usability of the ocean thermal energy conversion.

Convection in water and air is a mechanical flux. People use horizontal mechanical fluxes (winds and currents), but underuse the vertical ones [24, 25, 26]. Some of the future fuelless generators can float in water and air to harvest the convective fluxes, see Figure 5.

Typically, there is an instant temperature difference between water and land or surface and air; a thermoelectric power plant can use the corresponding heat fluxes. Temperature differences can be harvested by a thermoelectric generator (Seebeck [8]), a heat engine (Stirling [9]), or a pyro-magneto-electric generator (Tesla [10]); their differences are in size, cost, and efficiency.

Water evaporation results in cooling. To generate thermoelectric power, one can use a river or a lake in a desert, or one can cover a fraction of an ocean surface, thus blocking evaporation and creating a greenhouse effect. In Figure 5, a field of photovoltaic panels alters the local temperature.

Evaporation from an ocean surface increases salinity and density of water. Covering a fraction of ocean surface, one can create convection fluxes in both air and water.

Chemical fluxes include propagation of humidity in air and salinity in water (see section 2.1); an example of a fuelless generator converting salinity difference into electricity is shown in Figure 4.

There is an electrostatic voltage between the ground (or water surface) and upper atmosphere, but an average harvestable electric current is weak.

For economic reasons, people do not build fuelless generators if the capital cost is high, but the outcome is small. Consequently, many environmental energy fluxes remain unused. There is a hope that technological development and building large-scale infrastructure (for example, an underwater electric grid in the oceans) will make underused flux power more economically attractive.

3.3 Fuelless Power from Environmental Changes

In general, electricity from the environmental changes is more expensive than a flux power. Sometimes, a changing environment produces a flux (examples include winds and tidal water currents) or a temperature difference (between objects with different heat capacity). As mentioned in section 2.3, encapsulation of a fraction of a changing environment creates a difference, which can be used for electric generation. However, not only a flux or a gradient in space, but also a change with time can be a source of electricity.

For example, a thermo-magneto-electric generator (TMEG) converts a change of temperature into a change of a magnetic flux through a coil, which generates electric current. Known for more than a century since the patent of Nikola Tesla [10], it works, although it is not economically justified. Nevertheless, there is a hope that invention of novel materials [11] or coupling TMEG with other devices will make it useful (if not for generating electricity, then may be for cooling) [27].

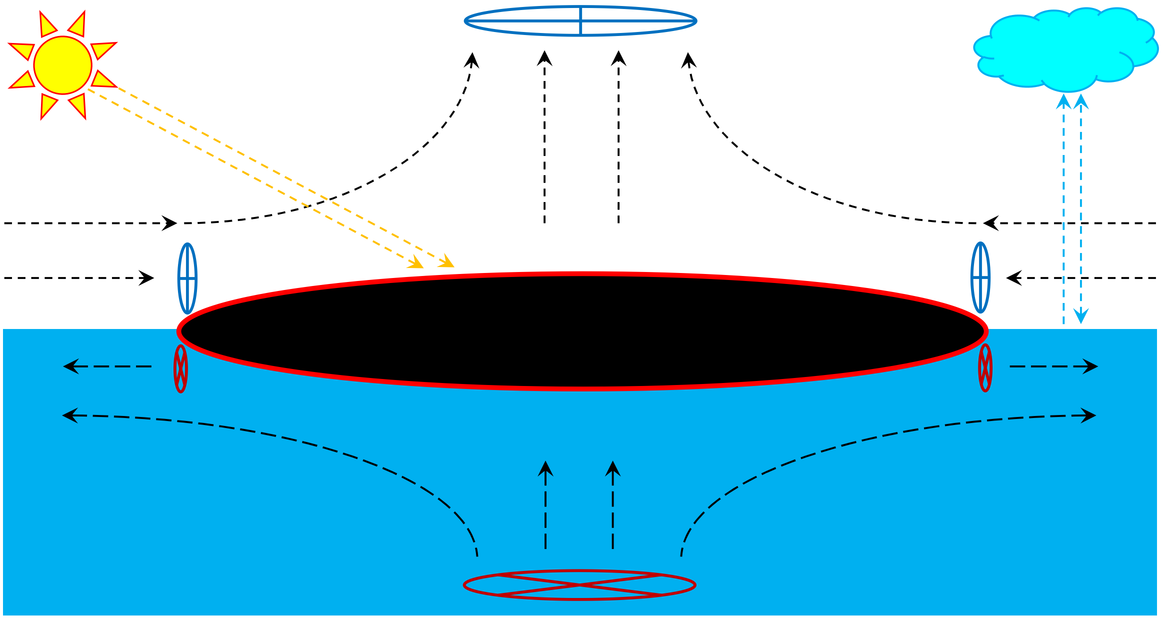

Figure 5 A model of a floating fuelless electric complex combining solar (black filled oval), wind (blue ovals with +), convection (ovals with horizontal elongation above in the air and below in water), water current (red ovals with X), wave (red perimeter of solar PV), and other fuelless generators. Shown are (reciprocating) convective flows in air (white) and water (blue), sunlight (orange dashed), water evaporation and rain (light-blue dashed arrows). See text in section 3.4.

3.4 Complex Use of Environmental Energy

A large enough power plant generates both electricity and environmental changes and fluxes, which are the sources of an additional energy. A complex use of both primary and secondary energy sources will provide more electricity, than a single-source fuelless power plant. The cost of an additional energy might be reasonable, if one augments a solar PV field by wind generators; one can also consider thermal [8, 9, 10, 23], convective [25, 26, 28], and other types of additional generators.

Figure 5 shows a model of a floating fuelless electric complex, which generates electricity from sunlight [29, 30], wind [24], water current [31], waves [7, 32], convection in the air [26] and water, temperature differences [8, 9], and probably even the salinity difference between the rain fresh water and ocean salt water (see Figure 4). As a cherry on a pie, one can add a conductive loop around the perimeter, which will generate voltage from fluctuating geomagnetic field. In addition, there are temperature changes [10], tides, air pressure fluctuations, atmospheric electricity, and geothermal heat below the ocean bottom. However, not all sources of energy are cost-effective to use [33].

In Figure 5, the field of solar panels is represented by the black oval; its perimeter with wave generators and other devices is shown as the red loop. Wind generators are schematically marked by the blue ovals with a cross; water generators are represented by the red ovals with X. Convectional generators in air (above) and water (below) are not to scale. Convection in the air and water is depicted by black dashed lines (short dashes in the air, long dashes in water). Similar to breeze, convective flows have reciprocating directions. The phenomena of water evaporation and rain are represented by the vertical light-blue dashed lines with arrows between the ocean surface and a cloud. Water evaporates from the ocean to the atmosphere, part of moisture returns back as rain, which falls both on the ocean surface and on the field of solar panels, where the rain water can be collected and used. Sunlight is the main source of power; solar light is cartooned by the orange dashed lines originating from the Sun (in the upper left corner).

Without the water part, a similar fuelless electric complex combining solar, wind, convective, and thermal generators can be used onshore.

While the sunlight is the dominant energy flux on the Earth, not all energy fluxes are generated by the sunlight. Geothermal heat comes from the Earth warm interior; the lunar (larger) and the solar (smaller) tides are caused by the changing positions of the Moon and the Sun relative to the rotating Earth. Complex use of primary and secondary energy from various sources should maximize outcome of the fuelless power generation. Thus, fuelless power plants can be expanded and transformed to electric complexes combining various types of generators.

4. Consumption

Large consumers obtain electricity from a power grid. They include industrial, transportation, commercial, and residential users. The U.S. consumers paid from 4 to 15 cents per kWh in 2019 [1]. As soon as the cost of electricity from the fuelless power plants of a particular type falls in or below this price range, their construction becomes profitable.

Small consumers can receive electricity from a mobile energy storage, charged periodically and delivered to a consumer. Energy transportation and storage is discussed in sections 2.3 and 5.

Far away from power grids, the price of electricity can be substantially higher, and less conventional fuelless generators can become economically viable. A robotic station (for example, an automatic weather station) in an uninhabited remote place (without an electric grid and without people) requires a durable long-lasting source of energy. Battery is not the best solution, due to a high cost of battery replacement. A long-lasting radioactive source of energy presents a long-lasting threat to the environment. A power plant with moving parts (e.g., a wind generator) requires periodic services. A solar panel requires periodic cleaning. A better solution is a fuelless source of energy, that does not require service for lifetime. Engineers can decide, whether it will be a simple thermocouple using temperature difference between the ground and the air, a more sophisticated geothermal plant, a more advanced thermo-magneto-electric generator harvesting changes of temperature of the atmospheric air, or another generator suitable for a particular application.

5. Future Directions in Energy Production, Storage, and Transportation

Zero fuel cost and a high installation cost are the competing factors that affect proliferation of the fuelless energetics. Diversification of energy sources, which include environmental fluxes and changes, is a challenge. Development of science and technology will decrease the cost and improve durability of energy infrastructure, needed for a complex use of environmental energy.

Topologically, an energy infrastructure is a network of "zero-dimensional" point objects (power plants, energy storage facilities, and consumers) linked by one-dimensional (1D) power lines. Historically [33], it is easier to obtain a permit for constructing a new point object (e.g., a power plant), than to allocate land for a new 1D object (e.g., a power line, a pipeline, or a road). Connectivity of the energy network is a problem. In the future, power of new generating sites may exceed the load limits of available transmission lines (if any), and alternative energy transportation technologies will enter the market. One can transport charged batteries, hydrogen, or renewable artificial fuels. Stationary energy storage facilities at the nodes of the energy network (preferably near generators and consumers) will be augmented by mobile energy storage. Technological advances result in a rapid reduction of cost of energy storage [13] and fuelless generation (Figure 2).

Energy sources for fuelless generation are distributed over large territories. Rapid construction of new generators and less rapid development of the grid power lines will create bottlenecks in energy transmission. If the high-voltage direct-current power lines are available, then long-distance transmission of electricity is cheap and efficient (with an added cost below 2 cents per kWh in the continental USA). However, transmission of energy across borders is problematic; this problem is political. The oceans and countries with a large territory (Russia, Canada, China, USA, Brazil, Australia, India, Argentina, Kazakhstan, Algeria, Congo, Greenland) possess significant resources for fuelless electric generation, while countries with a large population and developed industry (China, USA, European Union, India) are among the top electric consumers. Trans-border and trans-continental transmission of energy (from Iowa to Illinois, from Canada to USA, from Russia to China, from Africa to Europe, or from Australia to other continents) will not be limited to wires and cables. People will increasingly use transportable energy storage. In addition to use of mobile batteries (responsible for replacement of trolleybuses by electro-buses), one can produce hydrogen and other synthetic fuels, convert metal oxides into metals, etc. Transportation of the rechargeable sources of energy will compete with power lines (or their absence). There is a similar competition between pipelines and liquefied natural gas (LNG) carriers on the global market of the natural gas. This competition is between more durable lines and more flexible point energy carriers. In general, a line is more expensive to build, but cheaper to operate. Hence, the power grid will expand and become global. If the world did not change, then the power lines would win on a long timescale.

Competition between personal, local, national, and global interests shapes the energy market and affects environmental sustainability. Cooperation helps to build the global energy grid and increase trade of energy. Science provides new materials and technologies, which entertain consumers, enable space exploration and colonization of other planets, increase availability and diversity of sustainable fuelless generation, and reduce the cost of renewable electricity.

6. Summary

Environmental energy sources and their utilization by the fuelless power plants were considered. Importantly, electricity can be generated not only from a flux in the environment, but also from a change of the environment itself. Zero fuel cost and a high installation cost are the competing economic factors, which shape the future of fuelless energetics. Discovery of novel materials and technologies [11, 12] has a potential to lower the cost and increase a diversity of fuelless electric generators, suitable for a variety of consumers. Renewable energetics is growing [1, 2, 3, 13]; complex use of primary and secondary environmental energy sources will provide more electricity. The role of science is to push technology towards theoretical limits [34, 35].

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The author declares no competing interests. The author is the sole contributor to this work. The opinion of the author does not reflect the opinions or views of any international or governmental organizations, including the Ames Laboratory and the U.S. Department of Energy.

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