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Communication

Entropy theory of distributed energy for internet of things

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ABSTRACT

Entropy was first introduced in thermodynamics for describing the statistical behavior of molecules. In this paper, we use the entropy theory to describe the distribution and powering of small electronics in the era of internet of things. We refer the power transmitted from power plants to utility units as "ordered" energy for fixed sites, while refer the energy harvested from environment as "random" energy. Our conclusion is that the "ordered" energy is able to solve part of the power need for distributed electronics for IoTs, but the remaining part has to be supplied by the "random" energy harvested from our living environment using resources such as solar, vibration, motion and even thermal. The entropy idea defines the role played by energy harvesting as it will become increasingly important owing to the ever expanding usage of distributed electronics at the time of intelligence.

1. Energy and technological revolutions

In the history of human technology revolution, energy has played the most critical role (Fig. 1). Thermal energy was probably the earliest energy realized by human, from heating to cooking. Thermal energy was mostly supplied by burning biomass and latterly coal. Ever since the invention of steam engine, thermal energy was converted into mechanical energy, which results in the replacing of human labor by machine. Later, steam engine was used as the power source for railway transportation, which led to the first industrial revolution.

Starting from the invention of electromagnetic generator in 19th century, mechanical energy was converted into electric power. Owing to the unique characteristic of long distance transmission, electric power was quickly distributed worldwide and being used in every corner of our life. A conjunction of steam engine and electromagnetic generator is the foundation of modern power plant that directly convert highly concentrated energy sources such as coal into electric power for fast and long distance transmission. The dominant energy has been coal.

Since the exploration of oil around the world, liquid based fuels made automobile and aerospace industry possible. Oil is the most important form of energy for today's society, which has been referred to as "black gold". Any fluctuation in oil marked would impact the world economy significantly and it is one of the most important resources that the world is competing and grabbing for.

Ever since the invention of telegram and telephone, wired and wireless communication is an indispensable part of our life. With the development of semiconductor industry and microelectronics, human society enters the information technology area. The invention of and computers and internet has hugely impacted the way of information transfer, data sharing and the way the world works. Wireless communication and internet accessing are as important as food for human, and we cannot afford to have been disconnected from internet for a few hours in today's life.

As the world entering the era of internet of things (IoTs), sensor networks, big data, robotics and artificial intelligence, we are facing a lot of unknowns and challenges that we never expected or experience before. Every moving objects needs to be linked to the internet so that its motion and status being constantly tracked and monitored. By mimicking human behavior, talented robotics will be built, which will be operated by information derived from big data, the talents and wisdom of human could be challenged. But one thing we know is true, nothing works without electric power regardless how smart it can be! Therefore, in the new era of IoTs, robotics and artificial intelligence, what would be the energy to meet its needs? Besides coal and oil, what would be the new energy that will drive the era of IoTs? This is the objective of this article.

2. Energy for the era of IoTs and self-powering

Studies show that more than 30 billion of objects would be linked by IoTs by 2025. Sensors to be used to monitoring the location, moving

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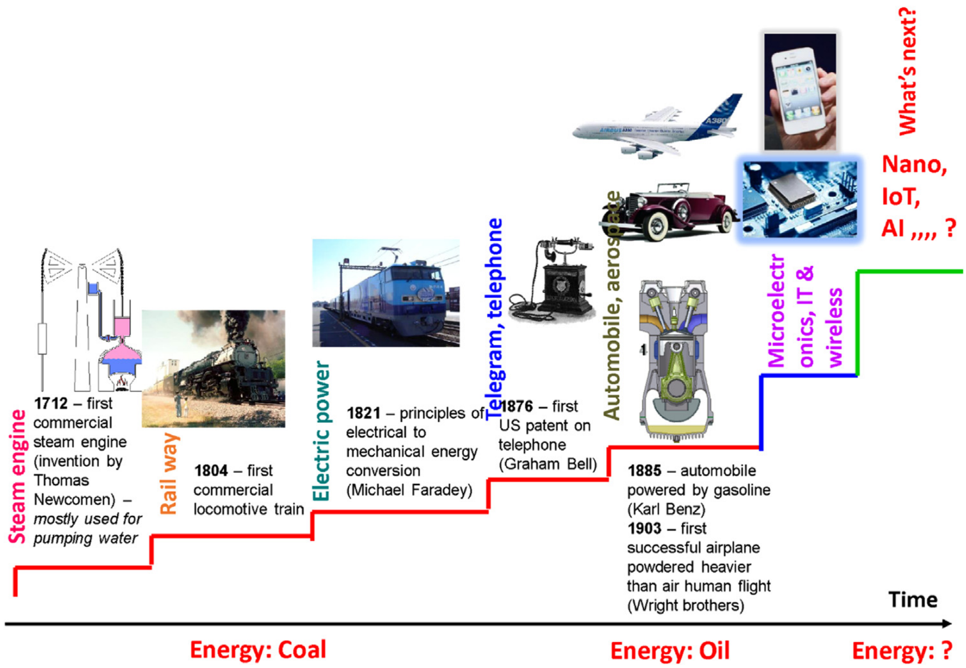

Fig. 1. Energy and technological revolution in human history. The technology in the last 3 centuries relied on coal and oil. As the world is marching into the era of internet of things, nanotechnology and artificial intelligence, what is the choice of energy?.

speed, operation status such as temperature, pressure and humidity of all the objects would be gigantically huge. Although the power needed to operate each sensor is small, typically microwatt to Watt range, but the number is so large. For the objects located at fixed locations that can be reached by hard wired power, one may rely on major grid. For sensors that are mobile and wireless, energy storage units such as batteries would be the nature choice for power. However, battery is limited by several major factors. First, battery has limited life time, so that it has to be constantly monitored, recharged and replaced for sustainable operation. Such work is impossible without being done by human. It is unbelievable if all these tasks would be done by human for tracking, replacing and treatment of widely distributed batteries. The other factor is the recycle of batteries and later treatment of batteries would be a huge task, especially with considering their mobility and wide distribution, possibly resulting in major environmental pollution. Based on a study of Cisco, 90% of the IoTs would be impossible if all of the components would be powered by batteries! [1]

A possible solution is to make each device *self-powered* by harvesting energy from the environment. This is possible because the power consumption of each device can be rather small, such as in the range of micro to tens of milli Watt. With considering the working status of each sensor, in periodic active mode and standby mode, it is feasible to use the energy harvested from the environment, such as solar energy [2] and/or motion/vibration energy [3,4]. This idea was first proposed by Wang in 2006, and it is now well received worldwide [5,6].

3. Concentrated power vs distributed power

Our traditional power supply is to use the cable transmitted power from power plant. Through transmission lines, power reaches each factory, school and family (Fig. 2a). This is possible if the sites or censorial is fixed. However, as for IoTs, the objects are widely distributed and possibly moving, they have to be powered by energy storage units and/or local power generators (Fig. 2b). Sources of distributed energy can be solar cell, wind energy, body motion energy, vibration energy, thermal energy and chemical energy. The idea is to utilize whatever is available in the environment at which the device is deployed. Small solar cells are available and economically effective,

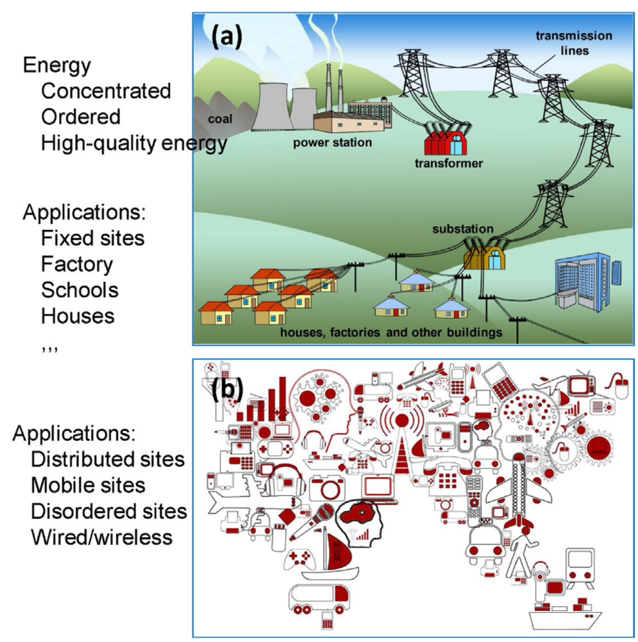

Fig. 2. Power distribution from major power plants to factories, schools and homes vs power distribution to distributed small electronic units. This "ordered" power supply to "disordered" power distribution is a result of entropy in energy utilization.

except it works only in day time once there is sun light. Small wind generator could also be a choice, provided the wind is abundant. Fuel cells can be effective approach by using hydrogen. Thermoelectric generator can also be possible if there is temperature difference. Piezoelectric/triboelectric nanogenerators can be used for converting mechanical triggering and body motion energy into electric power. These energies are not only new energy, but the energy for the new era – the era of IoTs [7,8].

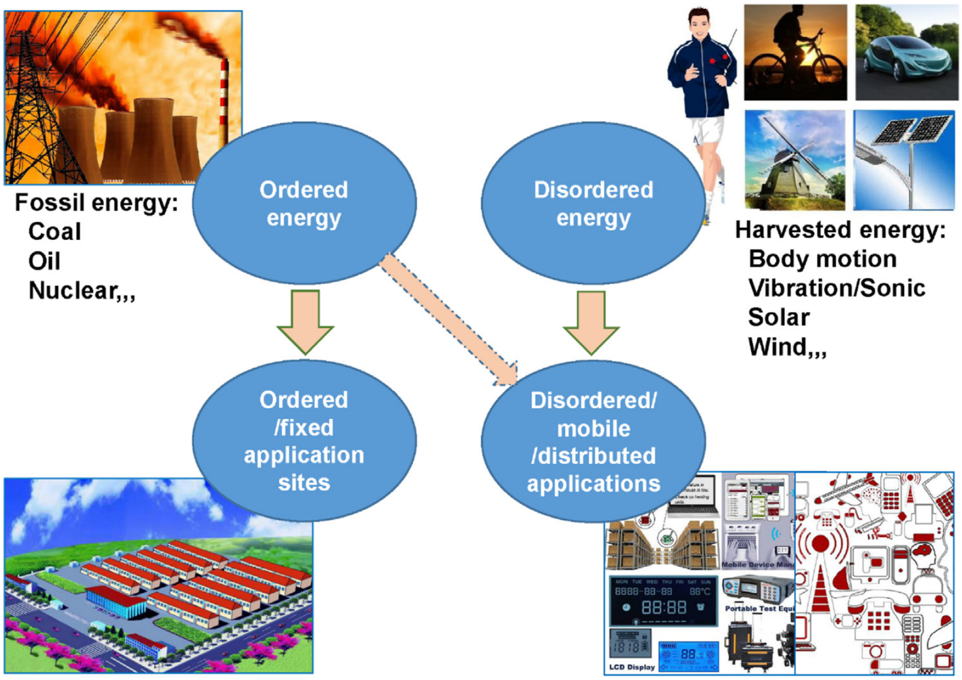

Fig. 3. Entropy theory in power distribution. The "ordered" power from power plants can be the major power for fixed sites with "ordered" utilization and a fraction of "disordered" distributed power utilization, while the "disordered" energy harvested from the environment can be applied mostly for solving distributed units instead of the ordered applications. This is a new field orientation for energy harvesting.

4. Entropy in energy distribution and utilization

The energy distribution for the era of IoTs can be understood from the entropy theory [9]. The power generated from a power plant is from a concentrated, "ordered" high-quality source, such as coal and oil, which are fossil energy with an irreversible usage. While the energy for driving the IoTs would be widely distributed, "disordered" due to mobility, and relatively low-quality (Fig. 3). As the world advances in the 21 century, more and more mobile objects and electronics are being produced, which means that the electronic components are going widely distributed and "disordered". Each of us now has at least one cell phone and other electronic components in our pocket each and every day. Unfortunately, this trend is irreversible.

From the first law of thermodynamics, for an isolated system, energy can neither be created nor perished, it can only transform from one form to the other, such as from mechanical to heat, heat to electricity. The conservation of energy for the entire earth, provided it is an isolated system, indicates that the total energy of the world is conserved, except it is being transformed from the concentrated, "ordered" and high-quality fossil energy into distributed, disordered and low-quality energy. This is an irreversible process. Global warming is inevitable because human has burnt too much of fossil energy.

In thermodynamics for describing molecular motion and temperature, entropy is used to describe the disorder, or randomness of a system. Entropy is closely related to the number Ω of microscopic configurations (known as microstates) that are consistent with the macroscopic quantities that characterize the system (such as its volume, pressure and temperature): $S = k_B \ln\Omega$. The second law of thermodynamics states that the total entropy of an isolated system always increases over time for an irreversible process.

Now look at the usage of handhold electronics, we have ever increased usage of smart phone based electronic components, which is an irreversible process. This means that the randomness of using electronic devices in the era of IoTs would follow the theory of entropy. We believe that the "ordered" energy from power plant can be effectively utilized for powering "ordered" sites for IoTs, such as factories, schools and houses, and in a lot of cases, the "ordered" energy can be used to power a certain percentage of units for IoTs if their locations can be affixed. The disordered fraction of the IoTs could be powered by the energy harvested from distributed sources. This means that the distributed power needs would rely on the energy harvested from the environment, which is the consequence of entropy in energy utilization.

Therefore, as the world marches into the new era, the traditional power plants may not meet the total needs of the IoTs. Traditional fossil energy based power plants are essential for the ordered operation of the world, while other energy generation technologies are supplements. The world is to be co-powered by both concentrated power plants to distributed units. Energy harvesting is inevitable for solving part of the power needs for IoTs. This is a new understanding about the field orientation of energy harvesting.

5. Self-charging power unit vs battery

Harvesting energy from environment provides an alternative approach toward energy storage units. Our today's research mainly focused on how to improve the power density and energy density of a battery, but regardless how high the energy density it can be, the battery will be drained out sooner or later. A new approach is to integrating an energy harvester, a power management circuit and energy storage unit into a self-charging power unit (SCPU) (Fig. 4) [10], which will not be drained out owing to the continuous charging of the battery by the harvested energy. The power management system make the energy generated to be stored at the maximum efficiency. The energy storage unit is required to serve as a "pool" that regulates the harvested energy for controlled output. In this case the density of the battery does not to be super high, but it can work sustainably. This is idea is for the self-powered system.

As for the SCPU, new challenges arise as for the energy storage unit. Since the input is pulses, one needs to effectively charge the battery with pulsed input instead of the conventional DC charging. This requires the design of the battery with rationally designed membrane thickness with considering the diffusion coefficient of the Li ions so that it can effectively being transported from cathode to anode [11]. Secondly, the leakage current of the storage unit such as supercapacitor must be reduced in order to retain the generated power [12]. This is because the input energy is small, which is different from the conventional DC charging that has unlimited input. Lastly, the recharging cyclebility of the storage unit has to be largely extended in order to

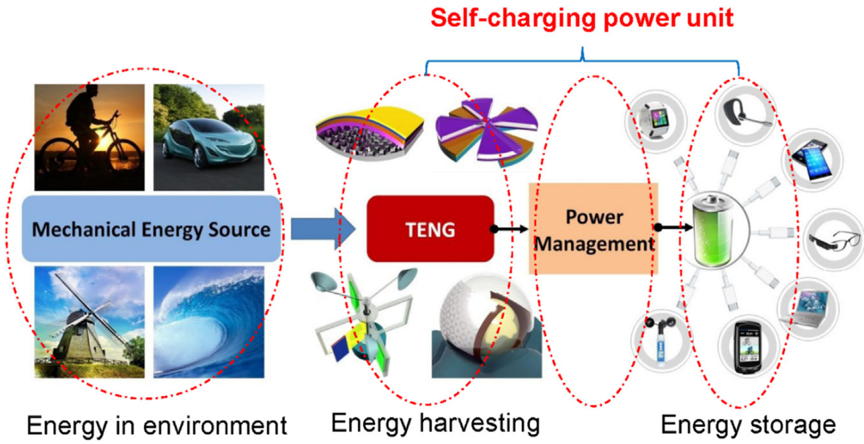

Fig. 4. Self-charging power unit that harvest energy from environment, managing the input power, and effectively store the harvested energy for sustainable driving of distributed electronics.

ensure the SCPU to work for a long lifetime with considering the pulsed input. All of these requires new study in energy storage.

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