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Smart energy systems

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Abstract. Some aspects of renewable and smart energy systems have been considered. Comparison of different renewable energy sources such as offshore wind, land-based wind, biomass, PV Solar, hydro-electric and geothermal has been demonstrated. The shift from solar cells (energy production) to batteries (energy storage) is the mainstream in the modern power supply. One of promising technology for the storage station is redox flow battery (RFB). RFBs can also be used as the power sources for electric vehicles. There is another type of batteries, the so-called metal-air batteries (such as Zn-air, Al-air), these are the smartest energy systems for mobile applications.

Keywords: smart energy systems, power supply, energy storage.

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1. Introduction

Every little thing needs energy to work, whether it is big or small. Traditional electrical grid driven by giant power plants was well suited to our life in the 20th century, since off-grid electrical power source, namely, batteries only needed to take care of systems with small power demands. However, dependency on fossil fuels caused the problems of the climate change. Total renewable electrification of our life including power-demanding transportation system is inevitable. Also in the world of IoT, everything moves, communicates, from tiny little thing up to giants, so that power storage and supply for an extremely wide range of power, energy and size is needed. We need to seek for a total renewal of our energy production, conversion and storage, consumption and recycling chain within the 21st century.

To begin with the electrical power generation, we all have witnessed a drastic progress of renewable energy systems in recent years. At the same time, the natural disasters caused by the global climate change have become increasingly evident and serious. In 2011, it was also the “Tohoku earthquake and tsunami” that caused the terrible nuclear disaster in Fukushima. We need a bold and great shift to renewable energy, as it is obvious that we cannot depend on nuclear energy for truly sustainable society.

2. Prospective of solar cells

It is surprising to hear still so many people talking about the high price of solar panels as the problem that obstructs their wide use. The supporters of nuclear energy are even not embarrassed to say that nuclear is cheap, dependable, clean, while solar is too expensive, too small. Such misperceptions among the people, especially in Japan, are hindering a nation-wide argument about the future of our energy system. The latest figures for the energy cost must be almost shocking to the people (Table) [1]. The cost of nuclear power greatly increased after the Fukushima disaster because many expensive safety measures had to be introduced. On the contrary, thanks to the global competition, Chinese manufacturers have reduced the price of solar panels so much that the solar electricity is cheaper than most of fossil fuel based power generations today. Many other renewable energies are also on the cheapest side, due to steadily increasing price of coal, oil and gas. These clean energies are no longer expensive.

People working on organic solar cells including ourselves used to speak about the cost reduction of solar electricity as the primary reason of their study. Once, there was a good reason to say so, but not anymore. Studies on organic solar cells and on organic semi-conductors in general are certainly important as science.

Table. Comparison of energy costs from various plant types (2016, www.solarcellcentral.com).

Energy plant type	Lifetime cost (¢ per kWh)
Peaker Natural Gas	18.0
Offshore Wind	**15.8**
Coal with CCS	14.0
Advanced Nuclear	10.3
Biomass	**9.6**
Conventional Coal	9.5
Natural Gas Combined Cycle with CCS	8.48
PV Solar	**8.47**
Hydro-electric	**6.8**
Land Based Wind	**6.5**
Natural Gas Combined Cycle	5.8
Geothermal	**4.5**

Note. Renewable energies are indicated in bold letters.

But our typical sales talk of "cost reduction" has become totally inadequate. Today's active studies on Perovskite solar cells are probably also not useful for their practical use. Si panels do their job perfectly. PV panels have a very long lifetime, being free of maintenance work, as there is no moving parts unlike the other generators. The raw material, quartz sand, is also abundant on our planet and is not toxic. Crystalline Si needs a lot of electricity for its production. But what if we can make new Si by the electricity coming from the Si panels? Even that will become possible after establishing the smart energy system with an energy storage, which will be proposed later in this article. So, is there anything good we can do for the everyday life of people with the organic solar cells?

Fig. 1. Colorful plastic DSSCs and "wearable solar clothe" to power a mobile phone.

Light weight, flexibility, colorfulness and transparency are the unique features of organic solar cells and people seek for alternative applications, not for serious power generation. One has to admit that such a move has been driven by the fact of the low efficiency and short lifetime of the organic devices. Dye-sensitized solar cells (DSSCs) employing zinc oxide (ZnO) as the photoelectrode can be fabricated on conductive plastic substrates, because well conducting and well adhering porous ZnO can be processed at low temperatures, by methods such as screen printing [2] and electrodeposition [3, 4]. We have demonstrated flexible and colorful DSSCs back in 2005, when we promoted a joint research with companies as a national project supported by new energy and industrial technology development organization (NEDO) of Japan. Star-shaped and red-colored DSSCs were prepared and attached to a dress as design accents to power a mobile phone (Fig. 1). It was to demonstrate design flexibility of such DSSCs to fit with various applications. Since other wearable technologies were immature at that time, the concept to use organic solar cells to power "wearable electronics" was a bit too early to take off. Today, various kinds of wearable device technologies are being established, such as sensors, displays and transmitters for wireless communication. Certainly, these devices do need power for their operation and the flexible organic solar cells can be ideally suited to this purpose. It is time to integrate technologies that we have into a "wearable system".

Let's get back to the energy issue. If solar cells are already so cheap, being one of the cheapest methods for electric power generation, why are we not seeing them to replace old technologies? It is only the cost of "power generation" that has become cheap for the renewables. They are not reliable at all, not speaking of the device stability, but because their power generation inherently fluctuates depending on weather. Our consumption also fluctuates. Simply, they do not match. Obviously, there are a lot more prices that we need to pay and a lot of technical challenges as well, in order to establish a dependable "renewable system". We need a total renewal of our energy system, from its generation to consumption. The past development of renewable energy has been achieved by connecting wind turbines and PVs to the existing grid. Germany, probably the most advanced country in renewable energy, can now produce more than 80% of the electricity they need on days with favorable weather. That certainly results in an "over production" of electricity. They can handle the giant fluctuation by selling/buying electricity with other EU countries connected on land. But for our islands of Japan, about 5% of the total electric power is probably the maximum we can install renewables in the existing power grid. What hinders the total shift to renewable energy is no longer the cost of power generation, but the lack of the infrastructure to fully utilize it.

3. Towards energy storage

So, what do we need to do to go forward? ICT must be fully utilized to balance production/consumption of energy to maximize the "efficiency" of the system. Power production predicted by weather monitoring and analysis of the past weather pattern must be compared to the big data of energy demand by people from a region to region. When there is too large deficit/surplus of energy, we need a hardware solution of "energy storage". Also, "micro-grid" and "internet of energy (IoE)" approach should be effective. Each region can do its best effort to manage the power production/consumption within the region. But when it still lacks energy, other regions with energy surplus can feed. This way, a "fail-safe" renewable energy society can be established while minimizing the demand on energy storage system (because storage is not cheap!).

The above-mentioned arguments created enough reasons for us to shift our studies from solar cells (energy production) to batteries (energy storage). Batteries are nothing new, but here, traditional batteries like lead-acid, Ni-MH, Li-ion are not of the interest. They are too small, too expensive and too short-lived. Li-ion batteries are the currently most advanced ones for their energy density. Residential storage systems using Li-ion batteries are already sold from several manufacturers. But they are just expensive toys for rich people who wish to enjoy future life earlier. The cycle life of Li-ion batteries is just about a few thousand cycles (maximum 5 years operation?) and the cost is still higher than 5,000 USD for a 10 kWh system (less than one day consumption for a regular-sized house). Li-ion batteries are currently the best choice for small power mobile equipment and electric vehicles. The highest energy density (how much electricity one can store per weight of device) is certainly welcome for mobile applications. But for an immobilized "storage station", light weight of the device is not at all needed. Rather, it has to have a huge capacity (MWh to GWh), be highly reliable for decades of its operation, thus be safe and cheap, whatever weight it may have.

The most promising technology for the storage station is redox flow battery (RFB). Although they are still called "battery", it is probably easier to understand what it does by calling it a "rechargeable fuel cell". In fuel cells, chemical fuels such as hydrogen and methanol are fed to the cell, oxidized to extract high energy electrons which drive the load, and eventually sink to O_2 from air by reducing it. RFB does the same thing but its operation can be reversed. When you feed fuel in, you can get electricity out, but when you feed electricity in, you get the fuel out, which can be easily stored and used later again. One of the leading example of RFBs is the vanadium-vanadium redox flow battery (VFRB, Fig. 2). Aqueous sulfuric acid dissolving vanadium ions is used as the electrolyte, whereas chemically inert conductive material (typically carbon) is used as the electrode. For charging, solutions with low energy states of vanadium (V(III) and V(IV)) are converted to those of high energy states (V(II) and V(V)) by electrolysis in the cell, pumped to the external storage tank. The process is reversed

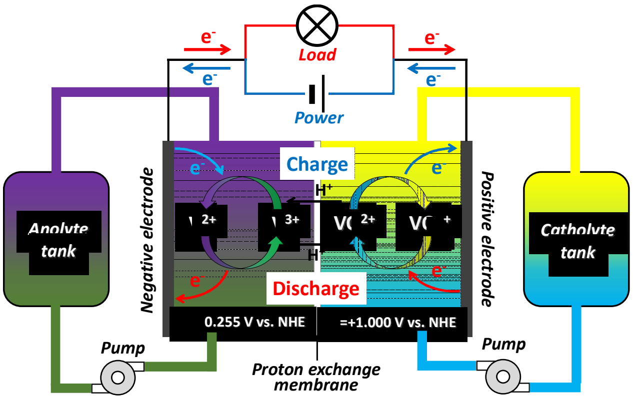

Fig. 2. Schematic of vanadium redox flow battery (VFRB).

Fig. 3. RFB powered electric vehicle "QUANTINO 48VOLT", developed by nanoFlowcell (http://nanoflowcell.com/). This street legal prototype claims over 1,000 km range out of 85 kWh achieved by 2×95 L ionic liquid fuel.

to discharge. Since the electrodes are only used for charge exchange, they do not degrade and the storage capacity simply depends on the size of the tank (while the power density depends on the size of the electrode). Regular batteries need a lot of expensive materials (such as $LiCoO_2$) for increasing the storage capacity, because storage takes place due to redox reactions of solid materials attached to the electrode. On the other hand, RFBs need only large tanks to store chemical solutions. The materials used in VFRB are relatively cheap, safe and do not degrade over time. Thus, RFBs are ideally suited to store a large amount of electricity generated by renewable sources.

RFBs can also be used as the power source for electric vehicles. A real size, serious proof of this concept has been demonstrated by a venture company, nanoFlowcell [5]. The sleek and stylish prototype car named "QUANTINO 48VOLT" (Fig. 3) achieves over 1,000 km range by one charge of 2×95 L liquid electrolyte fuel. The use of RFB-powered cars should be as easy as using today's cars with petrol engine. The energized liquid electrolyte solution can be quickly filled just like gasoline. The electrolyte solution for RFB can be made safer than gasoline, and can also be reused many times.

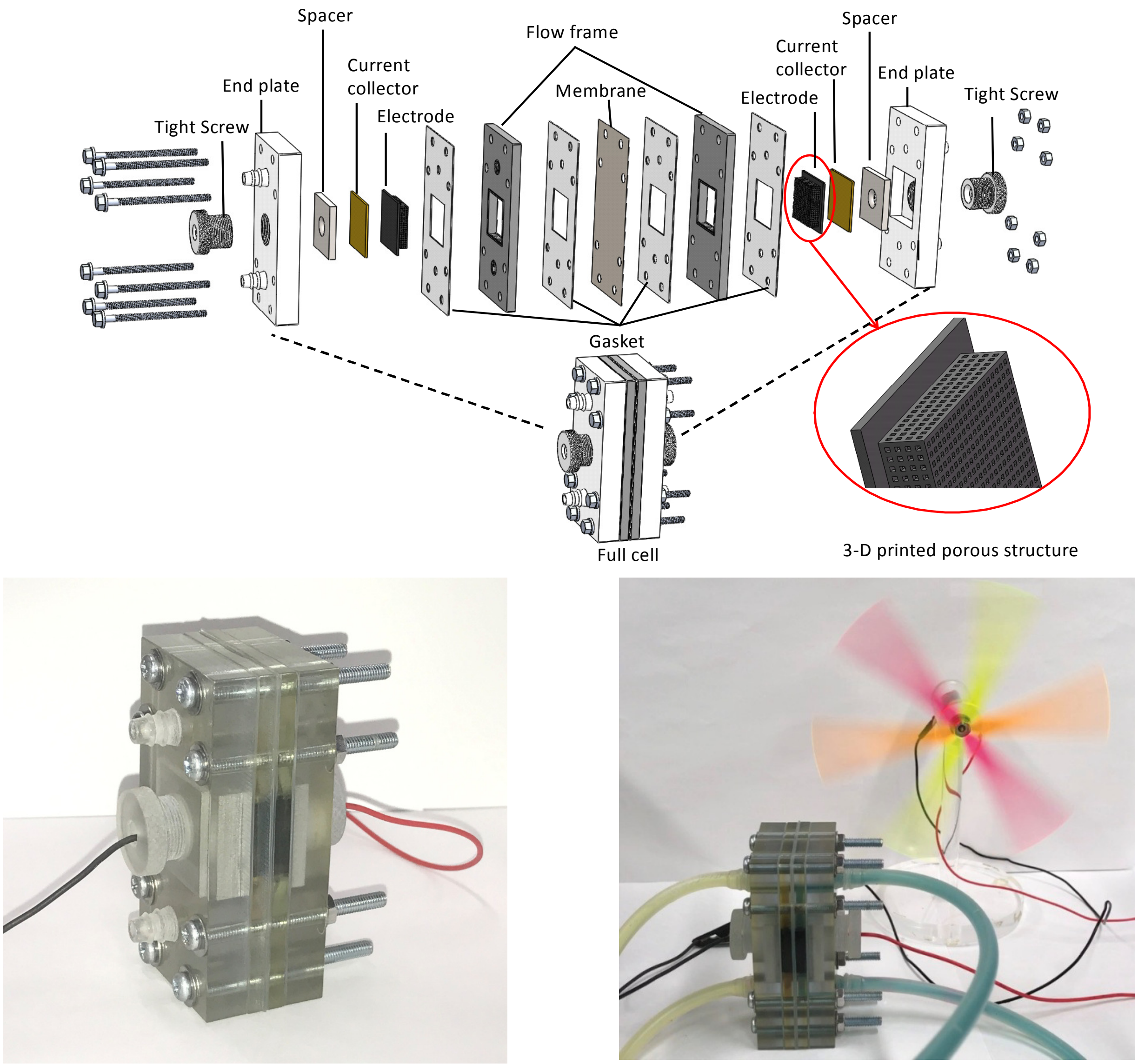

Fig. 4. CAD drawing for 3D printing of the flow cell and porous electrode for the prototype of VFRB and the pictures of complete cell and operation.

What research efforts are needed for further improvements of RFBs? There are many possibilities to find alternative materials for the electrodes as well as the redox chemicals to maximize the energy density, safety, resource abundancy and lifetime, while minimizing the cost. For example, VFRB and many other types of RFBs need very expensive Nafion® as the ion-exchange membrane. If we find an ion-selective storage electrode (out of cheap materials) and use it in a "semi-flow" configuration, we can avoid use of such expensive membrane. Organic redox molecules are also exciting challenges. Instead of using solutions of redox active ions like those in VFRBs, redox active ionic liquid could make the entire liquid as the storage medium to greatly increase the storage density [6]. Avoiding metals is also advantageous for safety and against resource scarcity. Safety also becomes an issue of top priority when we envision the use of RFB in mobile and wearable applications.

4. Smart fuel cells

Although it has not been our field of expertise, we also have started our challenges to study optimum cell design using 3D printing as the method of device fabrication. A prototype as shown in Fig. 4 has already been made and proven to work. Design of the flow channel as well as the electrode is important to increase the rates of charging/discharging (that inversely reduce the IR loss). 3D printing allows us to quickly test different cell design. We need to develop materials for the filaments to print different parts of the cell, such as the cell case and the electrode. For the latter, we are trying to form composites of inorganic nanoparticles and plastic for micro structured electrode to maximize the mass transport. Also, computer aid for hydrodynamic simulation could facilitate and accelerate the process of design optimization.

Finally, metal-air batteries (such as Zn-air, Al-air) can be the smartest energy systems for mobile applications. The electrochemistry of metal-air batteries is extremely simple. On discharge, the anode metal (= fuel) is oxidized.

$Zn \rightarrow Zn^{2+} + 2e–$ (E^0 = –0.7626 V vs. NHE),

$Al \rightarrow Al^{3+} + 3e–$ (E^0 = –1.676 V vs. NHE).

The dissolved ions typically exist as hydroxide, hydroxo-complex or may even be converted to oxides depending on the conditions, thus changing the formal potentials from those indicated above. Note that 2 and 3 electrons can be withdrawn from single Zn and Al, respectively, while only 1 out of Li (although Li is extremely light!). Zn and Al are also relatively cheap and abundant metals. The extracted electrons drive the load and reduce O_2 in air, just like any other fuel cells.

$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ (E^0 = +0.401 V vs. NHE).

The theoretical energy densities are as high as 1.35 and 8.1 kWh/kg of metal (without including O_2) for Zn and Al, respectively. Tiny button type of Zn-air batteries have been used, since long time as a power source for hearing aid devices, but those with less noble metals to achieve higher voltages (such as Li and Al) are still in the development phase. These metal-air batteries can also be made rechargeable, but it is probably not necessary to do so. Also, Zn-air is just fine as it is much easier to recycle Zn than those poor metals. Molten salt electrolysis is needed to produce Al to consume a lot of electricity, while Zn^{2+} can be reduced back to metallic Zn in water at room temperature. When people hear about “batteries”, they naturally think that they have to be charged. But are people happy to wait for charging their electric cars? Have you not had a trouble by forget charging your mobile phone? It is much better to use primary batteries, just like replacing dry batteries for toy cars, using metals just as fuel in place of gasoline. When you run out of electricity of your car, you get a new energy pack (cassette of metal and electrolyte solution) in a power station (no longer a “gas station”) and continue your drive for hundreds of kilometers. The used packs (electrolyte containing Zn salt) are collected to a recycle station where metals (= fuels) are regenerated by the power from renewable sources. This way, perfectly clean and convenient energy system can be created for mobile applications. The same applies to a mobile phone, for which only a tiny power capsule is needed for many days operation. No more trouble by forget charging. You can go to Kiosk to buy a new capsule!

5. Conclusions

There are so many challenges and a lot of new opportunities for “Smart Energy System”. It is time to start working for systems, rather than individual research topics. Maybe not all, but most of technologies are already available. People with different backgrounds must meet and assemble their expertise and knowledge to collaborate towards these new challenges.

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