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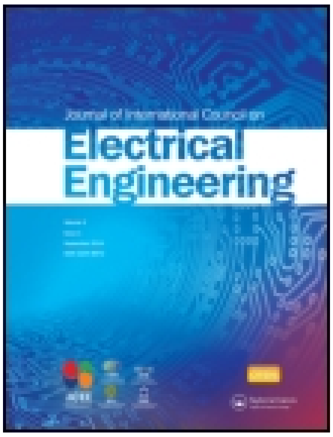

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Energy and information correlation: towards sustainable energy

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Sustainable energy is the solution for our long-term development. In the ever growing transitional world, we find ourselves caught between a time dependent on fossil fuels and a future subjugated by renewable energy sources. Yet, not everyone holds the same vision. Opinions vary not only about how dependable these renewable energy sources are but also how they will be able to sustain life post-fossil fuel era. Integrated energy and information is needed to address this issue. This paper examines the vision of energy sustainability and reviews the status of the world energy industry with consideration of the utilization of renewable energy. A concept of correlation of energy and information is presented. It is believed that through the application of information entropy, energy production and utilization can be enhanced for a sustainable development.

Keywords: sustainable energy; information; mass; entropy

1. Energy sustainability

The commonly accepted definition of 'sustainable development', according to the World Commission on Environment and Development, is 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. In theory, any sustainable development must not cause any damage to the planet. In reality, there are a lot of politics and challenges to make the environment sustainable. In a broader sense, sustainable development aims for a better quality of life for everyone, now and for generations to come. Sustainable development offers a vision of progress that integrates immediate and long-term objectives, local and global action, and regards social, economic and environmental issues as inseparable and interdependent components of human progress. Energy sustainability is one of the key success factors for meeting these objectives.

The operation principles of sustainable energy can be categorized as follows:

1. for renewable generation resources, the rate of harvest should not exceed the rate of regeneration (sustainable yield);
2. the rate of waste generation from a project should not exceed the assimilative capacity of the environment (sustainable waste disposal); and
3. for non-renewable generation resources, its depletion should require comparable development of renewable substitutes for that resource.

In order to fulfil and better position such sustainability development, apart from individual technology to ensure effective and efficient operation, an integrated energy and information approach is needed to have overall control and applications. Whenever there is a change of energy, the associated information alternation will also be observed. How we can use the collected information to enable better energy production and utilization, particularly applied to renewables. How we can influence the individual to conserve and better use energy is also critical and essential for sustainable energy. The energy industry has made a massive contribution over the past few decades regarding the provision of energy to meet the needs of the community, and will take an even stronger role in the future for sustainable energy development.

2. Energy industry

Changes in the energy industry over the past 20 years have been significant. The growth in energy consumption has been higher than anticipated, even compared with postulated high-growth scenarios. The energy industry has been able to meet this growth globally being assisted by those continuous increases in reserves' assessments and improving energy production as well as consumption technologies. The results of the 2013 WEC World Energy Resources [1] survey show that there are more energy resources in the world today than ever before.

The key indicators of energy supply during 1993–2011 and prediction are shown in Table 1. It can be seen that the population growth was 27% with a GDP growth by 190%, the energy provided was increased by 48% (1 Mtoe = 4.2 x 10^{16} J or 11.63 TWh).

Coal, oil, and gas will remain the main energy resources in many countries, although efforts are being

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*Corresponding author. Email: ccchan@eee.hku.hk made to move away from fossil fuels by adopting more renewables. Such fuel switching does not happen overnight. The leading world economies are powered by coal: about 40% of electricity in the USA and 79% of the electricity in China is generated in coal-fired thermal plants. These plants will continue to run for decades. The main issue for coal is the CO_2 penalty.

The global crude oil reserves are almost 60% larger today than in 1993 and the production of oil has gone up by 20%. If the unconventional oil resources such as oil shale, oil sands, extra heavy oil and natural bitumen are taken into account, the oil endowment of the world could be quadrupled. An increasing share of oil will be consumed in the rapidly growing transport sector, where it will remain the principal fuel in the next two or three decades.

Natural gas is expected to continue its growth, spurred by falling or stable prices and the growing contribution of unconventional gas, such as shale gas. In addition to power generation, natural gas is expected to play an increasing role as a transport fuel.

The future of nuclear energy is uncertain. While some countries, mainly in Europe, are making plans to withdraw from nuclear enery, other countries are looking to establish nuclear power generation. Nuclear energy still remains as one of the basic sources of energy.

The development of renewables, excluding large hydro, has been considerably slower than the expectation forecasted 20 years ago. Despite the exponential growth of renewable resources in percentage terms, in wind power and solar PV, renewable energy still accounts for a small percentage of total primary energy supply (TPES) in most countries. Their contribution to energy supply is not expected to change dramatically in the coming years. The continuing growth of renewables strongly depends on subsidies and other support provided by governments. Integration of intermittent renewables in the electricity grids also remains an issue, as it results in additional balancing costs for the system and thus higher electricity bills.

In the energy industry, demand for energy will continue to grow. Even if global energy resources seem to be abundant today, there are other constraints facing the energy sector, above all, significant capital investment in developing and developed economies is needed. The environment and climate, in particular, pose an additional challenge. Clean technologies will require adequate financing, and consumers all over the world should be prepared to pay higher prices for their energy than today. Energy is global and, to make the right choices, decision makers should look at the global picture and base their decisions on a thorough life cycle analysis and reliable energy information.

3. Energy efficiency

Energy intensity is measured by the quantity of energy required per unit of an activity. Energy efficiency improves when a given level of service is provided with reduced amounts of energy inputs or services are enhanced for a given amount of energy input. Energy efficiency helps address the ‘energy tri-lemma’ (energy security, energy equity, and environmental sustainability) and provides an immediate opportunity to decrease energy intensity. This will achieve energy savings and reduce the environmental impacts of energy production and use. The 2013 World Energy Council (WEC) report, World Energy Perspective: Energy Efficiency Technologies, [2] provides some quantitative indicators for the various phases of the value chain and for specific industries. Hence, energy efficiency is not just a matter of using efficient technologies; the solutions should also take into account economic aspects. Energy efficiency technologies will be widely used only when economically viable within their lifetimes and when there are no implementation barriers.

Energy efficiency is an important component of the energy economy. It is often called an ‘energy resource’ because it helps to decrease the use of primary energy resources and achieve considerable savings. There is tremendous potential for energy efficiency improvements along the entire energy value chain. Examples of energy efficiency improvement potential for main technology groups include:

- in oil and gas exploration, the energy efficiency of the electric system, which today is 20%, could be increased up to 50%;
- in power generation, the average efficiency of power plants is 34% for coal-fired installations compared with best available technology of 46% for coal and 61% for gas-fired units;
- in transmission and distribution, electricity losses reach 12% and above;
- buildings account for nearly 40% of the total energy consumption globally, and it is estimated that potential energy savings in buildings could reach between 20 and 40%.

For all above energy efficiency improvement potentials in both production and usage, the correlation between energy and information will pay a key role.

4. Energy, mass and information

Einstein gave us the equation that energy and mass are related by $E = mc^2$, but could information be another part of the equation? It is universally true that when there is a variation either in energy or material movement, information will be synthesized and disseminated. Hence, I (information) = E (energy) + M (mass) can be explicitly expressed, even when energy is hidden or intangible (for example, sunlight). Mass or material movement could be visually observed and associated information can be derived or formulated from raw data. For energy including its boundary of existence, some form of detecting device is required to capture the variation to provide meaningful information. Hence, to understand the energy resources development, both the quantitative and qualitative aspects of the nature of information are to be addressed.

Information cannot be created or destroyed, only transferred or transformed, according to the law of conservation of information. In other words, information can always be discovered, but never created or destroyed. The more energy variation being input into something, the more the information could be obtained from it. Hence, the law of energy conservation can similarly be applied to information, thus total information flowing into a system can be equal to the total information flowing out from a system. Such changes can be reflected by the entropy of the information. The Boltzmann and Shannon expressions provide expressions about entropy and information that provide boundary values for information in different ways.

5. Correlation between energy and information

In 1803, Lazare Carnot analysed the working cycle and efficiency of the steam engine and proposed that in any machine the accelerations and shocks of the moving parts represent losses of moment of activity. Building on his father's work, Lazare's son Sadi Carnot published *Reflections on the Motive Power of Fire,* in 1824, which posited that in all heat-engines falling through a temperature difference, work or motive power can be produced from the actions between a hot and cold body. He made the analogy with how water falls in a water wheel. [3] Count Rumford showed that heat could be created by friction, for example cannon bores are machined. [4] The first law of thermodynamics stated that the internal energy of an isolated system is constant. Hence the amount of energy and matter in the universe remains constant, energy can merely be changed from one form to another.

Based on the heat-friction experiments of James Joule in 1843 and the concept of energy, the first law of thermodynamics was unable to quantify the effects of friction and dissipation. In the 1850s, Rudolf Clausius objected to the supposition that if no change occurred in the working body, heat cannot of itself pass from a colder to a hotter body. Clausius described entropy [5] as the transformation-content, i.e. dissipative energy use of a thermodynamic system or working body of chemical species during a change of state. This was in contrast to earlier views, based on the theories of Isaac Newton, that heat was an indestructible particle that had mass. The second law of thermodynamics governs all spontaneous change.

Maxwell's demon is a thought experiment created by James Clerk Maxwell in 1867 in a letter he wrote to Peter Guthrie Tait, before it was presented to the public in his book on thermodynamics titled *Theory of Heat* in 1872 (see [6]). Maxwell wanted to use his demon to show that the second law of thermodynamics had only a statistical certainty.

In 1877, based on the general theory of statistics, Ludwig Boltzmann pointed out that there was some relationship between energy and information. [7] Recently, Chan and Jian proposed that such a relationship can be expressed as $\sum I \Leftrightarrow \sum E$. [8] With Boltzmann`s research, some collective result of molecular motions was observed. Leó Szilárd, in his paper of 1929, [9] 'On the reduction of entropy in a thermodynamic system by the intervention of intelligent beings', introduced the thought experiment now called Szilárd's engine and became important in the history of attempts to understand Maxwell`s demon. In Szilárd's view, Maxwell's demon is very intelligent; it can delete and restore the information. By following the second law of thermodynamics related to information, entropy should be considered when Maxwell's demon earned the information. This paper demonstrates the first time information was connected with energy.

Based on the thought of Szilárd, in 1956 Léon Nicolas Brillouin studied the correlation between entropy in information and entropy in thermodynamics, then postulated the formula: $K_B \ln 2(J/K)$. [10]

Hence, in order to obtain 1 bit of information, the system must decrease an amount of entropy of value $K_B \ln 2(J/K)$, where $k_B = 1.38 \times 10^{-23}$ is the Boltzmann constant. From information theory, Claude Shannon denoted the information entropy H of a discrete random variable X with possible values $\{x_1, x_2, \ldots, x_n\}$ and probability mass function $p(x)$ as shown in Equation (1), [11] where b is the base of the logarithm used and the common value of b is 2.

$$H(X) = -\sum_{i=1}^{n} p(x_i) \log_b p(x_i). \tag{1}$$

Shannon`s theory solved the problem of quantitative metrics in information.

Maxwell's demon can (hypothetically) reduce the thermodynamic entropy of a system by using information about the states of individual molecules; but, as Landauer et al. [12] have shown, to function Maxwell's demon must increase thermodynamic entropy in the process by at least the amount of Shannon information he proposes to first acquire and store; and so the total thermodynamic entropy does not decrease (which resolves the paradox). Landauer's principle has implications on the amount of heat a computer must dissipate to process a given amount of information, though modern computers are nowhere near the efficiency limit.

Japanese researchers recently produced a real demon in the laboratory, [13] which stands on the shoulder of Bennett, who thought that Maxwell`s demon controlled the door allowing molecules to flow from one room to another, but it only occurred at the moment the demon deleted its memory of the judgment of the molecule`s movements. [14] The Japanese experiment gives us a generalized second thermodynamics law as:

$$\langle \Delta F - W \rangle \leq K_B T I, \tag{2}$$

where *ΔF* is the free energy difference between states, *W* is the work done on the system, k_B is the Boltzmann constant, *T* is the environment temperature, and *I* is the manual information content obtained by measurements.

It is interesting to note the work of Szilárd, who associated the entropy decrease with the information access. Szilárd developed a model which was improved by Rolf Launder, who suggested that one bit of information in the system was equivalent to $k_B T\ln 2$, and he thought the entropy that Maxwell`s demon earned from controlling the gate would be reduced in this way. From the Japanese experiment and Bennett`s paper in 1987, it was discovered that Maxwell`s demon can abandon or restore the information, and the demon`s memory is limited; if the demon abandons any information, it means the entropy of the system will be increased. When the demon`s memory is full, it will start deleting information. In this way, the entropy of the system is increased. So we can still consider that Szilárd`s work more intuitively expressed the correlation between information and energy as:

$$\{\langle F - W \rangle / 1bit\} \leq k_b T \ln 2, \tag{3}$$

where *ΔF* is the free energy difference between states, *W* is the work done on the system, k_B is the Boltzmann constant, *T* is the environment temperature, and *I* is the manual information content obtained by measurements.

The Japanese experiment showed: without any external force (such as inject energy) and only per a sensor system like a camera, the microscopic particle can obtain enough energy from the process of measurement and people can also work out how much energy is transformed from the information that the particle carried from the process (or measurement). This evidence can prove energy comes from information.

Entropy has both a macro form and a microscopic form. The macro form is called the Clausius form (thermodynamic entropy) and is associated with thermal energy; the microscopic form is called the Boltzmann form (information entropy) and is associated with quantum energy.

Entropy is also used in communication systems and computer science, also called information entropy. But the basic meanings of information entropy and thermodynamic entropy are the same; they are both defined as the energy which is used to describe one system.

The presence of energy is through ‘field’, but the presence of field is based on the material in the field; thus, no material no field. Energy cannot escape from the existence of mass, but one kind of mass can only be produced from another kind of mass. The famous mass energy conservation $E = mc^2$ only pointed out that mass has energy, energy stays in mass, mass is actually a kind of state or carrier for energy, and energy is an adjunct of mass. Mass energy conservation is only used to express the relationship between mass and energy in amount, but never used to calculate how much mass can be transformed into energy.

In physics, both sides of the ‘equals sign’ must have the same definition of physical quantity, or both sides are independent properties but have the same nature, like ‘m’ and ‘E’ in mass energy conservation. Information is the description of the change of energy and mass, which means the change of state, the change of time, the change of dimension. As in Equation (3), the more information you want know, the more energy you need, and the better you can understand one kind of mass and hence deliver better control.

The Schrödinger equation describes how the quantum state of a physical system changes with time. The time-dependent Schrödinger equation (single non-relativistic particle) can be given thus:

$$I\bar{h}\frac{\partial}{\partial t}\Psi(r,t) = \left[-\frac{\bar{h}^2}{2\mu}\nabla^2 + V(\mathbf{r},t)\right]\Psi(\mathbf{r},t), \tag{4}$$

where μ is the particle’s ‘reduced mass’, *V* is its potential energy, ∇^2 is the Laplacian, and Ψ is the wave function (more precisely, in this context, it is called the ‘position-space wave function’) and probability of a quantum event occurring.

In managing a real case, Ψ includes all of the focused matters (cost, time, risks, etc.). We can use the form of Schrödinger equation and per differential or integral methods to work out the most important part, in which the most important part will be calculated with the largest weight.

6. Sustainable development using energy and information correlation

Only with the thorough understanding on the correlation between energy and information, the detour of the development of new energy can be prevented, hence the best road map for the sustainable energy can be developed.

The critical issues are not the upper and lower bounds that information/entropy considerations would provide. Rather it is the complex interdependence between the physical limitations of thermodynamic boundaries of energy transfer and the human dimensions of economic, social and political decisions that is crucial to this discussion.

What is most important is that the energy and material resources are limited by the physical resource limits on Earth and by our ability to harness solar energy in various forms. There is a relationship between the energy available in a particular system, the degrees of freedom of the system, and its total possible information content. Furthermore, important questions emerge about the management of energy and information. There is a very important issue with the way information on distribution of energy is managed in a grid plus storage system (e.g. solar panels, wind turbines, coal power plants, and electric vehicles as mobile storage), but that is limited not only by the total information content, but also by the technological options for energy production and the economic and social choices for deployment and distribution.

The fundamental reality is that energy and matter are limited and thus must be allocated and distributed with consideration of values, justice, and equality, while information can be distributed and shared as widely as desired, leading to questions of access and education to understand and use it. It would not be simply a matter of producing more energy and deriving information, but on changing the social use of energy and creating new business models and opportunities for innovation that is integrated more effectively with the understanding of the needs of the local and global society in the limited resource environment of Earth. The authors hope Equations (1)–(4) will assist in providing some guidance.

The use of information derived to control and optimize energy utilization has been adopted for the past few decades in power generation, transmission, and distribution systems. With the development of computer technologies, better control and operation has been achieved. The information derived from the electrical systems are voltages and currents; with the synchronized vector approach, faster and quicker real time responses are achieved. When a fault occurs in an electrical system, the energy change is reflected in a drop in voltage and increase in current magnitudes, allowing the protection system to detect the fault and operate appropriate circuit breakers to clear the fault within the required short period of time. It is essential that the change in energy provides the spontaneous information for managing the current status of the system. Measuring information entropy provides a means to control and enact with the energy. For a healthy system, the information entropy of the operating system can be utilized to provide a more effective optimization of the energy, for example minimizing various energy losses. For energy efficiency, the information so provided can help to accelerate human behaviour change for a more sustainable use of energy.

In a metropolitan city where various energies are being utilized for transportation, work environment, food preparation, and government services, there is a lot of energy consumption information. Such big data if properly assessed and analysed can help to better manage the whole city. For example, using a global position system on a service car, we can better optimize the trips to minimize energy consumption. With the behaviour of citizens on government services identified, a better platform and services can be provided and enhanced. Research and development in big data and extraction of relevant information can help to enhance sustainable energy utilization, integrating and harmonizing social, physical, and cyber needs to achieve a smart city.

7. Conclusion

The authors have reviewed global sustainable energy development and its challenges. The authors have further proposed the correlation between energy and information. By understanding the important relationship between energy and information and the use of information entropy for enhancing energy control, effective sustainable energy development can be guided.

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