ENERGY STORAGE ENGINEERING

BRIDGING THE SUPPLY-DEMAND GAP

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PREFACE

“Do not go where the path may lead; go instead where there is no path and leave a trail.”
Ralph Waldo Emerson

“Choose a job you love, and you will never have to work a day in your life.”
Confucius, Chinese philosopher

Life on Earth is dependent on different forms of energy storage that were perfected by nature over millions of years. Anticipating the winter months, plants store biological energy in their roots and in their fruits and seed to restart the biological cycle in the spring. Bees, ants and insect-species store energy supplies in the form of honey and food supplies over the abundant summer months in anticipation of the frugal winter months.

As the intermittent renewable sources of energy such as wind and solar energy are increasingly adopted as sources of energy, their sustainability as future energy supplies hinges on associating them with reliable energy storage options.

Renewable energy technologies have developed in recent years, with improved efficiency and lower cost. A barrier to their uptake is that they do not provide a constant supply of energy. Wind and solar farms only produce energy when the wind is blowing, or the sun is shining. However, electricity is needed around the clock, day, and night. Humanity needs to imitate nature and develop ways to store energy on a large scale before it can make the transition to renewable sources. Note that, except for nuclear energy, we are depleting what nature has stored over millions of years in the form of hydrocarbons within a centuries time scale. In the process of releasing this hydrocarbon stored energy we are modifying the atmosphere’s and oceans’ compositions and modifying the earth’s climate. Essentially, we are depleting what is solar energy stored in plants as coal and animals’ organic matter as petroleum over millions of years, within decades. It is sobering to think that our main depleting energy supplies are primarily dead plants and animals.

Even for existing conventional sources used in electricity production, energy storage is crucial for their efficient use. The present status of grid electrical production is an “on-demand” system where electricity is produced to satisfy instantaneous demand and the generated supply is lost if not used. The existing system needs to be evolved from being an analog of a food supply system without storage and preservation by refrigeration, salting, drying, canning or other methods. It is considered as an inefficient wasteful system that calls for challenging reliable improvement and innovation.

 

Figure 1. Mined Lignite or Brown Coal mined in Germany and Natural Gas are the primary sources of electricity globally.

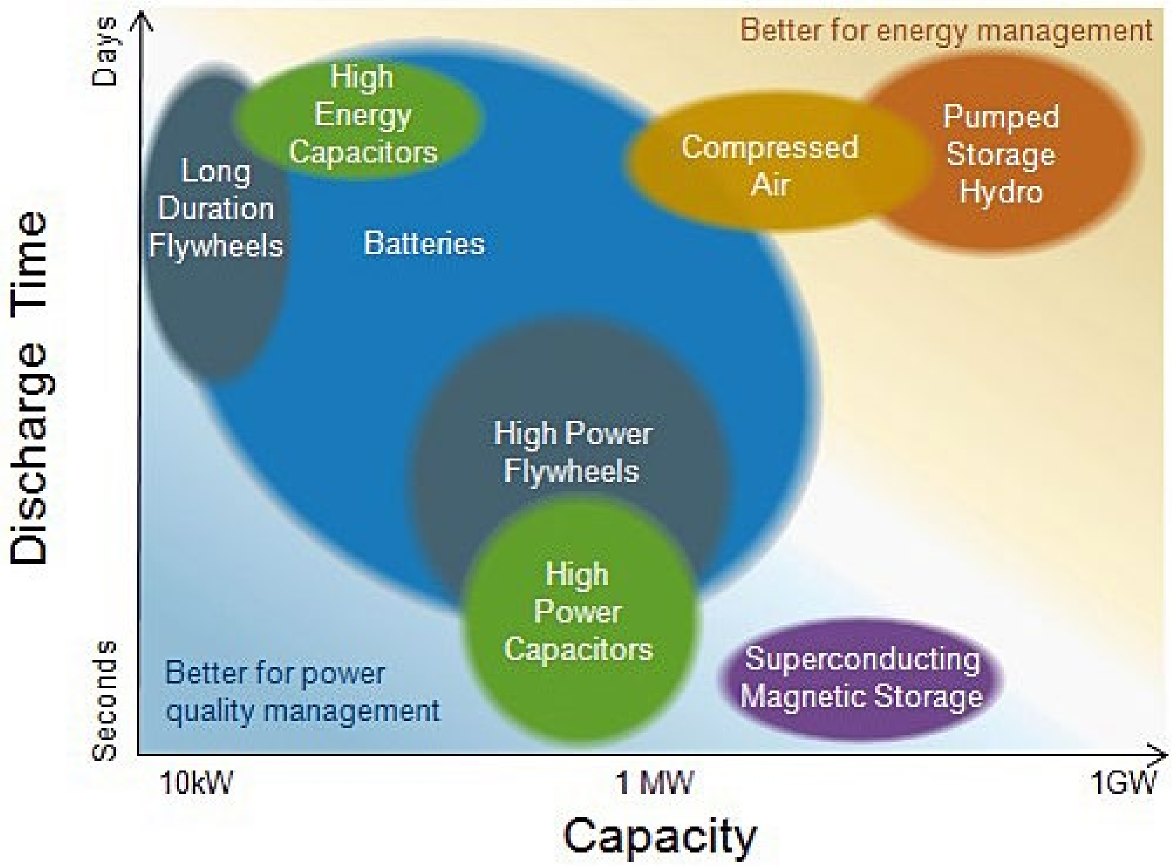

Figure 2. Ragone plot showing different energy storage options in terms of Discharge Time and Capacity in Watts. kW: kilowatt, MW: MegaWatt, GW: GigaWatt.

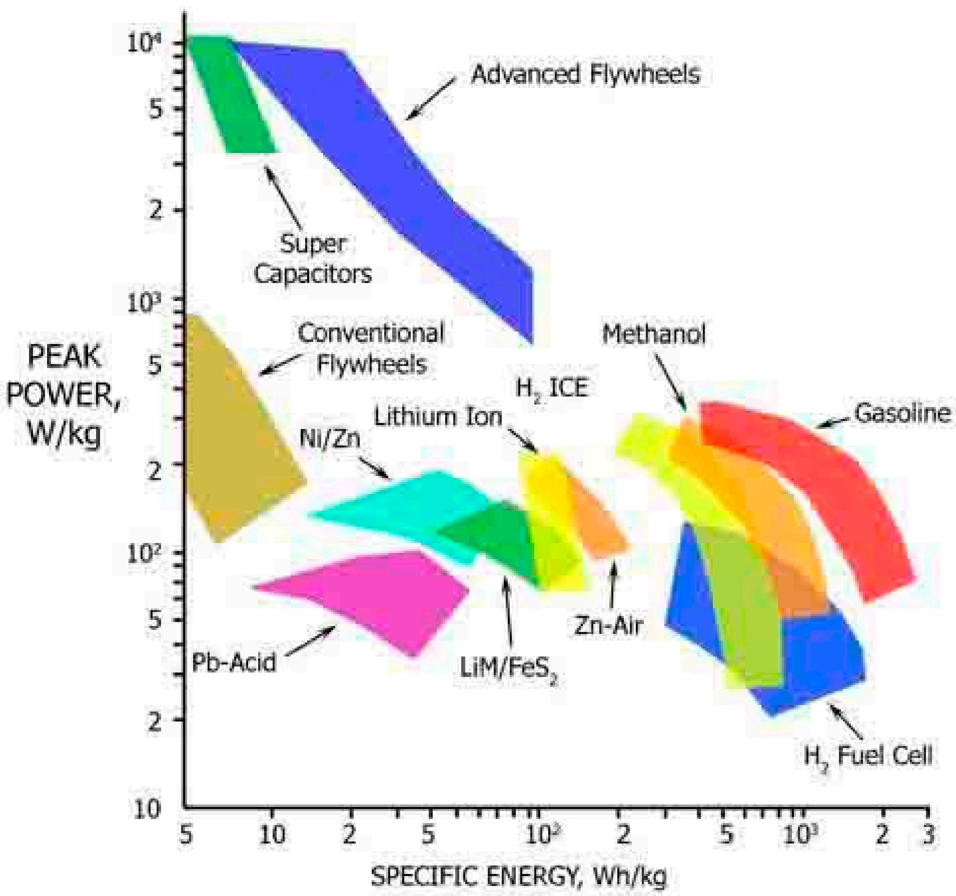

Figure 3. Ragone plot showing different energy storage options in terms of Specific Power in Watts per kilogram (W / kg) and Specific Energy in (Watts.hr / kg). ICE: Internal Combustion Engine.

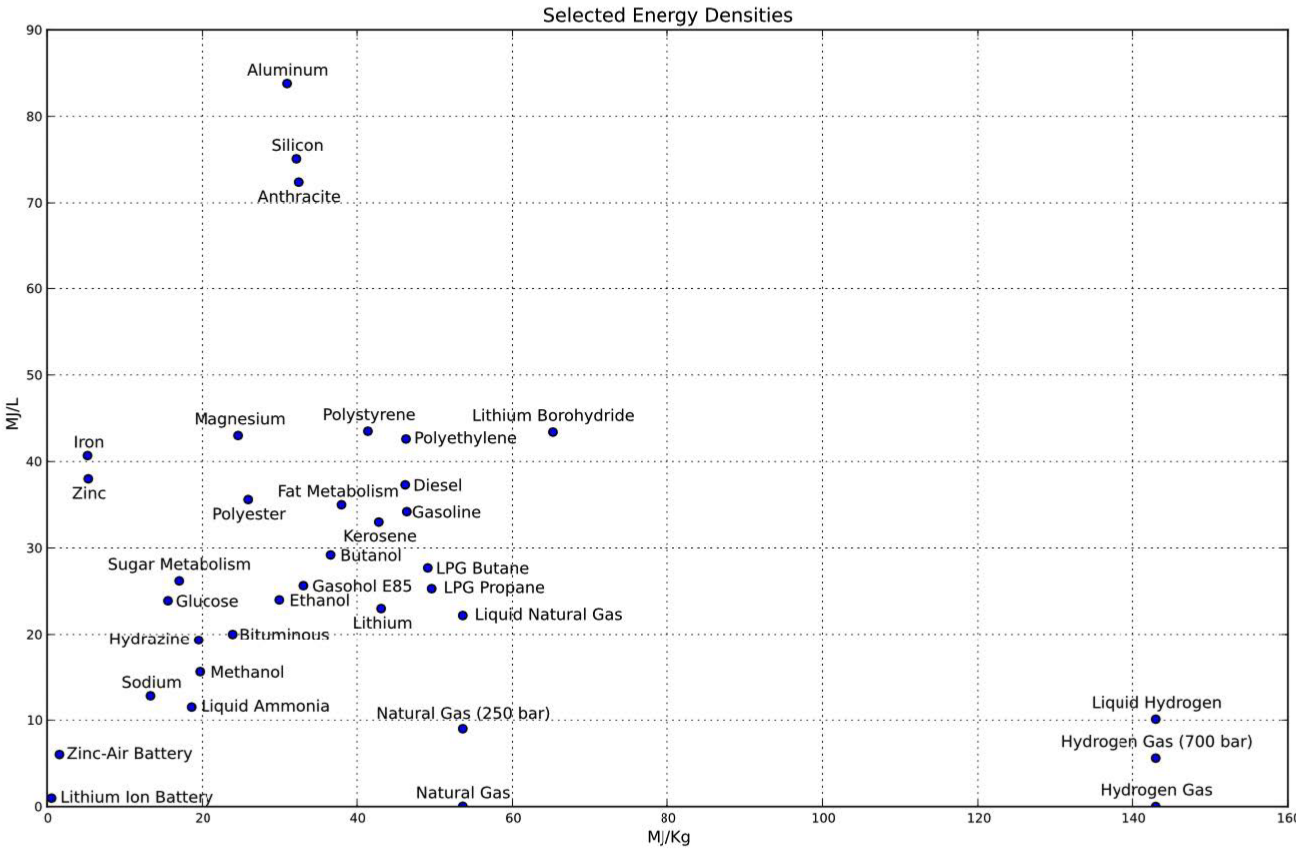

Figure 4. Ragone plot showing Energy Density in MegaJoules per Liter (MJ / L) versus Specific Energy in MegaJoules per kilogram (MJ /kg) of different energy storage options. A large disparity can be noticed between Lithium ion batteries currently used in Electrical Vehicles EVs and Hydrogen fuel cells under development in terms of Specific Energy.

HISTORICAL PERSPECTIVE

The origin of energy storage in human history dates back to Antiquity on the shores of the Nile River. There, biomass energy storage in the form of food supplies in times of plenty for use in periods of dearth, contributed to the rise of human civilization.

According to the Old Testament in Genesis 41:48-49:

> "And he gathered up all the food of the seven years, which were in the land of Egypt, and laid up the food in the cities: the food of the field, which was round about every city, laid-he up in the same. And Joseph gathered corn (wheat and barley) as the sand of the sea, very much, until he left numbering; for it was without number."

The energy/food storage process was in response to the expectation of seven years of bountiful crops to be followed by seven years of drought. The story goes that Egypt's King/Pharaoh dreamed two dreams. According to the Holy Quran:

Surat Yusuf (Joseph's Chapter) 12:43, The King (Malik in Arabic) said: "I do see (in a vision/dream) seven fat kine (archaic plural of cow), whom seven lean ones devour, and seven green ears of corn (wheat), and seven (others) withered. O ye chiefs! Expound to me my vision if it be that ye can interpret visions."

The Prophet Joseph interprets the meaning of the dream/vision to the King: "Egypt will have seven years of good crops followed by seven years of famine and the famine will be worse than the abundance. Joseph was thus entrusted with the store-houses in the entire land of Egypt.

Figure 5. Grain harvest and its storage in granaries/silos in Ancient Egypt at the Ramesseum memorial temple of Pharaoh Ramesses II, at the Theban necropolis in Upper Egypt, across the River Nile from the city of Luxor (Al Oksur: The Palaces, The Temples, in Arabic).

That food was to be stored as a reserve for the land against the seven years of drought that were to occur in the land of Egypt, so that the land may not perish through the ensuing famine.

The grain was stored in specially well-engineered and constructed granaries or silos; never built by alien creatures and definitely never in the Pyramids as suggested by some uninformed individuals. The moral of the story has direct implications both to biomass energy storage in the form of grain, to other energy sources as well as to economic and climatic change cycles.

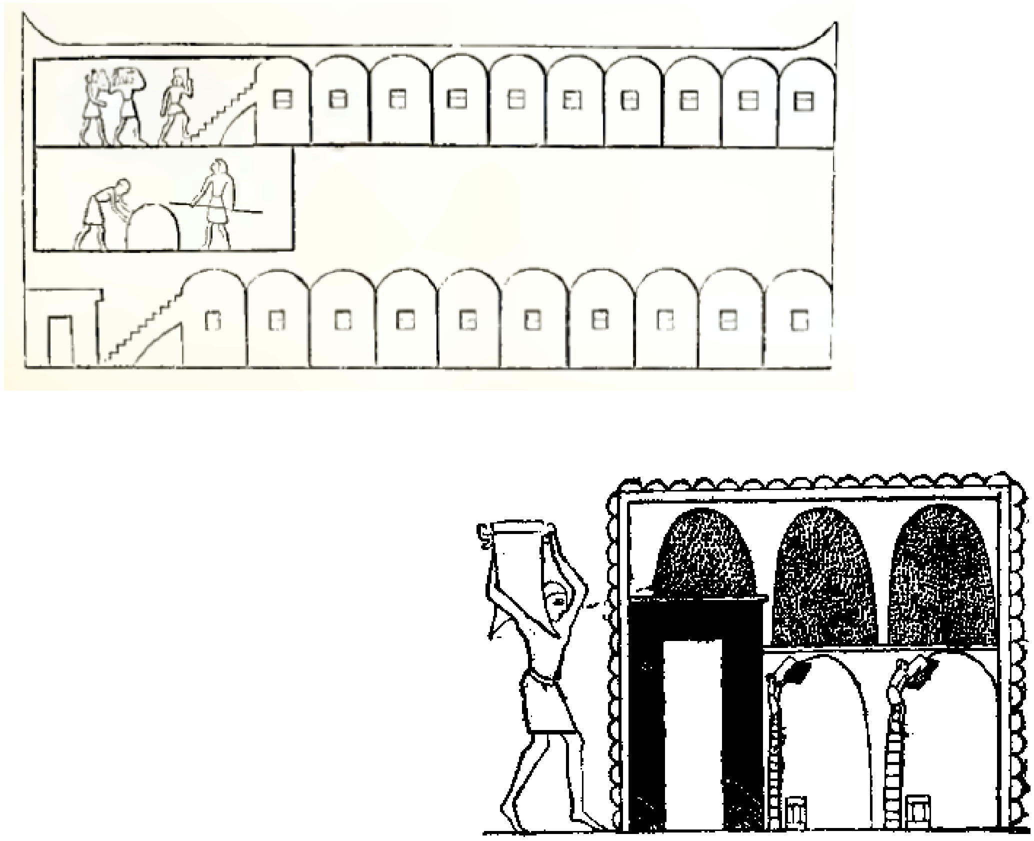

Figure 6. Egyptian grain storage in amphorae and granaries or grain silos. “Private granaries were generally in pairs, brick-built in the same long conical shape as the state granaries, and carefully plastered with mud inside and out.” [1].

Figure 7. Carved crystalline rock storage bowls at Abou Ghorab, Egypt. They were bases of storage grain silos with a drainage hole at their bottoms.

The Storage Systems of antiquity are described by Maspero and Oxon as [1]:

> “The taxation of ancient Egypt was levied in kind, and government servants were paid after the same system. To workmen, there were monthly distributions of corn, oil, and wine, wherewith to support their families; while from end to end of

the social scale, each functionary, in exchange for his labor, received cattle, stuffs, manufactured goods, and certain quantities of copper or precious metals. Thus it became necessary that the treasury officials should have the command of vast storehouses for the safe keeping of the various goods collected under the head of taxation. These were classified and stored in separate quarters, each storehouse being surrounded by walls and guarded by vigilant keepers.

There was enormous stabling for cattle; there were cellars where the amphorae were piled in regular layers, or hung in rows upon the walls, each with the date written on the side of the jar; there were oven-shaped granaries where the corn was poured in through a trap at the top, and taken out through a trap at the bottom. At Thûkû, identified with Pithom by M. Naville, the store-chambers are rectangular and of different dimensions, originally divided by floors, and having no communication with each other. Here the corn (grain as wheat) had to be not only put in but taken out through the aperture at the top.

At the Ramesseum, Thebes, thousands of ostraca (inscribed potsherds) and jar-stoppers found upon the spot prove that the brick-built remains at the back of the temple were the cellars of the local deity. The ruins consist of a series of vaulted chambers, originally surmounted by a platform or terrace. At Philae, Ombos, Daphnae, and most of the frontier towns of the Delta, there were magazines of this description, and many more will doubtless be discovered when made the object of serious exploration."

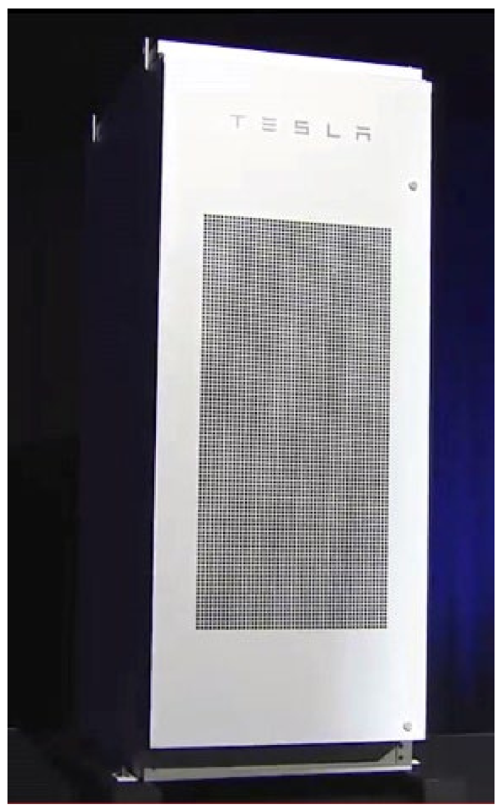

Figure 8. A 10 kW.hr Tesla "Power Wall" battery costing $3,500 and a 100 kW.hr Tesla "Power Pack" as replacements of existing "expensive, unreliable, poor integration, poor lifetime, low efficiency, not scalable, unattractive," and dangerous existing electrical storage batteries. Source: Tesla Power.

Figure 9. Nour (Al Nour: The Light, in Arabic) solar plant stores energy in Molten Salts at 400 degrees Celsius produces power for 3 hours after sunset from parabolic reflectors in the Sahara Desert at Morocco. Hydrogen as an energy carrier can be produced for export for fuel cell applications. Electricity can be produced for long distance high voltage DC (HVDC) power transmission.

Figure 10. Utility energy storage in storage packs in the USA.

Figure 11. Offshore wind turbine in Baltic 1 wind farm, Germany.

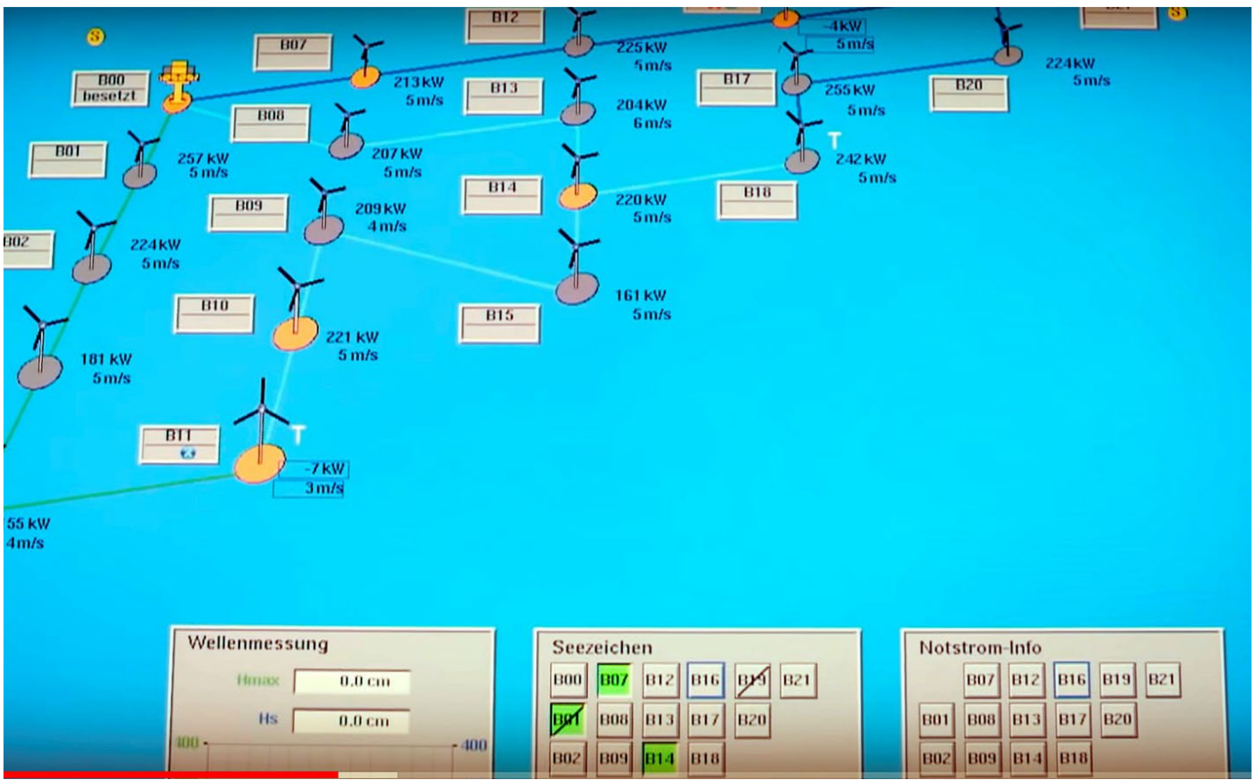

Figure 12. Control panel showing wind speed and power level in kWe, Baltic 1 wind farm, Germany.

Figure 13. Conceptual design of artificial wind Power Island in the North Sea.

Awaiting the development of dependable energy storage systems by the new generations of engineers and scientists, it is reported that solar energy production is unreliable in its present form as it only supplies power for a maximum 6-8 hours per day. Admittedly this power is produced when it is most needed. However, it does not reduce the size of the installed generation capacity since thermal generators as direct cycle or combined cycle gas turbine plants, have to be on hot, spinning standby, to kick-in when clouds cover solar farms. Such an installed spinning standby is costly in terms of capital cost, regardless of whether they are dispatching power into the electrical power grid or not.

It is amazing to realize that the existing North American electric grid, considered as the most complex machine ever invented and operated by humans, can work as well as it does with no substantial energy storage provisions. There is no standard way to store electricity on the present electric grid: if there is a surge in demand, the power companies have to fire up their extra spinning-reserve gas turbine power plants. It is an entire market for energy transactions without inventory nor buffer.

Electricity is delivered as a service instantaneously just in time, not as a commodity; suggesting the existence of an enormous amount of unnecessary waste. Consequently, a market is developing where a company like Tesla considers selling cheaply manufactured batteries to consumers, businesses, and homeowners to store that wasted grid-available energy at times of low demand for use at times of high demand or in times of emergencies. People can even generate their own energy from intermittent sources such as wind and solar energy, and with a modest backup system, reduce their dependency on the existing electrical utilities model.

Figure 14. Gigafactory1 solar-powered battery manufacturing facility in Nevada, USA. Source: Tesla Power.

The twenty-first century is witnessing the dawn in some cases, and maturation in others, of some prominent sciences and technologies: Nucleonics, Genomics, Proteomics, Informatics as well as Bioinformatics, Nanotechnology, Space Science, and Hydrogen Energy, in as much as the twentieth century has seen the emergence of Electronics. Without energy, there would have not been an Industrial Revolution. The USA would not be bread-basket to the world. There would be no technological, transportation and communication revolutions.

Renewable source of energy, with their intermittence issues, are heading towards center stage if the energy production system is supported by energy storage and conveyance technologies. At the end of 2013, the Ivanpah Solar Electric generating system came online sprawling over 5 square miles of federal land in the Nevada desert near the California-Nevada border line. The $2.2 billion project consists of 3 generating units, owned jointly by NRG Energy Inc., Google, and Bright Source Energy, has a rated capacity of 400 MWe. At 3 kWe of power need per home, this would in principle satisfy the electrical need for 400,000 kWe / 3 (kWe / home) = 133,333 homes.

Solar power, both thermal and photo-voltaic, still accounts for just 1 percent of the USA electrical production, it has ample room to grow with multiple centralized and distributed projects in the planning stages, particularly in the East-West southern corridor of the USA. Wind power complements it with a North-South corridor. Both approaches need energy storage and conveyance of the produced power for sustainability.

The solar industry, in conjunction with new energy storage technologies is growing at an unprecedented 30 percent per year growth rate. While solar energy is one percent of USA energy consumption in 2014, with such near exponential growth, it could approach 100 percent within 20 years at such a growth rate. That would mean a major transformation in the electrical utility sector of the economy.

For decades, researchers believed that there might be a ceiling to how much sunlight can be converted to electricity by a solar cell or solar panel: 34 percent. With solar panel manufacturers increasing their efficiencies from 12 percent to 24 percent in the last few years, the barrier has become a matter of concern. Solar Photo Voltaic (PV) is becoming a cheaper way to make both centralized and distributed electricity than coal, nuclear or gas-fired power plants. The State of California mandated that a 1/3 of all electricity generated in the state come from renewables by 2020, and large parcels of land were suddenly covered by black and blue PV panels. Scientists at Argonne National Laboratory (ANL) in the USA have developed an inexpensive material and the process for laying it onto solar panels that handily breaks through the 34 percent barrier. Using copper iridium selenide, they were able to convert more of the blue spectrum of light that hits solar cells into electricity. Most solar panels do not respond well to that part of the spectrum, and incoming photons end up primarily as heat, instead of producing a flow of electrons.

Experts suggest that cutting the average yearly energy consumption per capita to 1,600 kilowatts / year, a human's life expectancy would be cut in half to about 36.5 years. With the world population adding 250,000 new people every day, or 1 million new people every 4 days, a sustainable energy system is perceived as the only alternative to combat poverty and enhance the health and well-being of the world's population.

A sustainable energy system in turn depends on the ability to balance its supply and demand, much like in economics. Along this line of thought, a mixture of energy options, each with its own production and cost structure is envisioned for a robust structure.

Table 1. Cost of electricity from different energy sources, 2010.

Source	Electricity cost ¢ / (kW.hr)
Hydroelectricity	4.6
Coal	6.6
Geothermal	6.7
Nuclear	6.7
Natural gas	6.9
Biomass	9.5
Wind	11.0
Solar	38.0

Equally important is the ability to store the available energy in times of high supply and deliver it at the times of high demand. Bridging such a supply-demand gap is crucial in managing robust present and future innovative and creative energy architectures. This is a function of the intermittency or capacity factors of different energy options and the way energy is conveyed, "dispatched" or transmitted in between the production, storage and consumption centers.

Table 2. Typical capacity factors of different energy sources, 2010.

Source	Capacity factor [percent]
Nuclear	91.1
Coal	72.2
Natural gas, combined cycle	40.7
Petroleum	9.2
Geothermal	90.0
Hydroelectric	37.2
Onshore wind	20.0-40.0
Offshore wind	40.0
Biomass	90.0
Photovoltaic solar	12.0-19.0
Thermal solar	15.00

An energy option with a high capacity factor such as nuclear or coal can be efficiently used if the energy produced at times of low demand can be stored and supplied at times of high demand. An example is the battery storage of electrical cars during the night for later usage during the day.

SUSTAINABILITY OF ELECTRICAL RESOURCES: THE SMART GRID

In 1936, the writer F. Scott Fitzgerald, author of The Great Gatsby, wrote:

> "The test of a first-rate intelligence is the ability to hold two opposed ideas in the mind at the same time, and still retain the ability to function."

There are plenty of opinions on one side of the fence or the other. But the ability to take up two opposite ideas and process them at the same time is challenging. This applies to the role of conventional and renewable sources of energy in the future energy supply.

For a sustainable electrical energy supply, the engineering and scientific consensus is the need for the implementation of the "Smart Grid System" through "The Internet of Things, IoT" in both developed and emerging world economies. Using a Complex Systems description, its different components include an energy mix at its nodes with interconnected exchanges:

1. Centralized base power stations including nuclear, coal, hydroelectric and geothermal stations. These supply continuous electric service to industries and basic infrastructures such as street lighting.
2. Renewable Energies. These include wind, solar thermal and photovoltaic, essentially have a zero cost of the energy supply but suffer from their nature as intermittent sources and must be provided with backup systems such as gas turbines, except for biomass.
3. To overcome the intermittency problems of the renewables, storage systems such as battery, hydrogen and pumped storage, as well peaking sources such as natural gas turbines plants are also needed.

4. Distributed and decentralized power production, conservation and Smart-Metering for consumers and industry would encourage the use of the produced energy whenever it is available. In this case, they are paid for the energy they produce and pay for the actual unsubsidized price of the energy they buy, which would encourage its production.

To advance an analogy, consumers must be encouraged by laws and regulations to catch the fish, use some of it for their own need, and sell the surplus into the marketplace. This concept is implemented in Germany where farmers use part of their pastures to produce photovoltaic electricity, use part of it on their farms, store part of it, and sell the surplus to the electrical grid system. In Denmark, homeowners with small tracts of land produce wind power for their own use and the electrical utilities are obligated to purchase their excess surplus production and feed it into the electrical grid.

5. The Internet of Things (IoT), decentralized control of the smart grid system turning components of the Smart Grid system on and off depending on the demand.

According to the 2014 British Petroleum's (BP) 2035 Energy Outlook Report, the USA is projected to become energy independent by 2035 while also becoming the world's top liquids and natural gas producer. The report predicts worldwide energy demand to grow by 41 percent within the next 10 years; a slowdown of the 52 percent growth rate of the last 20 years. Energy production in the USA is expected to increase by 24 percent, while consumption would increase by just 3 percent. Energy used in power generation would increase by 10 percent. Coal is expected to remain as the dominant electrical power source, but its share would drop from 43 to 35 percent.

Globally, petroleum, natural gas, and coal are expected to account for 27 percent of the total energy mix beyond 2016, with nuclear, hydropower and renewables accounting each for 5-7 percent of energy demand.

Renewables, including biomass, are expected to be the fastest growing source of electricity generation and exceeding nuclear energy as a source of primary energy by 2025. The USA and other industrialized nations will see increased energy efficiency and see their economies grow whilst energy use falling.

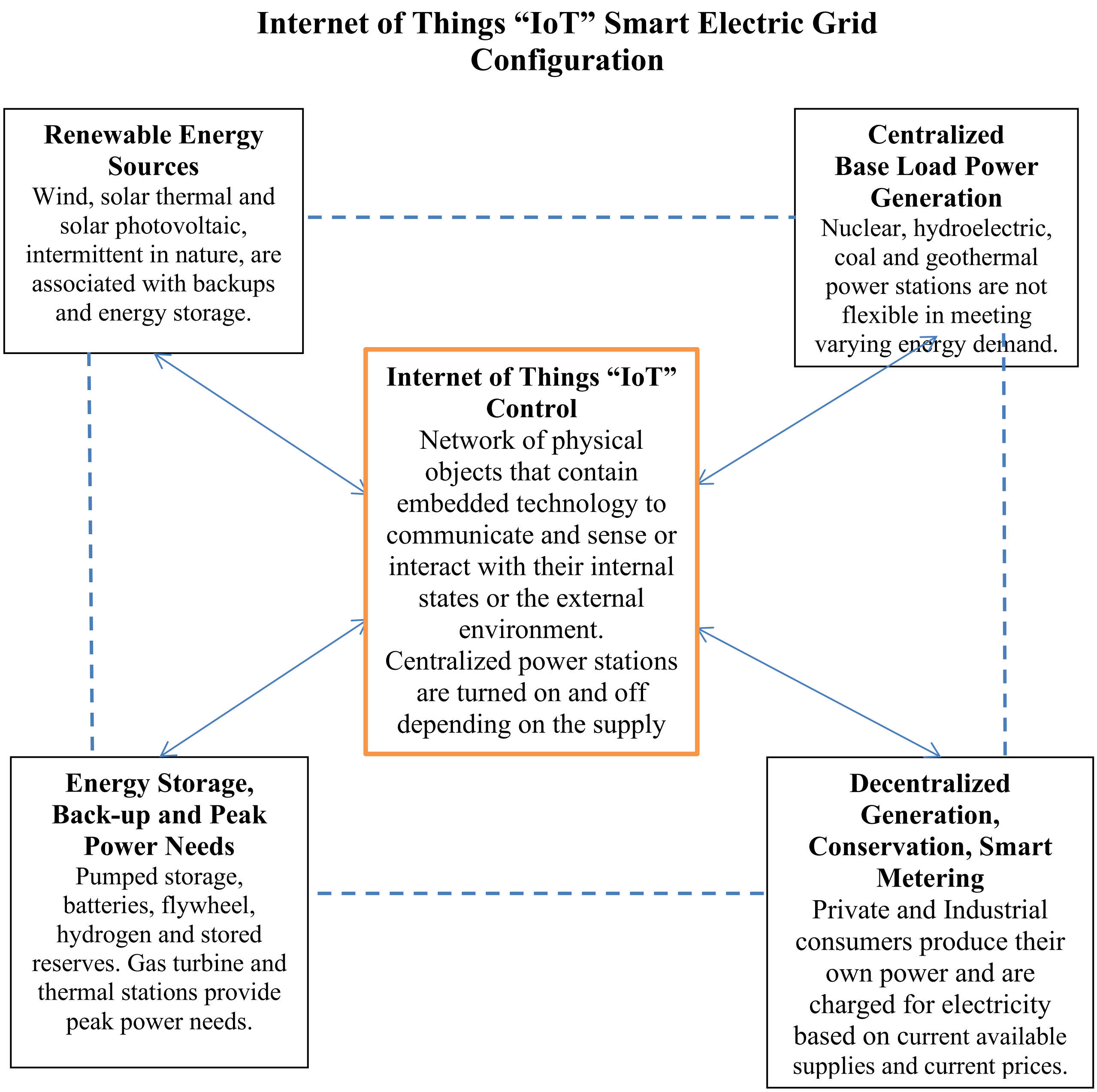

Figure 15. Smart grid configuration using Internet of Things “IoT’, connecting renewables and conventional energy sources to electricity consumers within the smart power grid. Energy storage is required for the successful implementation and sustainability of the inherently “intermittent” renewables that also require backup sources. Energy storage is needed as well to provide efficiency for the enormously wasteful “on-demand” conventional sources providing “base-load” as well as “peak-load” supplies that are wasted if not instantaneously transmitted and used.

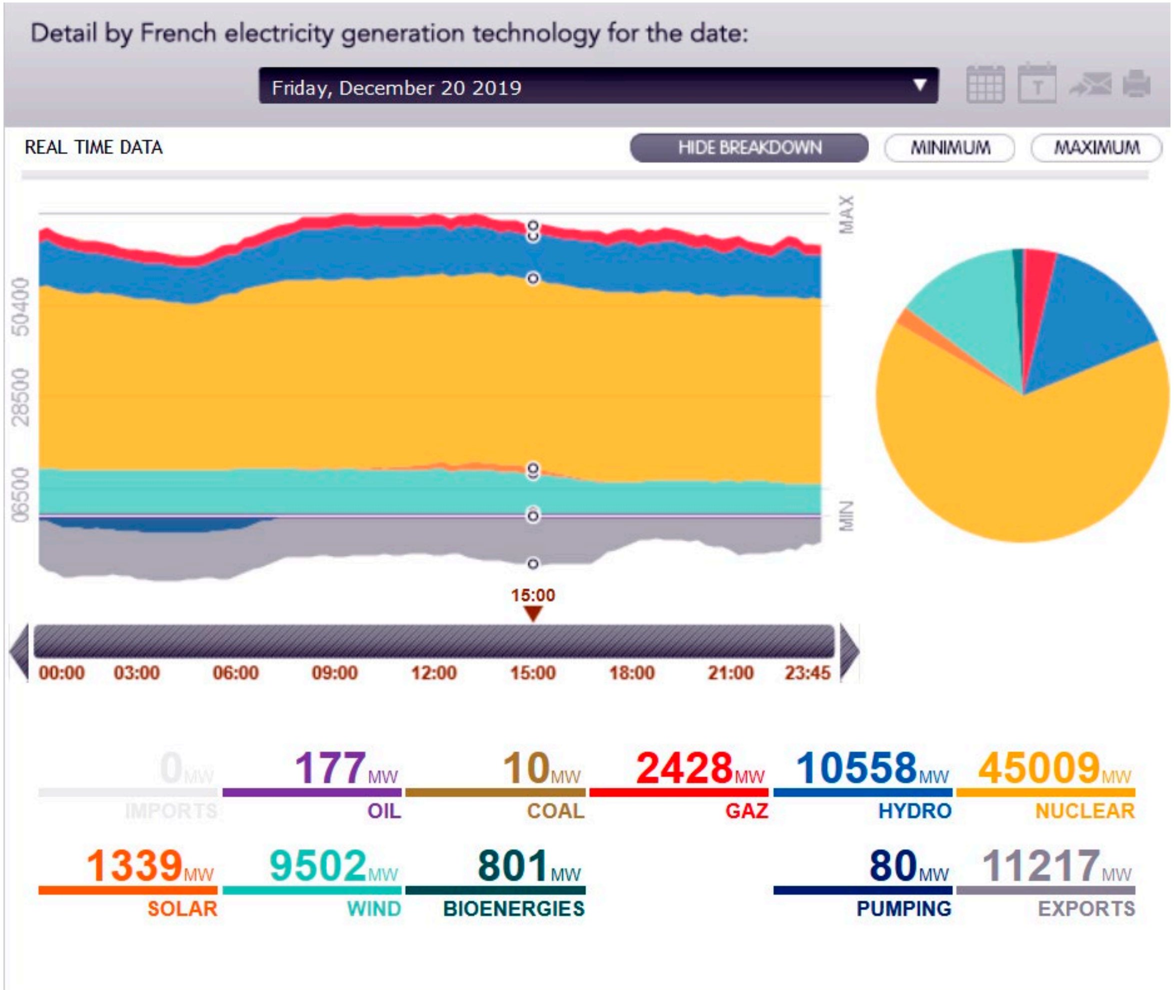

Figure 16. Energy mix including storage, over a 24-hour period on January 20, 2020, France [4]. Source: RTE.

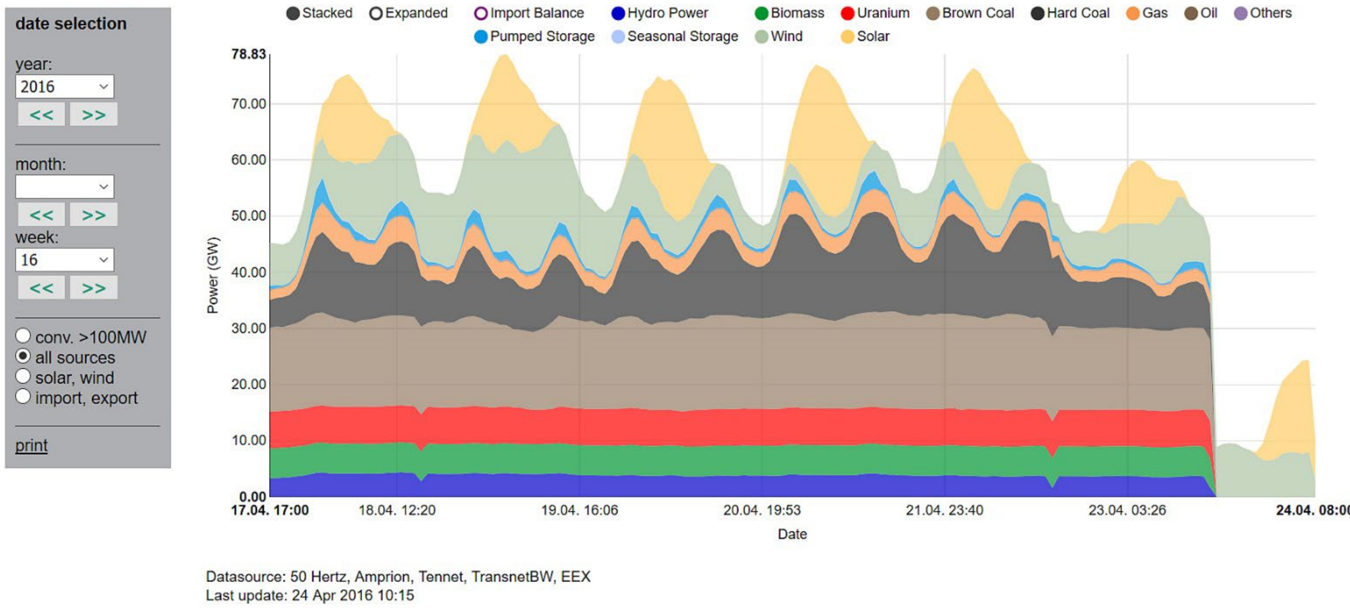

Figure 17. Energy generation from wind, solar and conventional sources in Germany on the 16th of April 2016.

Figure 18. Solar highway concept in China would store energy from Photovoltaics to refuel electrical vehicles.

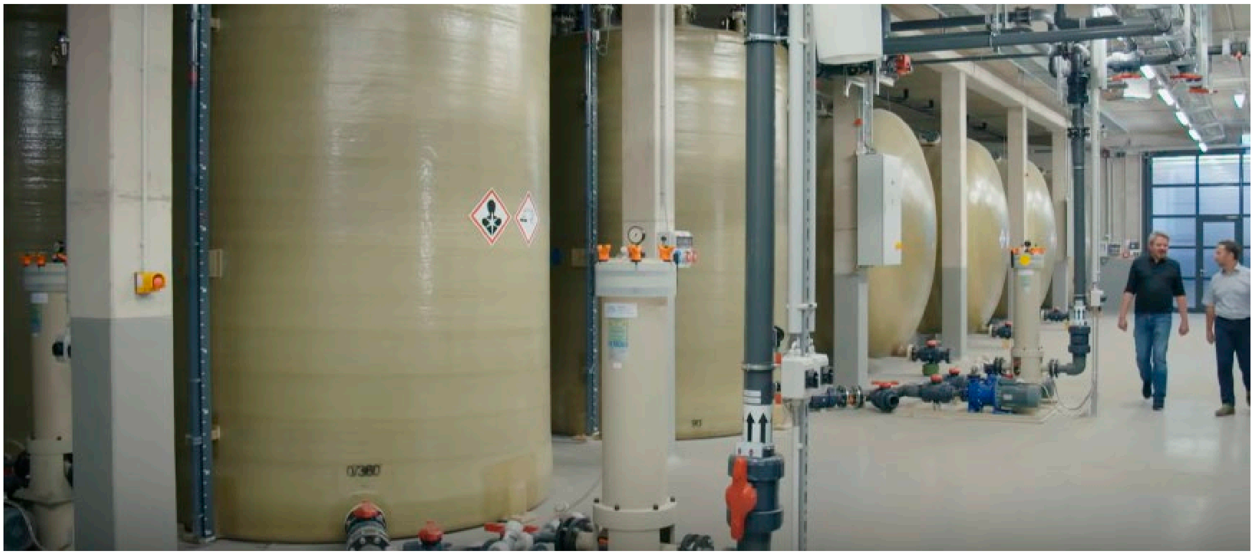

Figure 19. Large scale Redox flow batteries can store energy from consumer-owned DC current-producing wind turbines over long time periods without being connected to the grid.

Figure 20. Photo Voltaic (PV) Solar collectors atop a building.

NET METERING AND FEED-IN PROGRAMS

Net-metering (NT) allows homeowners with installed PV solar panels to sell the excess power produced by their solar panels they produce to the utilities managing the local electrical grids. FIT programs (Feed In Tariffs) pay solar producers many times the wholesale/retail cost of generation. Net-metering is typically - 14c/Kw.hr from the power companies and 2c/Kw.hr for power sold back to them, in addition for the payment for a separate meter and extra fees and taxes; an unfair arrangement.

Most utilities allow net-metering to be applied only as a bill credit against consumption.

They would not pay for the extra produced power. The reasoning is that since these people would then no longer be paying for the infrastructure that everyone else is paying for via base/consumption charges and get a free ride on the grid.

New net-metering state rules that apply to all power producers have been enacted governing the interaction between investor owned utilities and individual producers of wind power. Customers in the state of Illinois, for instance, are billed for the net power they use and receive credit for the excess self-generated power they send to the utility company. Net-metering currently applies to investor-owned utilities. Electrical cooperatives are developing their own interconnection standards.

However, it must be emphasized that while it is possible to offset an electrical bill, it is not possible to receive income from the utilities. Thus the new rules apply to residential and commercial customers who just want to zero-out their electrical bills and not become power producers. Allowing these producers to sell their excess power to the utility, like in some European countries, would provide a further incentive to wind and solar power generation.

The net metering laws in the USA are unfortunately toothless and do not yet seriously favor large-scale energy production by the small producers like those in the European countries, particularly Denmark. Through effective political lobbying and campaign contributions to unsuspecting and uninformed officials and lawmakers, they are presently discouragingly biased in favor of the electrical utilities, which do not encourage small power producers to connect to their grids less they potentially destabilize them. In fact, any potential wind power producer must obtain the approval, with the payment of an inspection fee, from the local power utility before being allowed to connect to the grid system. In their present lacking reactionary form, these toothless laws are defanged and do not encourage small scale production and make it totally unfeasible for small power producers to sell their excess power to the local grid. Consider the disadvantage, frustration and the unsolvable dilemma facing a potential solar power producer in the state of California [1]:

> "Last year I looked into installing a photovoltaic system on my house here in Southern California. Then I found out that I would have to sell any excess power back to Southern California Edison for less than Southern California Edison sells it to me."
>
> "Plus I would have to use a special meter. I would not be permitted to install the equipment myself (although I am an industrial electrician with more than 20 years of experience), and I would have to pay an approved contractor for the system installation."
>
> "Lastly, if there is a power credit at the end of the year (if I produce more power than I use), the credit is forfeited!"
>
> "Why bother?"

DISTRIBUTED VERSUS CENTRALIZED POWER GENERATION

Nevada, the "Silver State," has the fifth largest installed Photo Voltaic (PV) solar capacity in the USA. It is home to Tesla's "Gigafactory1," projected to produce storage batteries for electric vehicles and home energy storage. The Chief Executive Officer (CEO) of Tesla, Elon Musk is the chairman of the SolarCity Company.

Solar PV panels cost about $1,000 per kW. A small house system should be at least 2 kW. Add the cost of inverters, another two thousand, plus mounting framework, another 2 thousand, wiring and labor, bringing the capital cost to $10k for a small system. Real costs of power generated from solar panels is on the order of 25 - 30 cents per KW.hr. The costs are lower in States with more sunshine and less cloudy days, and can get under 20 cents per kWh.

The term "efficiency" of solar panels is used frequently. What really matters, is the price of the produced electrical energy. One can have a cheap, low efficiency solar panel that is much more cost effective than a high efficiency, but costly panel.

Nevada law requires the state to: "Encourage private investment in renewable energy resources, stimulate the economic growth of this State; and enhance the continued diversification of the energy resources used in this State," through net metering.

The Nevada state legislature ordered the Public Utility Commission (PUC), appointed by Nevada Governor Brian Sandoval (R), to formulate a new net-metering payment by the end of 2015 after the state maxed-out an allotted 235 MW net-metering program. As a consequence, Vivint Solar, a solar energy developer, pulled out of Nevada after the net-metering program became fully subscribed, which forced new solar installations to grind to a halt.

In 2015, the Nevada PUC voted 3-0 to reduce by 75 percent the payments that homeowners receive for solar energy and to also increase charges on them. The decision does not grandfather homeowners who have already installed solar panels, even though many of those people made their solar investments based on the net-metering payment provisions. The Alliance for Solar Choice, an industry trade group, filed a lawsuit against the PUC [2].

The Sunrun Company filed a lawsuit against Nevada Governor to obtain records of text messages between him and NV Energy electrical utility lobbyists. NV Energy, a major Nevada utility and a subsidiary of financier Warren Buffett's Berkshire Hathaway Company is opposed to the net-metering provision [2]. NV Energy position is that lowering the payments avoids shifting the costs to other ratepayers. NV Energy proposed to lower net-metering payments and to increase the fixed charges on solar homes, a decision that the PUC supported [2].

The SolarCity Company threatened to leave the state if the PUC moved forward on slashing the net-metering payments, and followed through on its threat. On December 23, 2015 SolarCity announced that it would stop selling and installing solar panels in Nevada. NV Energy said it was reviewing the PUC's decision to determine how it would affect its customers [2].

This leaves distributed power producers with the alternative of working outside their centralized power systems and creating their own. They can install their own solar panels, produce their own solar power, store their surplus, and sell electricity locally to their neighbors at a fair price determined by market supply and demand considerations. They can use the energy their solar panels produce instead of loading it into the grid for pennies on the dollar.

With the feed-in tariff reduced, electricity consumers have the alternative of buying the PowerWall storage and go "off-grid". The impediment is the cost of $60k per DC unit, and triple the amount with AC. A better choice is a lower-cost and longer-lasting combination of Ni-Fe and Pb-acid batteries. This is analogous to the abandonment of wired phone lines in favor of mobile connections. This could bring a "death spiral"; a positive feedback loop, as the owners of the grid must repeatedly raise the grid access charges to recover costs from an ever dwindling number of households connected to the grid.

The economics of "rent seeking" suggest that if anything is worth doing, it doesn't require government subsidies in order to get it done, as profit seeking capital will flow there for the Return

On Investment (ROI).

FUTURE CHALLENGES

It is surmised that at the core of the problem is a cultural tradition originating from the history of the well-established fishing industry in the European countries, such as Denmark, of favoring the small producer and providing him with a ready-market for his product.

In the USA, on the other hand, large scale producers are favored, and the small producers are forced into a "catch and release" sportsmanship inefficient corner; to carry out the fishing analogy. Should the capability of small scale producers be unleashed, a substantial supply of wind and solar energy would be provided into the supply chain, replacing fossil fuels, extending their depletion time, and reducing their prices.

Figure 21. Plugin electric cars could charge their batteries overnight with electricity supplied by electrical power plants. Norway with large hydroelectric power resources is planning a primarily electric transportation fleet. A battery-equipped car fleet would effectively act as a distributed energy storage system.

Figure 22. Electrical charging station at a highway intersection, Norway. Internal Combustion Engine (ICE) cars are planned to be eventually phased out.

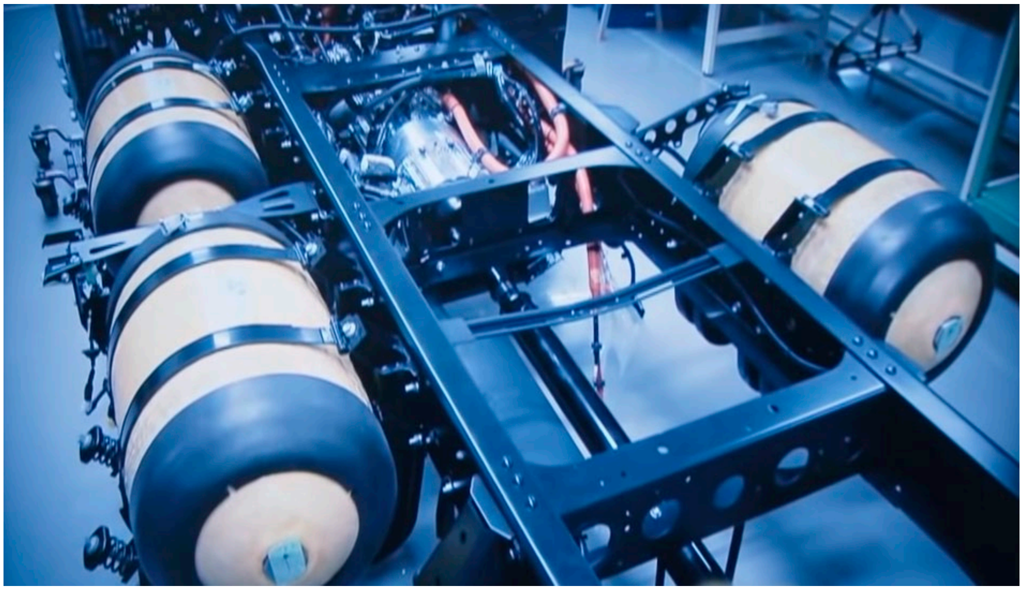

Figure 23. Chassis of truck using fast-charging (5 min) and longer-range compressed hydrogen as an energy carrier and a fuel cell feeding an electrical motor, Toyota, Japan.

Figure 24. Compressed hydrogen fuel tank configuration in Mirai fuel cell passenger car, Toyota, Japan. The need to cool the fuel cell with air inlets generates drag and affects the car's aerodynamics. Fuel cells can provide a home with its electrical needs for a week's period.

Figure 25. Hydrogen charging station, USA.

Figure 26. The “Solar Impulse” plane circled the globe using PV solar electricity, 2015.

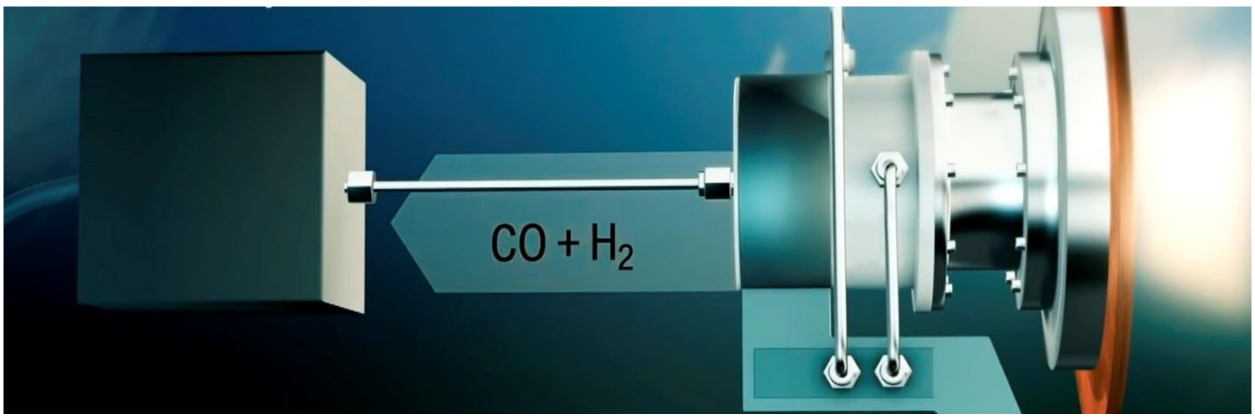

Figure 27. Concentrated solar energy can produce zero-net-carbon hydrocarbon fuel from CO_2 and H_2 from water in the atmosphere using the Fischer-Tropsch process.

On the other hand, a low capacity factor energy option such as solar or wind can be turned into a high capacity one if the excess energy produced during the day for solar is stored for delivery during the night, and the excess energy produced in periods of extractable wind is stored for use during periods when the wind resource is absent.

Another alternative is the production of hydrogen as an energy carrier at times of low demand for use in fuel cells at times of high demand. Yet other alternatives include thermal and pumped storage, compressed air, magnetic, electrostatic, biological storage in algae and mechanical flywheel storage.

Maintaining a decent standard of living will place higher demand on sustainable energy systems, particularly the renewable options. The average USA household spends $1,900/year on energy bills for just heating and cooling the home; excluding the transportation needs. Average homes in 2001 were 2,555 square feet, up from 2072 in 1981 adding to more demand on cooling and heating. American homes are increasingly wired for the new Information Technology Age with outlets charging new gadgets such as cellular phones, iPods, multiple computers, and 2-3 televisions including big screen televisions creating higher demand for electricity. The plasma large screen televisions have screens four times larger than the earlier units and consume 8 to10 times as much electricity as those that they are replacing. Entertainment and telecommunications account for 15 percent of home energy use. Six out of every 10 homes have a computer, up from one in 5 in 1992.

In its State of the World Reports, the World Watch Institute echoes these concerns. To the trends it started considering since 1984: shrinking forests, falling water tables, disappearing plant and animal species, it has added the new concerns of rising temperatures, melting arctic ice, melting glaciers, ozone depletion, more destructive storms, and dying coral reefs and amphibians. In general, signs of a growing world ecological stress and decline. Some of these symptoms can be attributed to the burning of fossil fuels and the need to a higher dependence on renewable and nuclear technologies. This makes the content of interest to members of the general public other than engineers, without sacrificing its scientific, physical and mathematical rigor.

The present work is written, primarily for the benefit of the authors themselves in a modest attempt at understanding the topics covered. Part of the material serves as course notes for students from the different engineering disciplines, as well as students from the Social Sciences and Humanities at the University of Illinois at Urbana-Champaign. The course is intended primarily by seniors and graduates in Mechanical, Electrical, Chemical, Aerospace, Civil and Environmental Engineering, as well as by Nuclear Engineering students with interest in the energy sciences and technologies. Students in Law and Physics and officers being commissioned into the USA Armed Forces are expected to benefit from it.

The material in this work covers the course curriculum, but attempts to supplement it with issues, concerns and questions, raised by the students, related to the class material. The issues arise from the intellectual curiosity of the students and the course attendees.

The material is presented in the portable document format (pdf), and requires a download of the freely accessible Adobe Acrobat Reader on any computer. The chapters are self-contained and can be read in the order that the reader wishes. The work is still in progress and is evolving and is frequently being updated. It is continually “under construction.” In fact, it is an ongoing experiment that started in 2009.

The hope is that this modest effort will contribute to the scientific literacy of the readers in the Energy Sciences area of knowledge, and satisfy their intellectual curiosity about our universe and our world, whose better future we all dream about.

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REFERENCES

1. G. Maspero, D. C. L. Oxon, "Manual of Egyptian Archaeology, and Guide to the Study of Antiquities in Egypt, for the Use of Students and Travelers," translated by Amelia B. Edwards, Institute of France, Collège de France, General Egyptian Museums, 1895. http://www.ajhw.co.uk/books/book79/book79c.html#fig_44

2. Nick Cunningham, "Warren Buffett Beats Elon Musk in Nevada," OilPrice, December 29, 2015, http://oilprice.com/Alternative-Energy/Solar-Energy/Warren-Buffett-Beats-Elon-Musk-In-Nevada.html.

3. Rachel Beck and Magdi Ragheb, "Production of Carbon-Neutral Hydrocarbons From CO_2 and H_2 In Lieu of Carbon Capture and Storage (CCS)," 10th International Conference on "Role of Engineering Towards a Better Environment, RETBE14, Alexandria University, Faculty of Engineering, 15-17 December 2014.
Abstract. Power Point Presentation.

4. RTE, French Transmission System Operator, "Power Generation by Energy Source." https://www.rte-france.com/en/eco2mix/eco2mix-mix-energetique-en