Addressing the Intermittency Challenge: Massive Energy Storage in a Sustainable Future

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I. INTRODUCTION

> "The problem of the commercial utilisation, for the production of power, of the energy of solar radiation, the wind and other intermittent natural sources is a double one. The energy of the sources must first be changed so as to be suitable in form; it must next be stored so as to be available in time."
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> *Reginald A. Fessenden, 1910 [1]*

The 21st Century industrial civilization that surrounds us is profoundly dependent upon massive energy storage so familiar that even the authors of this Special Issue seldom notice it. Seemingly unrelated to mankind's shrinking primary dowries of fissile or fertile nuclides and of fossil organic carbon, are the commonplace and unremarked piles powdered coal outside electric generating stations, the huge tanks of liquid hydrocarbons adjacent to our refineries, and the underground caverns storing natural gas near our cities.

This Special Issue focuses mainly on massive energy storage systems, but also includes a vision for small to medium sized storage and a discussion of the driving forces.

Energy, convenient in form and available upon demand, is taken for granted. In the best of scenarios, nuclear fission, even assuming that we solve the nuclear waste problem, does not appear to scale to meet global energy needs [2]. Once economical sources of fossil fuels approach depletion, we will have no certain recourse but renewables, primarily sun. But sun and wind and tide and wave are not available on demand because they are intermittent:

> "The wind bloweth where it listeth, and thou hearest the sound thereof, but canst not tell whence it cometh, and whither it goeth."
>
> *John 3:8*

> "If the sun we do not store,
> We have no power after four."
>
> *After a couplet by Nathan S. Lewis*

The challenges to our electricity supply, which are posed by the intermittency of most renewable sources, require solutions at four different time scales.

1) *Seconds*. Maintenance of *power quality* requires rapid energy transfers to mute the effects of switching transients, arcs, harmonic generation by nonlinear loads, etc.
2) *Subhour*. To offset unexpected mismatches between electricity demand and generation or to smooth transitions of composition within the mix of sources currently

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on line, *bridging power* is needed.

3) *Diurnal*. To offset the loss of primary sources due to intermittency and unpredictability, massive energy storage is required; and *energy management*, as it is presently understood, probably will not suffice.

4) *Seasonal*. The fact that the locally available supply of renewables suffices to meet the annual needs of a certain geographical area may be irrelevant unless storage is provided. This is so not only because day length varies no matter where one is on the planet, but also because both cloud cover and wind can be seasonal.

Obviously, diurnal and seasonal storage will require much larger facilities to back up the grid. On a modified Ragone chart where rated output powers are plotted against rated energy storage capacities, a significant metropolitan area would normally desire to appear with a rated output power of not less than 1 GW and a minimum energy capacity of at least 48 GWh [3][1]; with appropriate rationing, this should suffice to see the area through most emergencies. Therefore, we define a *massive energy store* as one possessing *both* a rated output power of at least 1 GW and a rated storage capacity of at least 2 GWd.

The storage of power line frequency electrical energy as electrical energy is limited to capacitors and inductors, and neither has proven particularly practical where massive amounts of energy are involved. Instead, "electricity storage" is commonly accomplished by transforming surplus grid energy into a different but conveniently stored form: 1) chemical energy, e.g., a charged ultracapacitor, a charged battery, gaseous hydrogen; 2) mechanical energy, e.g., a rapidly spinning flywheel, a cavity filled with compressed gas, an elevated reservoir up to which water has been pumped from a lower reservoir; and 3) thermal energy, e.g., a tank of hot liquid, or a cavity filled with hot pebbles and a heat carrying gas.

When electric power is needed, the stored energy is back-converted to electricity and returned to the grid. These conversions, however, are not ideally efficient, and each process is characterized by a figure of merit called the *cycle efficiency*, defined as the ratio of the total joules delivered to the grid over a suitable study period divided by the total joules received from the grid during the same period.

Further, an energy storage system is conveniently divided into three parts: 1) an input energy conversion module (ECM_{in}), which accepts energy from the grid and converts it to a storable form; 2) an energy storage module (ESM), which actually warehouses that storable form; and 3) an output conversion module (ECM_{out}), which turns the stored energy back into electricity and returns it to the grid. Obviously, for fair accounting, the state of the energy storage module at the end of the period must be the same as at its start. Equally obviously, loss can occur in either conversion step as well as during storage; surprisingly, cycle efficiency data of impeccable provenance are relatively rare, and rarer still is the precise attribution of the loss to identified mechanisms and locales.

Moreover, even though reviews, overviews, popularizations, and screeds of various persuasions exist in quantity, cf. [4]–[7], including a previous Special Issue of the Proceedings of the IEEE, vol. 71, no. 9, 1983, a classic review in the *Proceedings of the IEE* [8], and a designation as the "Achilles heel of renewable energy" [9], we nevertheless have found too few *recent*, technically deep articles on massive storage.[2] For this reason, we have assembled a number of articles that have been edited to emphasize practical detail and applications, even though the envisioned devices have in some cases not yet been commercialized.

It will be apparent that we have emphasized diurnal and seasonal storage, while the opinion piece article in this Special Issue focuses on shorter term storage, and that we have neglected batteries and fuel cells despite our section on chemical storage. We claim no revelations of certainty and have thought it best not to impose an orthodoxy of outlook: but we cannot include everything, especially items well covered elsewhere; whereas we can indeed include reminders that massive long-term storage is by no means the only important challenge confronting a smooth transition from energy stored in fossil hydrocarbons to intermittent renewable energy. But we would be remiss not to remind the reader that our forebears reading this Special Issue would most likely say, "We told you so":

> "It has long been recognized that mankind must, in the near future, be faced by a shortage of power unless some means were devised for storing power from the intermittent sources of nature . . . [The] problem of storing them in a practical way . . . has for many years engaged the attention of the most eminent engineers, among whom may be mentioned Edison, Lord Kelvin, Ayrton, Perry. . ." [10].

[1]The specification of energy in any unit other than the Joule is discouraged by the IEEE [3, s. 3.4.5.1]. However, units such as the kilowatthour and the gigawattday are remarkably informative for expressing large amounts of energy in units of a magnitude similar to that of the devices being discussed. The necessary equivalences are: 1 GWh = 3.6 TJ; 1 GWd = 86.4 TJ. Lest the reader be disturbed that many of the devices to be described are rather smaller than a gigawattday and not obviously scalable to such a massive size, let it be pointed out that most can be considered to be modules capable of being connected in parallel indefinitely.

[2]A probable exception to this generalization is the battery storage modality. It is a busy research area with a solid theoretical foundation, the U.S. Department of Energy (DoE) funding several battery-relevant Energy Frontier Research Centers, private industry investing heavily in batteries for automobile power systems, and several dozen review articles appearing in the two past years. In addition to batteries being well covered elsewhere, the topic is rather too broad to be included here; and, for reasons of cost and resource scalability, batteries are seldom included in the "massive" category.

While the main focus of this Special Issue is on massive storage, a vision for small to medium sized storage and a discussion of its driving forces are appropriate in order to build up a picture of overlapping issues. With this in mind the lead point of view article by Gopstein from the U.S. Department of Energy (DoE) discusses storage, for example, for assuring grid stability and promoting power quality.

The remaining articles fall into four categories: 1) energy policy, including supporting technical topics not *sensu stricto* on storage; 2) chemical storage; 3) mechanical storage; and 4) thermal storage. The available energy from all renewables added together (except solar) is less than 1% of that available from solar energy alone. Thus, many of the papers, herein, reasonably focus on storage given a dominant solar source.

Furthermore, the greater emphasis is on *solar thermal* as the source, because it is massively scalable for base-load power, whereas photovoltaics are better suited to niche energy harvesting [11]. Solar thermal, also known as concentrating solar power (CSP) uses mirrors to concentrate solar radiation to a hot focus; this can then be used to superheat steam and run a turbine for power generation.

How the themes of the papers in this collection tie together is discussed in the following.

II. ENERGY POLICY

The paper by Hart *et al.* sets the scene for this issue on massive storage by making the point that an energy portfolio of energy renewables, suitably connected to a grid, can be designed in a way that minimizes the need for storage. The paper discusses how at the planning stage, the effects of intermittency can be reduced by using optimization methods and large data sets to develop portfolios that best match the aggregated intermittent resources with the load.

With this viewpoint uppermost, it helps to foreshadow that the task of initially installing storage in future energy systems may not be as daunting as it might first appear. However, the catch is this approach only works for the first 1% of global incident solar power. Once we start tapping solar power at levels that exceed the sum of all other available renewable sources, the requirement for storage will increase. This motivates theme of massive storage in the Special Issue.

Given that CSP, also called solar thermal power, is a promising utility-scale solar generation technology, the paper by Madaeni *et al.* examines the value that energy storage can provide CSP by increasing the effective capacity value. This indicates that storage improves the economics of CSP and that economic issues may well be a driver in favor of storage.

As the number of grid-connected CSP farms increases, the resulting spatial diversity provides opportunity for averaging out the intermittency. Also, if CSP farms are connected across several time zones, and even across seasonal boundaries, the need for storage is lessened. There is a tradeoff between spatial diversity and storage. Thus, the requirements for storage in the end game, of many CSP plants connected across transnational boundaries, may be tenable. Natural gas is the cleaner of fossil fuels and reasonably plentiful for assisting with evening out intermittency in the transition phase toward determining and implementing optimum massive storage requirements. Thus, there is some logic in the idea of coevolution of new gridlines with natural gas pipelines.

This is the ambitious vision expressed in the paper by Taggart *et al.* that argues Asia's unique geography, factor endowments, and economic growth favor a "Pan-Asian Energy Infrastructure" patterned after the European DESERTEC Industrial Initiative. Taggart *et al.* focus on Australia's Outback and China's Mongolian solar resources as major nodes for a transnational energy grid stretching from Beijing to the Great Australian Bight.

The key to exploiting the tradeoff between spatial diversity and storage is a growing UHVDC grid infrastructure. To this end, the paper by Hammons *et al.* examines the challenges and state of the art of ultrahigh voltage (UHV) DC transmission.

This completes the collection on papers that cover issues affecting storage tradeoffs and we now introduce a collection of five papers on chemical storage.

III. CHEMICAL STORAGE

The paper on ammonia storage by Dunn *et al.* considers the question of closed-cycle storage at the CSP plant for evening out intermittency. Their method of storing this energy is based on the reversible dissociation of ammonia.

The paper by Converse considers storage requirements driven by seasonal variation and considers the use of hydrogen as the chemical storage medium. The paper compares hydrogen with other storage methods such as compressed air storage and pumped hydro. The paper shows that volumes required for hydrogen storage are lower, resulting in lower capital costs; however, the question of electrolysis efficiency in producing hydrogen is suggested as an item for further study.

Thus, the next paper by Ursúa *et al.* was invited to describe the strengths and weaknesses of electrolysis for producing hydrogen and reviews the state of the art.

Hydrogen is attractive as a storage medium, due to its high-energy-per-weight ratio and that on combustion it produces water. So whether used in a closed or open cycle, the earth's balance of water is always sustainably maintained. Its attractiveness as a closed-cycle chemical storage medium for CSP plants is further enhanced by synergy if it can be used for massive open-cycle mobile storage to power automobiles, for example.

Use of hydrogen as an energy carrier for transport applications is often associated with fuel cells. However, an internal combustion engine converted to or designed for hydrogen, can attain high-power output, high efficiency and ultralow emissions, at a cost currently far below that of fuel cells. More importantly, because of the possibility of bifuel operation (i.e., use of a dual tank with engine switchable between hydrogen and gasoline) the hydrogen engine can act as an accelerator for building up a hydrogen infrastructure. Thus, the article by Verhelst *et al.* was invited to present the current state and future prospects for hydrogen internal combustion engines (ICEs).

An alternative to CSP generated hydrogen is the use of CSP to generate sustainable hydrocarbon fuels. This can be achieved using the atmosphere itself as the carbon source. Further research is required to calculate the rate limits to production of this type of fuel, because the carbon must be extracted from such large volumes of air. In the worst case, this approach may provide an adjunct to hydrogen fuel and may provide the second source of fuel for bifuel engines. To this end, the paper by Pearson *et al.* was invited.

This completes our collection of papers on chemical storage and we now introduce a collection of three papers on mechanical storage.

IV. MECHANICAL STORAGE

Review articles on energy storage, e.g., [5, Fig. 4], usually consider massive long-term storage of the province of fuels (free hydrogen, hydrocarbons, etc.) or of compressed air or of elevated masses (normally water).

The paper by Grazzini and Milazzo was therefore invited to introduce compressed air energy storage, and is a thermodynamic tutorial on the relevant design parameters, and their influence on the system efficiency.

An elevated mass approach is described in the paper by Pickard, who reviews the state of the art and future prospects for underground pumped hydro storage.

Both techniques seem reasonable, but neither has been subjected to the rigorous large-scale testing needed to base a planet wide massive storage system upon them.

Whether one utilizes underground storage for 1) hydrogen or liquid hydrocarbons, or 2) compressed air, or 3) ordinary water, the geotechnical limitations of the underground reservoirs are all important. Therefore, the paper of Uddin was invited to introduce issues of geotechnical feasibility.

This completes the collection of papers on mechanical storage and we now introduce a collection of five papers on thermal storage.

V. THERMAL STORAGE

It makes little sense to convert electricity to heat to store it because of the low efficiency of back conversion. However, in a CSP environment, the solar thermal energy can in principle be stored as sensible heat for significant periods with little loss. Then, upon demand, that heat can be used (for example) to spin a steam turbine and generate electricity. The question then becomes the nuts and bolts issue of how best to do the storage. We therefore commissioned a series of papers to discuss some presently available techniques.

Howes discusses massive thermal storage using gravel as the medium. A second paper with Dunn as the lead author and new collaborating authors considers molten salt as the thermal storage medium. The paper by Laing *et al.* considers concrete as the storage medium. Cabeza *et al.* then review and compare a number of materials for storing sensible heat, summarizing their properties and the heat transfer challenges.

Finally, Harries *et al.* conclude this section on heat storage by using the solar thermal energy for two complementary tasks: 1) to drive a Stirling cycle heat engine connected to an electric generator; and 2) to dissociate a metal hydride and drive off its hydrogen. In the absence of solar input, the drive system commences to cool and the dissociated hydrogen recombines exothermically with the metal, releasing heat which continues to drive the engine and its generator. The energy stored in reversible chemical bonds can be of several fold higher density than that held as sensible heat in molten salts. There are, however, novel challenges associated with this increase of energy density; and workarounds for problems such as hysteresis and disproportionation reactions are currently under active development.

VI. CONCLUSION

While a policy of a mixed energy portfolio is likely to be maintained in the immediate future, there is little doubt that the endpoint of our energy future will be predominantly solar simply because it is the largest inexhaustible source available to us.

Bearing this in mind, this Special Issue on massive storage rests on the premise of a predominantly solar-based future. Thus, many of the papers herein consider CSP as the main source of base-load power, simply because this is the most realistic massively scalable future option.

All nonsolar renewable sources of energy, added up together, come to about 3% of the solar power incident on the world's deserts alone [11]. Thus, for the endpoint, the real question is not what energy mix to adopt but what energy storage mix to adopt.

This Special Issue has reviewed chemical, mechanical, and thermal forms of storage. It is likely that each form of storage will have its niche depending on local conditions, local economics, and resources. It is our hope that this collection of papers motivates further research into all types of massive storage.

Also, research into the tradeoff between spatial diversity and required storage capacity will be of great future interest. Future analysis should also assess the sustainability of different storage methods in terms of the materials they utilize.

In the transition phase towards a renewable energy future, it is expected that intermittency will be dealt with by complementary use of renewables with natural gas. The interim use of natural gas will allow time for massive storage methods to gradually phase in. ■

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ABOUT THE GUEST EDITORS

William F. Pickard (Life Fellow, IEEE) received the Ph.D. degree in applied physics from Harvard University, Cambridge, MA, in 1962.

Since then, he has pursued a continuously evolving career in teaching and academic research, the preponderance of which has been spent as a Professor in the Department of Electrical and Systems Engineering, Washington University in Saint Louis, St. Louis, MO. His research areas have included: high voltage engineering; electrobiology; the biological effects of electromagnetic fields; and biological transport and systems biology. He now concentrates upon the theory and practice of massive energy storage because the sustainability of an industrial civilization depends upon reliable dispatchable energy even though the major renewables are intermittent. His current foci are 1) the theory of heat exchangers upon which thermal storage depends; and 2) underground pumped hydro, the electrotechnology that seems most easily scalable to the multiterawattday levels needed.

Derek Abbott (Fellow, IEEE) was born on May 3, 1960, in South Kensington, London, U.K. He received the B.Sc. degree (honors) in physics from Loughborough University of Technology, Loughborough, U.K., in 1982 and the Ph.D. degree in electrical and electronic engineering from the University of Adelaide, Adelaide, S.A., Australia, in 1997, under K. Eshraghian and B. R. Davis.

From 1978 to 1986, he worked at the GEC Hirst Research Centre, London, U.K., in the areas of semiconductors and optoelectronics. On migration to Australia, he worked for Austek Microsystems, Technology Park, South Australia, in 1986. Since 1987, he has been with the University of Adelaide, where he is currently a Full Professor in the School of Electrical and Electronic Engineering. He holds over 350 publications/patents and has been an invited speaker at over 80 institutions, including Princeton University, Princeton, NJ; Massachusetts Institute of Technology (MIT), Cambridge; Santa Fe Institute, Santa Fe, NM; Los Alamos National Laboratories, Albuquerque, NM; Cambridge University, Cambridge, U.K.; and École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland. He coauthored the book *Stochastic Resonance* (Cambridge, U.K.: Cambridge Univ. Press, 2008), and coedited the book *Quantum Aspects of Life* (London, U.K.: Imperial College Press, 2008). His interests are in the area of complex systems and multidisciplinary applications of physics and engineering. In terms of energy policy, his interest lies in a complex systems approach to analyzing global energy issues, with a particular emphasis on sustainability of the required resources.

Prof. Abbott won the GEC Bursary (1977), the Stephen Cole the Elder Prize (1998), SPIE Scholarship Award for Optical Engineering and Science (2003), the South Australian Tall Poppy Award for Science (2004) and the Premier's SA Great Award in Science and Technology for outstanding contributions to South Australia (2004). He has served as an editor and/or guest editor for a number of journals including the IEEE Journal of Solid-State Circuits, *Chaos* (AIP), *Smart Structures and Materials* (IOP), *Journal of Optics B* (IOP), *Microelectronics Journal* (Elsevier), *Fluctuation Noise Letters* (World Scientific), and is currently on the Editorial Boards of the Proceedings of the IEEE and *IEEE Photonics*. He has appeared on national and international television and radio and has also received scientific reportage in *New Scientist*, *The Sciences*, *Scientific American*, *Nature*, *The New York Times*, and *Sciences et Avenir*. He is a Fellow of the Institute of Physics (IOP), with honorary life membership.