

# Seasonal Energy Storage in a Renewable Energy System

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**ABSTRACT** | Because of a concern that in developing transitional energy systems the endpoint system requirements should be kept in mind, this paper focuses on storage in a renewable energy system that uses no fossil fuels. Based largely on the current seasonal patterns of consumption and wind and solar energy generated, it is estimated that the energy storage capacity that would be required to supply the electrical energy for the United States for a year given that the source of the electricity is from solar, wind, or a combination of the two, is in the order of 10%–20% of the total annual demand. While the uncertainty within and between published estimates of biomass availability is quite large, a partial review of the literature indicates that the global biomass primary energy potential could satisfy seasonal energy demands in a sustainable manner. The storage volumes required for biomass and hydrogen, another storage possibility, to meet seasonal storage needs are considerably smaller than that required for compressed air or elevated water.

**KEYWORDS** | Biomass potential; energy storage; renewable energy; seasonal energy storage

## I. INTRODUCTION

This paper examines energy storage in renewable energy systems, in which no fossil fuels are used. Interest in such a system is justified partly by the finiteness of fossil fuel reserves. To be sure, the reserves are large but so is the projected use in the 21st century [1]. Not only is the source of fossil fuels finite, but the acceptable level of carbon

dioxide in the atmosphere is essentially finite as well [2]. Hence, the extended use of fossil fuels is limited by both the source and the sink.

It is conceivable that we are headed toward a nuclear breeder-fission energy system [3], fueled eventually by uranium from the sea, renewed over time by runoff from the land [4]. However, concerns about cost, safety, and weapons proliferation have slowed the development of such technology; therefore, this paper considers an energy system supplied only from renewable resources.

No doubt, it will be many years before we get to such a system. However, it is important that the transitional system be compatible with the endpoint system. For example, if hydrogen were to be needed for seasonal storage in the endpoint system, it would seem wise to build the appropriate infrastructure into the transitional system. In other words, design of the endpoint system may be needed when designing a transitional system.

It is convenient to distinguish between short-term storage, for a period of seconds to a few days, and long-term seasonal storage, in which the holding period varies from a few days up to several years. For example, solar radiation has both a short-term variation, day versus night, and a long-term seasonal variation, summer versus winter. In many cases, it is possible to deal with short-term variations by dropping the load for a few hours, e.g., domestic water heating, or storing the energy, e.g., in a battery, or as heat in water or solids, to be used at a later time. Seasonal variations involve much larger amounts of energy that must be stored over longer periods. Thus, the size and the cost of the store become paramount in selecting a storage technology.

Based on a review of the costs of energy storage technologies, Converse [6] suggested that the need for large-scale energy storage might justify the use of hydrogen rather than electricity as the principle energy carrier in a renewable energy system. This paper is a reexamination

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and update of that previous one with emphasis on the following storage technologies: woody biomass, compressed air, pumped hydro, and hydrogen, with particular attention paid to their ability to provide for seasonal energy storage.

This paper begins with an estimate of the energy storage capacity that would be required to supply the electrical energy for the United States for a year given that the source of the electricity is from solar, wind, or a combination of the two (Section II). Recognizing that biomass is easily stored, literature on its global potential availability, subject to the need for food supply, forest products, and environmental amenities, is examined (Section III). The importance of developing an efficient economical compressed air energy storage system that does not use natural gas is discussed (Section IV). The published costs and efficiencies of several short-term storage technologies are presented (Section V). In order to evaluate technologies for seasonal storage, the efficiencies and storage volumes required to store 10 EJ of energy are compared for compressed air energy storage (CAES), hydrogen, elevated water, and biomass (Section VI).

## II. SEASONAL STORAGE—A CASE STUDY FOR THE UNITED STATES

The required size of seasonal storage depends on several factors and is therefore difficult to determine. However, a rough estimate of the required seasonal electrical storage can be made based on the monthly data of electrical energy consumption and the generation from solar, wind, and hydro. As shown in the Appendix, data from the United States over the period 2000–2007 [5] indicate that had all the electrical energy come from solar collectors, it would have been necessary to store from 21% to 27% of the annual consumption; and had it all been from wind, 5%–13% of annual consumption would have been required; and if it had been half from solar and half from wind, 7%–16% of annual consumption would have been required. The actual value would depend on the weather, the individual region, its makeup of demand and supply, the transmission system, and the role of nonelectrical forms of energy. The point is that the seasonal storage is likely to be quite large. In this paper, for illustrative purposes, we assume that a store able to provide 10 EJ (10% of annual consumption) would be required in the United States.

There is a tradeoff between seasonal storage and generation capacity. For example, if all the energy were supplied from wind, in 2007, there would have been no need for seasonal storage had the generation capacity been increased by 51%.<sup>1</sup> All the storage requirements presented above, and in the Appendix, are based on the assumption that the generation capacity is just sufficient to generate the annual consumption. Since the monthly demand and

resource vary from month to month, there are some months in which the generation is less than the demand even though the annual demand and supply are in balance. Seasonal storage absorbs the monthly fluctuations with generation capacity that satisfies the annual demand with no excess production. One could reduce the amount of storage required if the generation capacity were increased. In some months, there would be excess production to discard. The optimal amount of storage would depend on the unit cost of storage, the unit cost of generation, the variation of storage required with the generation capacity available, and the disposal cost, or value, of the excess production. Either way, with seasonal storage or excess generational capacity or a mix of the two, the lack of balance between monthly demand and monthly generation results in a cost.

The excess production solution may well collapse into a storage problem if the excess production has value. For example, the excess production of electricity, since it is a source of inexpensive electricity, might lead to the production of hydrogen, which would need to be stored.

In this paper, we avoid this optimization problem and focus on the seasonal storage, as computed in the Appendix, as a measure of the extent of the lack of balance between the monthly demand and generation.

## III. THE BIOMASS OPTION

One of the desirable properties of fossil energy is that it comes in the form of a chemical fuel that can be stored indefinitely and has a high energy release when reacted with air. The fact that it can easily be stored means that it is able to meet the seasonal changes in demand. Of the various sources of renewable energy, only photosynthesis directly produces a chemical fuel that is easily stored for long periods.

One could envision a renewable energy system in which coal, oil, and natural gas are replaced by biomass, and products derived from it, since it is available as a combustible solid and can be converted to liquid and/or gaseous fuels. In such a system, energy storage could be done the same way as we do now, with inexpensive tanks and piles, but is there enough biomass to provide all the primary energy<sup>2</sup> that we now obtain from fossil fuels?

### A. Biomass Primary Energy Potential

Currently, 2006, the annual global consumption of primary energy is 495 EJ (100 EJ in the United States), of which approximately 426 EJ is from coal, oil, and gas while biomass provides only 38 EJ used as fire wood and about 7 EJ used for fuel and electricity [7]. Primary energy consumption is estimated to increase to 712 EJ by 2030 [8]. Obviously the use of biomass would have to be greatly

<sup>1</sup>Based on the monthly use and wind-based generation of electricity in the United States in 2007 [16].

<sup>2</sup>Primary energy is the thermal energy equivalent.

expanded if it were to replace all the primary energy that is now obtained from fossil fuels.

A number of estimates of the biomass primary energy potential have been published in which biomass potential is defined as the amount of primary energy that could be produced per year without affecting food and forestry production, nature reserves, biodiversity, or animal grazing.

Fischer and Schrattentolzer [9] estimated the total bioenergy potential of the base year 1990 to be 225 EJ. For comparison, the actual use of bioenergy in 1990 was 46 EJ. They estimated that by the year 2050, the bioenergy potential could be between 370 and 450 EJ.

Hoogwijk *et al.* [10] estimated that the bioenergy potentials in 2100 would vary from a high of 1115 EJ for a scenario with a reduced population (7 billion) and high technology (GNP = 529 trillion \$) to a low of 395 EJ in a scenario with high population (15 billion) and low technology (GNP = 243 trillion \$). In the first of these two scenarios, approximately 1895 Mha of abandoned agricultural land<sup>3</sup> is available whereas in the second only 830 Mha is available due to the higher demand for food and poorer agricultural technology.

Campbell *et al.* [11] concluded that currently there are 385–472 Mha of abandoned agricultural land available. Assuming the aboveground biomass production is 4.3 tons/ha/y [11] and using 400 million hectares this yields 1.72 billion tons/y. They assume that the energy content is 20 kJ/g to obtain primary biomass energy production of only 34 EJ/y.

Smeets and Faaij [12] estimate the excess (excess in that the demand for round wood and fuel wood has been satisfied) net primary production potential of forests in 2050 in EJ/y to be: theoretical, 71; technically accessible, 64; economical, 15; and ecological–economical, –8. Residues and wastes add 35 EJ/y, for a net production of 27 EJ/y.

A study by Nonhebel [13], which considered food as well as biomass energy production, concluded that biomass alone could not satisfy the demand for food and energy in the world. When the methodology was applied to the United States alone, the conclusion was the same [14].<sup>4</sup>

While there is considerable uncertainty within and between these estimates, it seems safe to conclude that while the biomass primary energy potential may be smaller than the expected primary energy consumption, it might be adequate for seasonal storage if the seasonal storage requirement is on the order of 10% of annual consumption.

## B. Other Considerations

A potentially strong demand for biomass is in the production of liquid fuels for transportation. While hydrogen and electricity are candidates for propelling the transportation system, liquid fuels currently dominate the field and ethanol from biomass is already being used. However, Converse [14] estimates that, with current technology using cellulose as well as starch, replacing the 2001 United States demand for gasoline with liquid fuel from biomass in the United States could possibly be done, but only if, for example, 65 Mha of land currently used for pasture and other uses were available, grains were no longer exported, animal production were reduced by 50%, and soybeans were replaced with switch grass. This may appear as a rather unlikely set of events but it serves to emphasize the rather drastic changes that would be required to move off fossil fuels.

Competition with food production might be reduced by separating the essential food components in biomass, e.g., proteins, from the energy components, e.g., sugars [15]. For example, currently in the production of fuel ethanol from corn, animal feed, distillers' dry grain, is separated and fed to animals. Furthermore, a shift to a vegetarian diet would free up land currently used for animal production. However, it is often pointed out that many people are currently malnourished and additional land allocation is needed for increased food production. For example, much of the biomass production potential identified by Hoogwijk [10] is on abandoned agricultural land; would it not be possible to bring some of this land back into food production if there were an economic demand? Inequities in the economic system, independent of the production of biomass for energy, obviously play an important part in the distribution of food.

With regard to CO<sub>2</sub> emission, it must be acknowledged that biomass releases CO<sub>2</sub> when it is combusted. Of course biomass has the ability to regrow, absorbing CO<sub>2</sub> from the atmosphere as it does. For annual crops this replacement is rapid, but for forest growth it may take a century or longer. However, as long as the net forest growth is nonnegative, harvesting does not reduce the overall absorption of CO<sub>2</sub> by the forest; but it does reduce the absorption rate from what it would have been had the net growth been positive. Regulating the harvest to maintain a balance between growth and removal is obviously important, but possibly difficult to achieve, if the forest resource is to be sustained. Even removal of dead and dying trees has a negative effect in that nutrients are removed. Along this line it should be noted that forestry, as currently practiced, seldom involves the use of fertilizer.

## C. Biomass for Space Heating

The demand for space heating has a strong seasonal variation, and woody biomass, as we know from long experience, is easily stored and used for this purpose. Its use has largely been replaced with natural gas and fuel oil.

<sup>3</sup>“Agricultural land can be abandoned because of surplus cropland or because of a decrease in suitability of the soil due to climate change” [10]. Some scenarios have a declining human population, more trade, and/or better technology, all of which can increase the amount of abandoned agricultural land.

<sup>4</sup>A menu of renewable energy sources, needed to supply the energy demands actually supplied in 2001, is presented in the final section of [14].

## Converse: Seasonal Energy Storage in a Renewable Energy System

Natural gas in the United States residential sector varied from 1.0 EJ/mo in January 2008 to 0.105 EJ/mo in August 2008 [16]; and in the commercial sector it varied from 0.55 EJ/mo in January 2008 to 0.13 in August 2008. Presumably, this reflects the variation in the need for space heating and air conditioning.

In 2008, the natural gas consumption in the residential and commercial sectors equaled 9.23 EJ. Converse [14] estimates that the net unutilized growth plus the residues from current operations in the United States forests could yield 8 EJ/y, while maintaining forest biomass inventory and without reducing wood products production. Hence, in the United States, forests might be able to supply the seasonal store needed for space heating. Using the forest production for other uses, such as electrical generation, might have to be curtailed. Combined heat-and-power generation could alleviate this situation.

### IV. COMPRESSED AIR ENERGY STORAGE

In the established process, air is compressed adiabatically causing the temperature to increase along with the pressure. During storage, heat is lost, reducing the temperature. During the subsequent expansion the temperature of the air tends to drop and heat from the combustion of natural gas is added to increase the work obtained during the expansion through a gas turbine. The first such plant (290-MW capacity) was built in 1978 in Huntorf, Germany [18]. The second, and only other, was built in Alabama, United States, in the 1990s [19]. Both involve underground storage. Current work by a group in the European Union [20] aims to eliminate the natural gas and approach isothermal compression and expansion. They plan to store the heat generated during adiabatic compression and use the stored heat to reheat the air during expansion in a “sliding

pressure” air turbine. A second approach, in which the cooling and heating is carried out directly during the compression and expansion, is being developed by SustainX (West Lebanon, NH) [22].

Staged compression with intercooling approaches isothermal compression, and staged expansion with heat addition approaches isothermal expansion. A hypothetical five stage process in which the heat removed during compression is stored and added back during expansion has been analyzed to have a round-trip work efficiency of 72% [21] (i.e., 72% of the electrical energy used to compress the air is recovered in the electricity produced). However, for similar conditions, adiabatic compression and expansion, without heat addition from natural gas, would yield a round-trip efficiency of approximately 24% [23]; hence, the importance of developing an economical means of quasi-isothermal compression and expansion.

The compressed air could be stored in underground caverns; hence, large scale storage is possible. Pickard *et al.* [24] regard this as one of the preferred storage technologies for the large-scale energy storage that they forecast will be needed in a renewable energy society.

### V. COST COMPARISONS OF STORAGE TECHNOLOGIES

The cost and efficiency of several storage technologies, as developed by Steward *et al.* [25], are presented in Table 1. The table is based on the assumption that stored energy is drawn down at a rate of 50 MW/h for six peak hours each weekday, and then charged during the rest of the time, i.e., used as short-term storage. As presented, CAES with natural gas (#8) and pumped hydro (#7) have significantly lower costs than the hydrogen systems (#2 and #3). Cost estimates of CAES without heat injection have not yet been published.

**Table 1** Summary of Storage Costs and Efficiencies [25]

Technology	Levelized Cost of Output Electricity, cents/kWh	Roundtrip Efficiency %
1. H <sub>2</sub> O Electrolysis, above ground H <sub>2</sub> storage + Fuel cell	28	34
2. Same but with below ground H <sub>2</sub> storage	24	35
3. Same as 1 but with H <sub>2</sub> expansion/combustion turbine	19	48
4. NiCd Battery	83	59
5. NaS Battery	25	77
6. Vanadium Battery	28	72
7. Pumped Hydro	13	75
8. CAES with nat'l gas heat	10	53*

[Key parameters: Life: 40 yrs.; Interest rate: 10%; Debt financing: 100%; Off-peak renewable electricity cost = 3.8 cents/kWh; natural gas cost: 7\$/MMBTU; Mid-case values of efficiency of fuel cell = 50% , of electrolyzer = 68% and combined = 34%]  
 \*Defined as electrical energy out/(electrical energy in + heat in). If the definition used by Kim and Favrat [23], electrical energy out/(electrical energy in + 0.4 x heat in) the result is in good agreement with the value of 71.6% obtained by Kim and Favrat for a two stage system with heat addition.]

When used on a daily basis pumped hydro appears to be a winner; historically nuclear plants have used it to even out their operation in preference to CAES. Pickard *et al.* [24] conclude that, with the lower reservoir underground, this would become widely used in renewable energy systems. However, in the case of seasonal storage, this may not apply. The costs in Table 1 for pumped hydro are based on a reservoir that is filled and emptied daily whereas seasonal storage requires a reservoir that is cycled only once a year. Thus, it would be difficult to pay off the large cost associated with man-made reservoirs.

## VI. COMPARISON OF STORAGE VOLUME REQUIRED FOR SEASONAL STORAGE

### A. Compressed Air

The volume of compressed air needed to store a given amount of energy can be computed from the following isothermal relationship [21]:

$$V = E/(p \ln(b))$$

where  $E$  is the energy stored;  $p$  is the environmental pressure;  $b$  is the compression ratio.

For the case where  $E = 10$  EJ (10% of the current United States energy consumption),  $p = 1$  atm., and  $b = 300$

$$1 \text{ atm.} = 101.3 \text{ e} - 15 \text{ EJ/m}^3$$

$$V = 10 \text{ EJ}/(101.3 \text{ e} - 15 \text{ EJ/m}^3 \times 300 \times \ln(300)) \\ = 5.78 \text{ e}10 \text{ m}^3 = 57.7 \text{ km}^3.$$

At an expansion efficiency of 80% the required volume is  $57.7/0.8 = 72 \text{ km}^3$ . Since isothermal operation is assumed in this estimate, this is the minimum volume that would be required.

### B. Compressed Hydrogen

The heat of combustion is 120 MJ/kg and the density at 300 bar is  $20 \text{ kg/m}^3$  [26]. Hence, the heat released upon combustion is  $2.4 \text{ e}6 \text{ kJ/m}^3$ . The stored hydrogen is mixed with compressed air and burned in a expansion/combustion turbine. Assuming 70% efficiency from the

stored hydrogen to the product electricity for the hydrogen combustion turbine [25], [27] means that  $1.68 \text{ e}6 \text{ kJ}$  of output energy is obtained from each  $\text{m}^3$  of storage volume. Hence, the required storage volume is  $5.95 \text{ km}^3$ .

### C. Elevated Water

Work to raise 1 kg 1000 m =  $9.81 \text{ e}3 \text{ Nm} = 9.81 \text{ kJ}$ . Hence, the mass of water required is  $10 \text{ EJ}/9.81 \text{ kJ/kg} = 1.02 \text{ e}15 \text{ kg}$ . The volume of water is  $1.02 \text{ e}15 \text{ kg}/1 \text{ e}3 \text{ kg/m}^3 = 1020 \text{ km}^3$ . At 90% efficiency, this becomes  $1133 \text{ km}^3$ . Since two reservoirs, upper and lower, are required, the result becomes  $2266 \text{ km}^3$ .

### D. Biomass

$$20 \text{ MJ/kg} \times 600 \text{ kg/m}^3 = 12 \text{ e}6 \text{ kJ/m}^3$$

$$10 \text{ EJ}/12 \text{ e}6 \text{ kJ/m}^3 = 8.3 \text{ e}8 \text{ m}^3 = 0.83 \text{ km}^3$$

$$\text{At 30\% efficiency} = 0.83/0.3 = 2.77 \text{ km}^3.$$

These results are summarized in Table 2 along with estimates of the capital cost of storage [6]. The capital cost of biomass storage is assumed to be nil through the use of outdoor piles of wood chips and seasonal harvesting. It points out the advantage of using woody biomass; hydrogen is second best, CAES third, and elevated water is surprisingly poor.

## VII. DISCUSSION

In a previous paper [6], it was suggested that the low cost of below-ground hydrogen storage might justify the choice of hydrogen, rather than electricity, as the principal energy carrier. The National Renewable Energy Laboratory (NREL) study [25], summarized in Table 1, does not support this possibility for short-term storage; pumped hydro (at 13 cents/kWh) and CAES with natural gas heat (at 10 cents/kWh) are found to be significantly less expensive than water electrolysis with below-ground hydrogen storage followed by a hydrogen expansion/combustion turbine (at 19 cents/kWh). The cost of CAES without heat from natural gas is unknown. It could be less without the expense of the natural gas and the related combustor. It could be more if the efficiency is reduced or the equipment more expensive. Development of a successful design for isothermal operation of CAES thus is important if CAES is to be

Table 2 Comparison of Volumes to Store 10 EJ

Technology	Efficiency %	Volume $\text{km}^3$	Capital Cost \$/kWh stored [6]
Compressed Air at 300 atm.	80	72.	10
Compressed Hydrogen at 300 atm.	70	6	0.058-0.029, 0.18
Elevated water at 1000 m	90	2300.	16.8
Wood	30	2.8	nil



preferred to hydrogen storage. Pumped hydro stands out as not only the low-cost option, but as the only one with which we have experience. The problem seems to be whether there are a sufficient number of acceptable sites for a system that requires two reservoirs separated by a significant head. Perhaps this can be overcome by building them under ground [24] but that would no doubt add to the cost.

The above discussion and the costs on which it is based apply to short-term storage, not seasonal storage, where the cost of the store that holds the energy becomes paramount. Unexpectedly, on the basis of volume, as exhibited in Table 2, the wood pile behind the house, i.e., woody biomass, seems most appropriate if it has not been used for something else. Barring that, hydrogen, which requires a smaller volume than compressed air or pumped water, becomes attractive, at least worth a careful study of costs and leakage problems. The low efficiency of electrolysis, however, means that if hydrogen were widely used the amount of land required for solar and wind energy required might prove excessive. This could be offset for certain unique uses for hydrogen such as jet propulsion and chemical reduction, e.g., in the production of  $\text{NH}_3$ , an important fertilizer, since the conversion back to electricity would not be required. The volume required by pumped hydro is quite high, making it less attractive for seasonal storage.

There is an important interaction between short-term and seasonal storage. For example, if the need for seasonal storage were to dictate a large geocavity store for, say, hydrogen or compressed air, why not use it all the time for short-term storage as well. Here the solution to the seasonal storage problem influences the solution to the short-term storage problem, and in-so-doing has a decisive effect on the choice of the principal energy carrier. Furthermore, if we were to put off the seasonal storage problem by prolonged use of fossil fuels, we might find that when we do abandon them, we have country full of electrical transmission lines and wished we had some hydrogen pipelines, or vice versa. It behooves us to study possible endpoint sustainable energy systems thoroughly before we build a transitional system.

## VIII. CONCLUSION

Based on the current patterns of consumption and supply, it is estimated that the energy storage capacity that would be required to supply the electrical energy for the United States for a year given that the source of the electricity is from solar, wind, or a combination of the two, is in the order of 10%–20% of the total annual demand. While the analysis is oversimplified, the need for a large seasonal store is quite likely (Section II).

While the uncertainty within and between published sources is quite large, a partial review of the literature indicates that the global biomass primary energy potential is not likely to be large enough to replace all uses of fossil fuels, but that it probably could satisfy seasonal energy demands in a sustainable manner (Section III).

From the literature it appears that quasi-isothermal operation of compressed air energy storage (QCAES) should be able to achieve an efficiency of 60%–70%, without the injection of heat from the combustion of natural gas (Section IV).

Construction of a quasi-isothermal system and experimental determination of the cost and efficiency thus has a high priority (Section V).

In order to consider these technologies for seasonal storage, the efficiencies and storage volumes required to store 10 EJ of energy are compared for CAES, hydrogen, elevated water, and biomass. The volume required for biomass and hydrogen is considerably smaller than that required for compressed air or elevated water (Section VI).

The paper grew out of the postulate that the needs of an endpoint renewable energy system should be borne in mind when building the transitional system. ■

## APPENDIX

### ESTIMATION OF THE ENERGY STORAGE CAPACITY REQUIRED IN RENEWABLE ENERGY SCENARIOS FROM CURRENT MONTHLY ELECTRICAL USE, AND WIND AND SOLAR ELECTRICAL PRODUCTION DATA

#### A. Introduction

As renewable energy sources provide a greater portion of the total energy supply it becomes necessary to increase the amount of energy storage in the system. Hence, the estimation of the required storage capacity is necessary in constructing a renewable energy scenario. While a detailed optimization that considers location and transmission is needed to obtain accurate estimates of the optimal storage, it is possible to use the current patterns of electricity consumption and generation to estimate the storage capacity required to offset the seasonal variation in supply and demand.

#### B. Analysis and Results

The method for estimating the required energy storage capacity is illustrated in Table 3. The total United States monthly electricity use, in GWh, is presented in column B, and as percent of the annual amount generated, in column C. The monthly electricity from wind, in GWh, is presented in column D, and as percent of the annual amount generated from wind, in F [5]. The required storage capacity, as computed from (3), is presented in column G.

*Case 1—Wind Is the Sole Source:* An energy balance yields the following equation:

$$\text{Store}(n+1) = \text{Store}(n) + \text{Wind}(n) - \text{Use}(n) \quad (1)$$

Table 3 Storage Analysis for 2007

<p>A Year, month  B Monthly electrical use, GWh [5]  C Monthly electrical use, % of annual use  D Monthly electricity produced from wind, GWh [5]  E Monthly electricity produced from wind, % annual electrical use  F Monthly electricity produced from wind, % annual production from wind  G Storage, as % of annual use, at end of the month when all energy is produced from wind  H Monthly electricity produced from solar, GWh [5]  I Electricity produced from solar, % of annual solar electricity production  J Electricity storage, as % of annual use, at end of month when the electricity is produced from a mix of 50% wind and 50% solar,  K Electricity storage, as % of annual use, at end of the month when the electricity is produced 100% from solar.</p> <p> <math>G(n) = G(n-1) + F(n) - C(n)</math>  <math>J(n) = J(n-1) + 0.5F(n) + 0.5I(n) - C(n)</math>  <math>K(n) = K(n-1) + I(n) - C(n)</math> </p>										
A	B	C	D	E	F	G	H	I	J	K
2007 January	339968	8.49	2452	0.72	7.12	5.1	12.84	2.10	6.5	11
2007 February	311810	7.78	2520	0.81	7.31	3.73	19.24	3.15	0.07	-0.03
2007 March	308331	7.70	3047	0.99	8.84	4.41	48.49	7.93	0.75	0.20
2007 April	291254	7.27	3172	1.09	9.21	6.34	54.46	8.90	2.54	1.83
2007 May	317826	7.94	2952	0.93	8.57	6.98	84.19	13.76	5.77	7.66
2007 June	350339	8.75	2620	0.75	7.61	5.84	84.46	13.80	7.73	12.71
2007 July	379914	9.49	2158	0.57	6.27	2.62	85.79	14.02	8.38	17.25
2007 August	407865	10.18	2699	0.66	7.84	0.27	75.16	12.29	8.26	19.36
2007 September	342713	8.56	2867	0.84	8.32	0.03	68.21	11.15	9.44	21.95
2007 October	319830	7.99	3377	1.06	9.80	1.85	49.23	8.05	10.38	22.01
2007 November	301907	7.54	3095	1.03	8.98	3.30	24.30	3.97	9.32	18.45
2007 December	333586	8.33	3490	1.05	10.13	5.10	5.40	0.88	6.50	11.00
2007 Annual	4005343	100.	34450	0.86	100.	5.10	612	100.	6.50	11.00
<p>The storage required for 2007 is:  For 100 % wind: <math>6.98 - 0.03 = 6.95</math> % of annual use  For 100 % solar: <math>22.01 - 0.03 = 22.4</math> % of annual use  For 50 % wind and 50 % solar: <math>10.38 - 0.07 = 10.31</math> of annual use</p>										

where  $Store(n)$  is the amount in storage at the beginning of month  $n$ ;  $Wind(n)$  is the amount generated by wind in month  $n$ ; and  $Use(n)$  is the amount used in month  $n$ .

Dividing through by  $U(\text{annual})$  and multiplying the  $Wind(n)$  term by  $U(\text{annual})/W(\text{annual})$  yields the following equation:

$$S(n+1) = S(n) + W(n) * W(\text{annual})/U(\text{annual}) - U(n) \quad (2)$$

where  $U(\text{annual})$  is the total electricity use in the year;  $W(\text{annual})$  is the wind electricity generated in the year;  $S(n)$  is the  $Store(n)/T(\text{annual})$ ;  $W(n)$  is the  $Wind(n)/W(\text{annual})$ ; and  $U(n)$  is the  $Use(n)/T(\text{annual})$ .

Noting that in this case  $W(\text{annual})/T(\text{annual}) = 1$ , (2) becomes

$$S(n+1) = S(n) + W(n) - U(n). \quad (3)$$

In terms of the columns in Table 3, this equation becomes

$$G(n+1) = G(n) + F(n) - C(n). \quad (3a)$$

Beginning with an arbitrary store of 5.1% of annual usage [i.e.,  $S(0)$ ], values of  $S(n)$ , presented in column G, are computed from (3a) using the corresponding values of  $W(n)$  and  $T(n)$  from columns F and C. As shown in column G, the store drops to a low of 0.034% of the annual production in September, and reaches a maximum of 6.977% in May. Hence, we conclude that in this case the required storage capacity is  $6.977 - 0.034 = 6.94\%$  of the annual electricity production.

*Case 2—Solar Electricity Is the Sole Source:* In terms of the columns in Table 3, (3) becomes

$$K(n+1) = K(n) + I(n) - C(n). \quad (3b)$$

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Column K is computed from the data in columns I and C. The initial value of 11% is arbitrary but was chosen to keep the store positive (nearly). The minimum storage of  $-0.03\%$  is reached in February, and the maximum of  $22.01\%$  in October. Hence, the required storage capacity when all the electricity comes from solar energy is  $22.01 - (-0.03) = 22.04\%$  of the annual electricity produced. This is much more than is required for the case of wind because the solar energy is concentrated in the summer (May–September) whereas in this year (2007) the wind (column F) was more distributed throughout the year; it peaked in spring and late fall.

*Case 3—The source Is 50% Wind and 50% Solar:* In terms of the columns in Table 3, (3) becomes

$$J(n+1) = J(n) + 0.5 I(n) + 0.5 F(n) - C(n). \quad (3c)$$

Column J is computed from the data in columns J, F, and C. The initial value of  $6.5\%$  is arbitrary but was chosen to keep the store positive. The minimum storage of  $0.07\%$  is reached in February, and the maximum of  $10.38\%$  in October. Hence, the required storage capacity when all the electricity comes from solar energy is  $10.38 - 0.07 = 10.31\%$  of the annual electricity produced.

*Annual Variation:* Table 3 presents the analysis for the data from 2007. This analysis was repeated for 2000–2007. The corresponding required storage capacities are presented in Table 4. Owing to the strong increase in the solar radiation during the summer, the solar case consistently requires much more storage than when wind is the source.

Table 4 Required Storage Capacities

Year	Storage Capacity, % annual.		
	Wind	Solar	50-50
2000	13.5	21.34	7.47
2001	5.25	31.72	16.76
2002	7.27	21.88	13.32
2003	5.85	24.71	13.25
2004	8.2	26.78	15.52
2005	4.9	27.02	13.36
2006	9.01	24.24	9.174
2007	6.95	22.04	10.31

## C. Conclusion

Neglecting losses due to energy conversion in storing, the required storage varies from about 8% of annual use when wind is the sole source, to about 24% when solar is the sole source, to about 13% when the source is a 50/50 mix of wind and solar. These estimates of storage capacity are greatly increased when conversion losses are considered. For example, based on the efficiencies in [25], when solar electricity is converted to hydrogen by electrolysis and then reconverted to electricity via a combustion turbine, 50% of the annual production of electricity would have to be sent to the electrolysis unit, and the storage would have to hold hydrogen having an energy content of 34% of the annual production in order to provide 24% of the annual production as electricity from the combustion turbine. The large amounts of storage required suggest that overproducing renewable electricity during certain periods and/or managing the seasonal load might well be considered in order to reduce the storage requirements.

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