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Substitution of coal power plants with renewable energy sources – Shift of the power demand and energy storage

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ABSTRACT

Because of their Global Climate Change contributions, it is desirable to reduce the amount of the global CO_2 emissions. One of the ways to accomplish this is the substitution of coal with renewable energy sources, most notably wind and solar. However, the availability of wind energy and of insolation does not follow the diurnal and annual demand patterns of electric power. The large-scale substitution of coal with wind and solar significantly shifts the demand for the rest of the power producing units. When the contribution of wind and solar exceeds approximately 25% of the total annual energy produced, there are time periods within a year when excess electricity is produced that must be wasted/dissipated. This presents a severe constraint for the substitution of coal-generated electricity with renewables. At such production levels diurnal or seasonal storage of energy becomes necessary and hydrogen storage offers the best alternative. Based on the hourly, electricity demand of a region in North Texas, which has very high availability of wind and solar energy and is considered prime region for renewables, extensive calculations are made for: (a) the solar and wind rated power that are necessary for the substitution of part or all the power currently supplied by a coal-fired power plant; and (b) the storage requirements for this substitution. Significant seasonal and diurnal energy storage, on the order of 250,000 m^3, is required for the total substitution of coal in the region. The calculations also reveal that the substitution of coal with the renewable energy sources may be optimized for minimum energy storage capacity.

1. Introduction

The global production of electricity has been continuously increasing in the last 120 years. Since 1980 the average annual rate of global electric energy growth is 4.93% and this implies that the electricity demand doubles every 14.5 years [1–3]. Coal is still the major primary energy source for the production of electric energy with coal power plants producing globally more than 39% of the total electricity [1]. Because the combustion of coal in power plants produces CO_2, the Greenhouse Gas with the highest environmental impact, and contributes significantly to the observed Global Climate Change (GCC) in the last thirty years there have been several regional and international efforts to decrease the use of coal for the production of electricity and curb the production of CO_2 emissions. Despite these international efforts, the relative fraction of coal for the production of electric energy has been slowly increasing, from 37% in 1980 to 39% in 2014. In the same period, the contribution of renewables other than hydroelectric increased from 0.7% in 1980 to 6.8% in 2015 [2]. If the global CO_2 emissions are to be reduced, the substitution of coal power plants with renewable energy sources – primarily wind and solar that are widely available – becomes an important task in regional and national energy planning and management.

The production of electric power in all the electricity grid systems is dictated by the instantaneous demand for power. Base-load, intermediate-load, and peak-load units balance the power demand and supply in all the regions of the globe. Wind and solar energy are clean renewable sources, but they are not available at all hours of the year. Even when they are available, they may not have the intensity to supply the entire demand for power. For example, during the evening of July 17, when a great deal of electric power is demanded by the air-conditioning systems in Texas (and all hot regions on earth), there is zero insolation and the weak breezes are insufficient to satisfy the high power demand. The substitution of a high fraction of the produced electricity from coal with renewable sources has a second consequence. Coal power plants are base-load plants; they operate with Rankine steam cycles; and cannot be switched on and off frequently. Their production capacity may be reduced to 80% of their rated capacity, but the plants must be continuously in operation, day and night. Frequent

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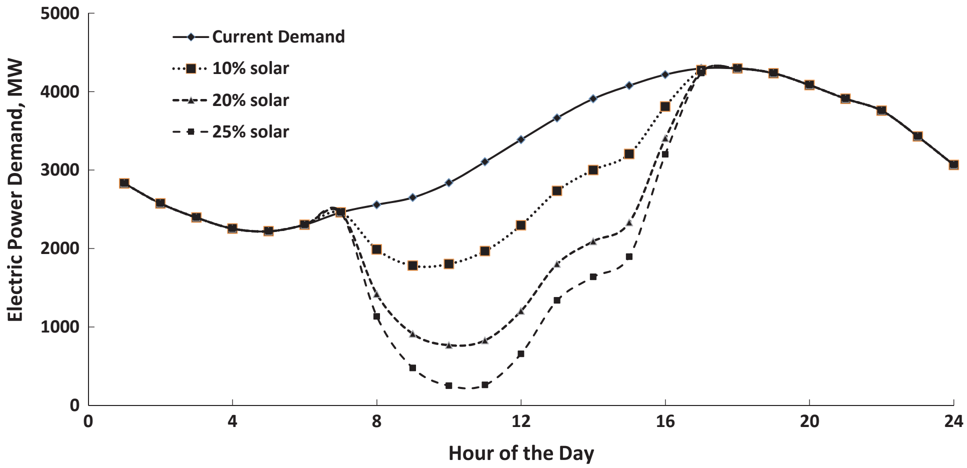

Fig. 1. Shift of the power demand for the non-solar power plants in the San Antonio, Texas, region when 10, 20, and 25% of the electric energy is produced by solar units.

generation stoppages and significant power reduction would damage the machinery of the steam units.

If a region decided to "become green," and produce a high fraction of the electric energy by solar installations, which only produce at daylight hours, there will be a significant reduction of the electric energy demand from the non-solar units during the daylight hours, when all the solar energy is produced. This negatively affects the operation of the base-load units for the parts of the day, when the insolation is high, but the power demand is not. Fig. 1 depicts the expected modification of the summertime weekday power demand in San Antonio, Texas, when 10, 20 and 25% of the buildings in the City become Zero-Energy Buildings (ZEBs) and produce by insolation as much energy during an entire year as they consume, while still connected to the electricity grid [2]. It is observed in the figure that the power demand from the non-solar power units shifts from the solid line (which represents the current demand) to the broken lines that are labeled by the fraction of the total energy generated by solar units during the 24 h. The area enclosed by the broken lines and the solid line represents the fraction of electricity generated by insolation during the day. The demand curves for the non-solar units exhibit a large dip during the early daylight hours and have been called *U-shaped demand* curves or *duck curves* [4,5]. The sharp dip of the curves during the early morning hours implies that the power production from non-solar units in the region must be reduced accordingly in order to accommodate the energy production of the solar units. In the case of San Antonio, if 28% of the daily energy is supplied by photovoltaic (PV) units, all the other power plants in that region would have to shut down between 9:00 and 11:00 am. This represents a severe limitation on the production of solar-generated electricity for the region. This is not a regional problem that applies to San Antonio alone. The same limitations would apply to all the other regions where substitution of fossil fuel-generated energy with solar energy is desirable.

Similar trends for the power demand of the non-renewable units would occur if a fraction of electricity higher than 25% were produced by wind power. During the hours of high wind velocity the power demand for the non-wind units becomes zero or negative, which implies that some of the produced power must be dissipated and wasted.

Because large, base-load steam units – primarily coal and nuclear – cannot adjust their power production as frequently as the production by the renewable energy units fluctuates, the regions are served by electricity grids will have to pursue a combination of the following [2,4]:

(a) Reduce the number or completely eliminate the current base-load power plants, both coal and nuclear, and substitute them with other units, e.g. gas turbines, that may start and stop at will following the regional power demand. The substitution requires substantial investment that will make electricity significantly more expensive. Also the CO_2 emissions are reduced but not eliminated with this option.
(b) Offer incentives (e.g. power pricing) to partly control and adjust the electricity demand of the consumers in the region in a way that increases the electric power demand during the hours of high production from renewables. This may be easier accomplished for solar energy, which is periodically variable, and becomes very difficult for wind energy. This solution is only partly effective because full control of the electric power demand is impossible to achieve.
(c) Invest in utility-level storage capacity that would store the excess power produced during the high production hours and seasons. This will enable many of the base-load plants – most notably the nuclear power plants that produce cheap electricity and do not emit CO_2 – to operate in conjunction with the renewable units.

The control/adjustment of the power demand has been the subject of several recent studies. A study for the island Oahu (state of Hawaii) revealed that the substitution of 40% of the total electric energy from wind and solar entails "significant operational challenges," especially during periods when the electricity generation from renewables diverts from the forecasts. The study concluded that demand control through electricity pricing has the potential to smoothen the power system operation and partly balance demand and supply [6]. Power demand adjustment in combination with chilled water storage for air-conditioning, has been suggested as the solution to using a high fraction of electricity from renewables and maintain grid stability and reliability in a micro-grid system [7]. The chilled water solution has been adopted successfully in the five terminals of the DFW airport, but it only shifts the power demand to the night hours and does not necessarily increase the use of renewables [2]. A more recent study has highlighted the importance of energy storage when an increasing fraction of electric energy is derived from renewables and explained the link between the shape of the electric power demand curve and the amount of the storage system capacity [8]. The study correctly emphasized the distinction between the energy produced and the instantaneous power needed by the consumers. Another recent study examines the data for the residential demand for power, highlights the necessity for energy storage and offers alternatives that would make buildings and clusters of buildings grid-independent and reliant on renewable energy only [9]. The currently available energy storage methods, their capabilities and their estimated costs have been the subjects of two recent studies [10,11].

This paper examines the effect of the partial or total substitution of coal-derived electric power by a combination of wind and solar units in the North Texas region and highlights some the limitations that would accompany this substitution. The region is typical of the Southwest part

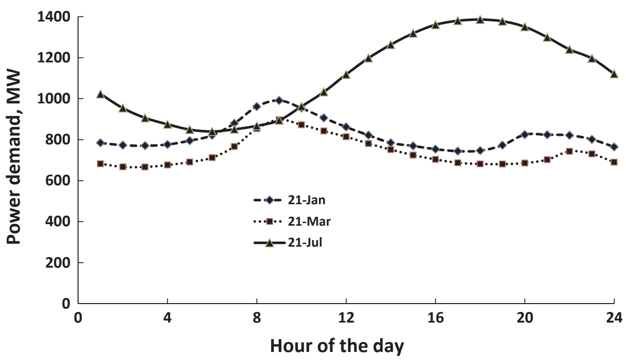

Fig. 2. Typical electric power demand during three workdays of the year 2016.

of the USA, where the high summer temperatures and the use of air-conditioning cause high electric power demand during the summer days and early evenings. One of the reasons for the choice of this region is that it has very high potential for the production of renewable energy from wind and solar and is one of the prime areas in the USA for investments in the production of both solar and wind power. The region is served by ERCOT, the power grid that serves most of the state of Texas. The main contributions of the paper are the identification of the necessary utility-level storage system that may be used in this region and the calculation of the maximum annual and monthly storage capacity that is needed. The emphasis of this work is not so much on the details of the coal-to-renewables substitution, but on the determination of when storage capacity is needed and how much storage becomes necessary for a given penetration of renewables in the electric energy mix.

2. Power demand and production in the North Texas region

Fig. 2 shows the demand for electric power in the region covered by this study during three typical workdays of the year 2016: January 21, when heating and auxiliary power for heating is used in all buildings; March 21, when very limited heating is used in the buildings of the region and the demand for air-conditioning is very low; and July 21, when the air-conditioning demand is high. The observed high electricity demand and the shift of the maximum power demand to the late summer afternoon occur because of the air-conditioning use in the region.

It is observed in the figure that the variability of the demand during the summer days is significantly higher than during the spring and winter days. The ratio of maximum to minimum electric power demand is 1.65 for the summer day, 1.34 for the spring day and 1.33 for the winter day. For the entire region, the maximum electric power demand during the entire year was 1440 MW and the minimum 539 MW. The total electric energy demand in the region during 2016 was 7,231,000 MWh.

The region is currently supplied from a base-load coal unit of 720 MW total nameplate capacity; several gas turbines that operate as peak power units; one solar PV unit of 10 MW total nameplate capacity; and several wind farms with approximately 200 MW total nameplate capacity [12]. The power production units are connected to the ERCOT grid, which supplies several other regions in Texas. As a result, part of the power produced in the region is diverted to other regions and, when needed, other regions contribute to the power demand of this region. The base-load demand in this region is approximately 600 MW, and is primarily supplied by the coal-fired plant. Part of the power produced by the latter is diverted to nearby regions.

3. Negative power demand in the region

Coal power plants produce approximately 1.15 kg of CO_2 with every kWh of electricity, the highest amount of all fossil fuel units [2].

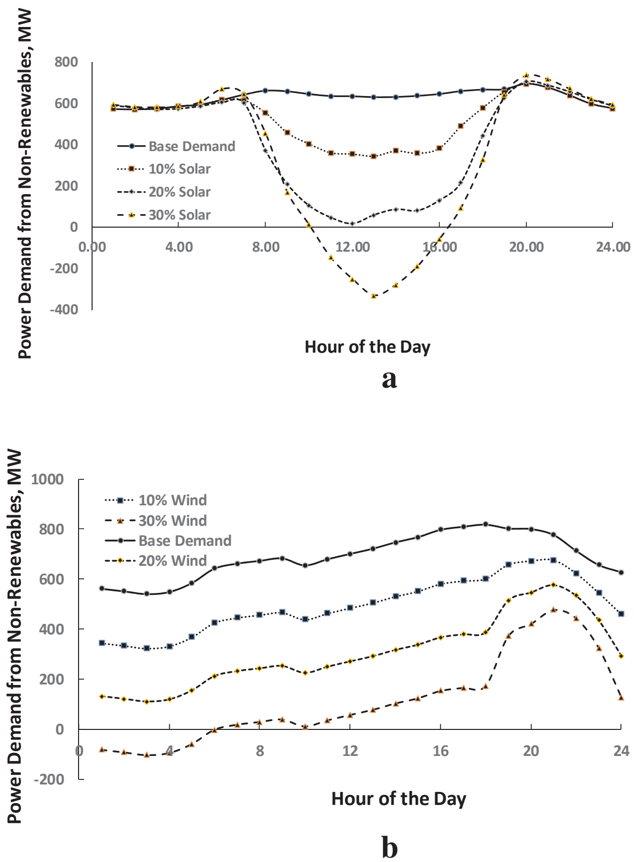

Fig. 3. (a and b) The effect of power production from solar (upper) and wind (lower) units on the demand from the non-renewable power production units.

Because of the adverse environmental effects of the gas and its significant contributions to the GCC, it has been recommended that coal power plants be gradually phased out in favor of renewable energy that does not contribute to GCC. It becomes apparent from Fig. 1 that this substitution is not very simple, because of the effect of the U-shaped demand curve. When there is a sufficient number of wind and solar units in the region, so that the contribution of renewable energy exceeds 25% of the annual energy produced and consumed in the region, there are periods during the year, when the power demanded by the rest of the power plants becomes negative. During these periods, the power supplied to the region by renewables is not only sufficient to meet the entire power demand but, in addition, some of the produced power must be dissipated. Fig. 3a and b shows the effect of the fraction of annual energy produced by solar PV units (upper figure) and wind turbines (lower figure) on the power demand from the rest of the power plants in the region during two days in the spring of 2016. It is also observed in Fig. 3a that, if the total annual energy produced by the solar units is 20%, the PV installations produce almost the entire power demand for the region. When the contribution of the solar units increases to 30% of the total energy for the day, the PV systems produce significantly more power than the region demands between 10 am and 4 pm of that day. The implications of the latter are that, if the region were served by an autonomous grid, all the other power plants must be shut down during these hours and that, in the absence of outside power routing or storage, the excess electric power must be dissipated and wasted. It is observed in Fig. 3b that, if the total annual energy produced by wind is 30%, the wind turbines would produce more power than the region demands between midnight and 6 am of that day. It must be noted that the modified demand of the non-wind installations is not U-shaped. However, the effect of the modified demand is the same: when 30% of the energy is produced by wind power, the demand from the other production units shifts significantly and becomes negative during several time periods within a year.

The shutting down of several types of base-load steam power plants for a few hours during a day is impractical, because these plants need several hours to come back on-line and produce full power. Nuclear power plants that use *boron shimming* for the reduction of reactivity and thermal power (most of the PWR and BWR power plants in the USA and several other countries are of this type) require tens of hours to produce full power starting from cold, and most of the coal-fired units need at least four hours to do so. Frequent stoppage and start-up of steam power plants reduces their thermal efficiency and may even cause severe damage to their equipment. It is apparent from Fig. 3a and b that, if the number of wind and solar energy installations increases significantly and if these installations produced more than 20% of the total annual energy in the region, other modifications must be made for the power production system to maintain its flexibility and to reliably supply the needed electric power in the region at the time periods it is needed.

One obvious solution to this problem is to replace all the vapor-cycle power plants (coal and nuclear) with gas turbines that may be switched on and off in minutes. This option would also exclude the production of power from the nuclear units, which do not emit CO_2 and do not contribute to the GCC. In addition, gas turbines emit CO_2. A second solution – and this is a solution that may be extended to a totally carbon-free electric power production – is to store the excess energy, when it is produced, and use it later to reduce the peak power demand. The second solution has the beneficial effect of eliminating the peak-power units that have very low thermal efficiency. One of the aims of this paper is to determine the capacity of the energy storage system under the second scenario.

4. The energy storage system

The region under consideration, the Central North Texas region, has very high wind energy potential (the yearly average wind velocity at 75 m above ground is 10.1 m/s) and high solar potential (the yearly average insolation on a 30° inclined, stationary surface facing the south is 243.1 W/m^2, with peak irradiance 1030 W/m^2). Because of this, the Central North Texas region has attracted a great deal of investment in renewables and is a prime candidate for the partial or total substitution of energy from coal to energy from renewables, either wind or solar or a combination of the two. Because the supply of solar and wind energy does not necessarily follow the power demand in the region, the coal to renewables substitution will require utility-level, high energy storage. This is best achieved using chemical storage (in hydrogen or batteries) or pumped water systems as the storage medium [13,14,10,11,15,2]. The region under consideration does not have points of high elevation that could accommodate pumped hydroelectric storage systems [2,15,14,11]. For this reason, the two other two types of storage have been considered for the regional grid:

1. A hydrogen storage system that produces hydrogen by electrolysis. The hydrogen is generated and stored under pressure in a group of tanks, where the maximum pressure may reach 500 bar. The tanks may be strategically placed throughout the region to minimize transmission losses. It must be noted that this is known technology: Several commercially available automobiles operating with fuel cells – among these, the *Honda FCX Clarity*, the *Kia Borrego,* the *Hyundai ix35 FCEV*, the *Ford Focus FCV,* and the *Toyota Mirai* – have hydrogen storage systems with operating pressures as high as 700 bar. A system of fuel cells, associated with the storage system supplies electric power to the region via voltage inverters, when additional, peak-power is needed [2,10].
2. Stacks of solid-state, lead-based or lithium-based batteries connected in parallel and in series that supply ac power to the grid via inverters [16].

In general, solid-state batteries have higher round trip efficiencies than hydrogen storage in the short term, e.g. the diurnal cycle, but have very low specific energy. The specific energy of lithium batteries is approximately 0.4 kWh/kg and that of lead batteries is 0.03 kWh/kg [2]. Elementary calculations prove that the weight of batteries required for the utility-level storage is extremely high, even if lithium batteries were chosen. The corresponding quantity for hydrogen is 31.2 kWh/kg. At the utility-level storage required in this case – of the order of $300 * 10^6$ kWh – the mass of batteries becomes prohibitedly high and expensive. An additional consideration that favors the use of hydrogen is that batteries suffer from self-discharge and dissipate a great deal of the stored energy over long periods of time, which implies that seasonal energy storage would be very inefficient with a battery system. This leaves compressed hydrogen storage the only viable option for energy storage in the region.

The efficiencies of the other equipment associated with the energy production and storage, such as Maximum Power Point Trackers (MPPTs), are higher than 95% [17]. With the current state of technology, very small amounts of energy are dissipated in these systems. For brevity, in the report of the calculations that follow these efficiencies are lumped together with the efficiencies of electrolysis that produces the hydrogen and of the fuel cells that convert the hydrogen to electric power. The last two efficiencies are significantly lower and determine to a great extent the overall efficiency of the storage system.

Fig. 4 is a schematic diagram of a typical system envisioned for the production, storage and distribution of the electric energy. The photovoltaic cells and the wind turbines generate electricity from solar and wind energy respectively, whenever these forms of energy are available. The electric power produced is fed to the grid most of the time. When the demand of the electricity grid is low and may not absorb the quantities of electric energy produced by the renewables, then the excess energy is directed to water electrolysis systems that produce hydrogen, which is stored in hydrogen tanks under pressure. The hydrogen energy is converted to electric energy in fuel cells and is fed to the grid, whenever needed, after it passes through a dc to ac inverter.

5. Modeling of the substitution of coal with renewables

The coal to renewables substitution may be achieved with the development of several wind farms and PV installations that may be built anywhere in the region. When the solar and wind units produce more power than the regional demand, the excess energy is stored in hydrogen tanks and used at a later time to reduce the peak power demand. The production of hydrogen occurs by electrolysis, the hydrogen is stored at a maximum pressure of 500 bar and the hydrogen to

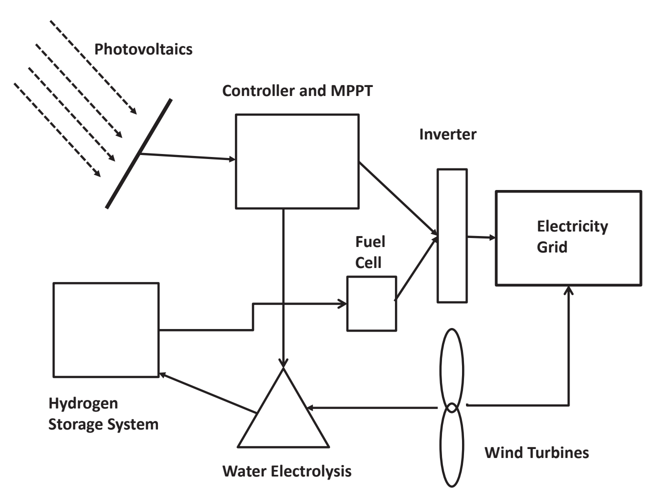

Fig. 4. Schematic diagram of a system for the production, storage and distribution of electric energy.

electricity conversion occurs in fuel cells. These energy transformations involve thermodynamic irreversibilities, which dissipate a fraction of the energy produced by the renewables. The dissipation and the energy that becomes available to the electricity grid may be calculated from the efficiencies of the energy storage processes [2,12, 18].

At a given hour of the year the energy production of a PV system is:

$$E_{SPi} = A\eta_{Si}\dot{S}_i T, \tag{1}$$

where $\dot{S}_i$ is the total irradiance – direct and diffuse – on the PV panels; A the total area of the panels; η_{Si} is the efficiency of the PV cells, which weakly depends on the local temperature; and T the time of operation of the panels. The timescale of all the calculations in this study is T = 1 h, and, hence, when the insolation is given in kW/m^2, the energy production is obtained in kWh. The efficiency of the PV systems is almost constant at temperatures below 25 °C and equal to the stated efficiency by the manufacturer, η_{sc}. The efficiency drops linearly at higher temperatures following the equation [19,20]:

$$\eta_{Si} = \eta_{sc}[1-k_{sc}(T-25)] \quad for\ \ T > 25\,°\text{C}. \tag{2}$$

Values for the temperature sensitivity coefficient, k_{sc}, are in the range 0.002–0.006 °C^{-1} [17]. In this study, the sensitivity coefficient value $k_{sc} = 0.0025$ was adopted.

The corresponding energy production from a wind turbine is:

$$E_{WPi} = \frac{\pi}{8}\eta_{Wi}D^2\rho V^3 T, \tag{3}$$

where η_{Wi} is the efficiency of the wind turbine; D is the wind turbine diameter; ρ is the density of the air (approximately 1.19 kg/m^3); V the air velocity at the hub of the turbine; and the timescale T is again 1 h. Three-blade, horizontal axis wind turbines are used for the harnessing of the wind power. Typical characteristics of large wind turbines were considered for this study: rotor diameter 90 m; tower height 75 m; cut in velocity 3.5 m/s; rated velocity 15 m/s; cut out velocity 25 m/s; and rated power 3 MW.

The solar and wind data sets for the region enable us to calculate (among other variables) the local insolation, $\dot{S}$, on a surface of any position and orientation as well as the wind velocity at the standard height of meteorological stations, 9.1 m, during all hours of a given year [21]. The velocity of the wind at the turbine rotor hub was calculated using the turbulent boundary layer velocity profile equation:

$$\frac{V(H)}{V(h)} = \left(\frac{H}{h}\right)^{1/7}, \tag{4}$$

where H is the tower height and h is the height of the instrument at the meteorological station (9.1 m). The available solar and wind data in the region enable us to calculate the hourly production of wind and solar energy during all the hours of a year.

The total energy production during the hour of the year, *i,* is the sum of the energy supplied by the wind and solar installations:

$$E_{Pi} = E_{WPi} + E_{SPi}. \tag{5}$$

For the coal with renewables substitution study, it was stipulated that a fraction of the base load power in the region, which is approximately 600 MW and is now supplied by coal, is switched to power produced by the solar and wind energy units. When the production of solar and wind energy is too high (because of high winds or very high insolation during a time period) to cause further reduction of the base-load demand, then the excess energy produced is stored as hydrogen and used at a later time period to reduce the peak demand in the regional grid. The reduction of the peak demand has the advantage of minimizing the use of small and older gas turbines with very low thermal efficiency. This strategy determines the energy level of the storage system. The energy that is available to be stored or taken from the storage system is equal to the difference between production and demand:

$$\delta E_{Si} = E_{Pi} - E_{Di}, \tag{6}$$

Not all the energy diverted to the storage system is actually stored because of the thermodynamic irreversibilities in the conversion of electric energy to the chemical energy of hydrogen. Similarly, not all the chemical energy stored in hydrogen is converted to electric energy to be fed back to the electric grid. The thermodynamic irreversibilities of the conversion processes are taken into account by the efficiencies of the electrolytic process, η_{el}, and of the fuel cells, η_{fc}. Accordingly, the energy storage level at the hour (i + 1) is:

$$\begin{aligned} E_{Si+1} &= E_{Si} + (\delta E_{Si})\eta_{el} \quad if\ \ E_{Pi} \geqslant E_{Di} \\ E_{Si+i} &= E_{Si} - (\delta E_{Si})/\eta_{fc} \quad if\ \ E_{Pi} < E_{Di}, \end{aligned} \tag{7}$$

where E_{Si} is the energy storage level at the previous hour, i. The values of the efficiencies used in this study are: η_{el} = 78% [15], and η_{fc} = 75% [22]. The dc to ac inverter efficiency is 95%.

For the reliability of the electric grid system it was stipulated that the energy storage system must store enough energy to fulfill its mission and power the regional grid for a minimum of ten days. If there is a system failure, malfunction or adverse weather conditions, which temporarily reduce the amount of renewable energy produced, then the grid operators will have enough time to respond and purchase hydrogen, or divert energy from a different geographical area to ensure that the electricity supply in the region will continue uninterrupted. As a result of this constraint the stored energy in the system does not attain the value zero at any time in the year.

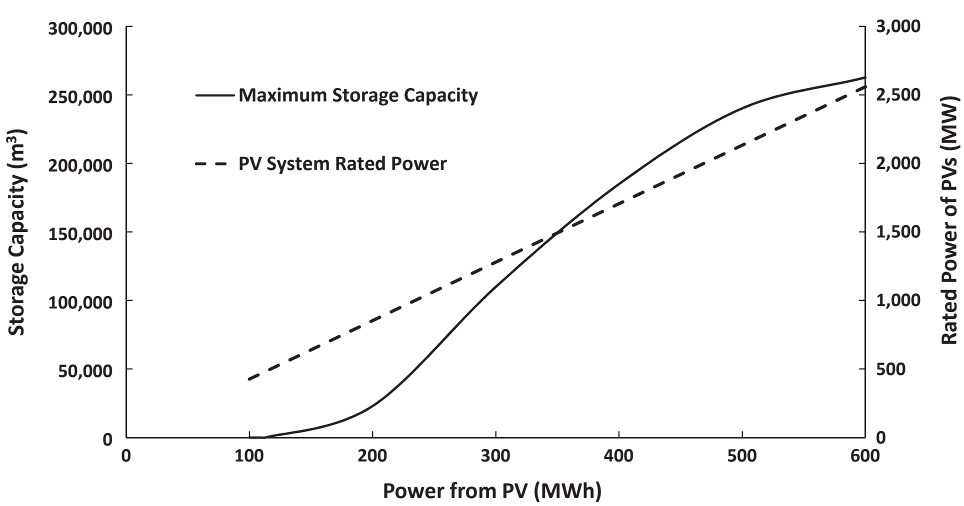

Fig. 5. PV rated power (right axis) and hydrogen storage (left axis) requirements for the substitution of 100–600 MW base load power by photovoltaics.

6. Results and discussion

Fig. 5 shows the results of the calculations when 100–600 MW of base-load power is switched from coal production to production by photovoltaics. The substitution of 100 MW base load power with renewables corresponds to 12.14% substitution of the total annual energy demand in this region and approximately $276 * 10^6$ kg of CO_2 per year emission reduction. The rated power of the PV units that are necessary to produce this energy as well as the hydrogen storage requirement at the ambient temperature and 500 bar are also shown in this figure.

It is observed that the storage curve is an S-shaped curve, but not exactly a sigmoid curve. When 0–113 MW of base power is substituted with PV cells, no energy storage is necessary. The regional electric grid system is capable to absorb this produced amount of energy from PV cells without the need for storage. Storage is needed when the PV units produce more than $990 * 10^6$ kWh per year. The necessary storage capacity increases as the base-load power to be substituted increases and shows some leveling when the substituted power reaches above 450 MW. Since the existing coal power plant uses bituminous and sub-bituminous coal with average heating value approximately 26,000 kJ/kg, one may use the energy production numbers to estimate the annual CO_2 emissions avoidance. The latter is reported in Table 1, when electric power between 100 and 600 MW is substituted from coal to renewables [2].

Fig. 6 shows the hourly variation of the amount of energy storage in hydrogen throughout the year. The seasonal variations of the storage level are apparent in this figure. It is observed that the minimum storage level occurs in the late winter (February), when the insolation increases and the demand for power in the region approaches its minimum. The storage level peaks in late May, when the high air-conditioning demand and higher power demand starts. From June to early October more than 60% of the stored energy is used to balance the peak demand periods when air-conditioning usage is at its highest in the region.

Fig. 7 is similar to Fig. 5 and shows the results of the same substitution using wind power. In this case, no storage is required when wind substitutes up to 109 MW of electric energy of the coal unit. Again, it is observed that the storage capacity curve is S-shaped and levels at the upper part of the substitution power range. It is also observed in the figure that the storage capacity using wind power is significantly higher than using PV systems. This happens because wind power is high in this region during the spring and the autumn seasons, when the electric power demand is at the lowest. The excess power in the spring and autumn needs to be stored and used in the summer and winter seasons, when the power demand is high. Regarding solar, the maximum of the insolation and of the solar power produced by the PV system is highly correlated with the maximum demand periods of the region, which are influenced by the air-conditioning use. For this reason, the necessary energy storage capacity for the coal substitution by PVs is substantially lower (but not insignificant).

Fig. 8 is similar to Fig. 6 and depicts the hourly variation of the amount of energy storage in hydrogen throughout the year, when the wind supplies the entire amount (600 MW) of the substituted base-load power. It is observed that the maximum storage level occurs again in the late May and the stored energy decreases to its minimum in October, when the demand for air-conditioning subsides. A secondary maximum occurs toward the end of November as a result of the higher winds in the autumn season.

The availability of wind and solar energy in the region are weakly correlated, primarily during the afternoons of the summer season. The weak correlation implies that when both wind and solar energy are used for the substitution of coal in the production of electric power, lesser storage will be needed. Fig. 9 shows the required storage capacity when 300 MW of base-load power are produced by a combination of wind and solar energy. The ordinate in the figure is the percentage of solar energy used for the substituted power. The percentage of wind power generated is equal to 100 minus the solar percentage. It is observed in the figure that, when a combination of wind and solar energy is used for the substitution of coal, the needed storage capacity may be significantly reduced. The minimum storage capacity in this case occurs at 43% solar. Similar curves with a well-defined minimum are obtained when the substituted power varies from 150 MW to 600 MW.

The minimum storage capacity required by the coal to renewables substitution varies with the base-load power, which is substituted by the renewables. Fig. 10 depicts the minimum storage needed as well as the percentages of wind and solar energy that result in this minimum. It is observed that, for minimum storage, when the power to be substituted with renewables is higher than 400 MW (two thirds of the total base-load power substitution from the coal unit) the energy contributions of wind and solar energy become approximately equal, at 50% each. It is also observed that, because both wind and solar power are used and that the two are weakly correlated, the threshold when storage is needed increases to approximately 149 MW of the substituted base-load power.

Fig. 11 shows the hourly variation of the hydrogen storage level (in kmol and in MWh) at the minimum required storage level, when 600 MW base-load power is substituted and the contribution of the two renewable energy sources is approximately 50% for each one. In comparison to the other figures that depict the hourly variability of the level of storage it is observed that the energy storage level at the optimum combination of renewable sources is significantly lower. As with Fig. 6 for solar energy substitution, the minimum storage level occurs in the late winter. In this case, approximately 85% of the stored energy is used in the period May to October to supplement the peak power units in the region. The maximum required storage in this case is approximately 10% less than substitution with solar energy alone and 43% less than substitution with wind alone.

It must be noted that what is considered in this study is a straightforward substitution of the base-load power from coal with the two available renewable energy sources, wind and solar. Several other scenarios are possible to be implemented that would involve a higher use of the gas turbines in the region – albeit at an increase of the CO_2 emissions. The several gas turbines that currently produce electric power in the region may come in the optimization considerations to further minimize the storage requirements. Also, because the region is connected to the ERCOT electric power grid, electric power that may be received and supplied to the other parts of the grid will become part of a greater optimization scheme. However, all the possible scenarios point to the fact that the significantly higher use of wind and solar energy in the region and the desired significant reduction of CO_2 emissions will necessitate substantial utility-level energy storage, which in this case may only be achieved with hydrogen storage systems. These deductions point to needed research and development in the areas of: (a) suitable energy storage systems; (b) better understanding of the criteria for the fossil fuel to renewables substitution, (c) optimization of the regional and national processes for the higher use of renewables and energy storage, and (d) integration of solar and wind units with geothermal energy units that provide base-load power [2,23] and with

Table 1
Annual energy produced by renewables and CO_2 emissions avoidance at 100–600 MW power substitution.

Power from Renewables, MW	100	200	300	400	500	600
Energy from Renewables, kWh/yr	$876 * 10^6$	$1,752 * 10^6$	$2,628 * 10^6$	$3,504 * 10^6$	$4,380 * 10^6$	$5,256 * 10^6$
CO_2 avoidance, kg/yr	$1,010 * 10^6$	$2,021 * 10^6$	$3,031 * 10^6$	$4,041 * 10^6$	$5,052 * 10^6$	$6,062 * 10^6$

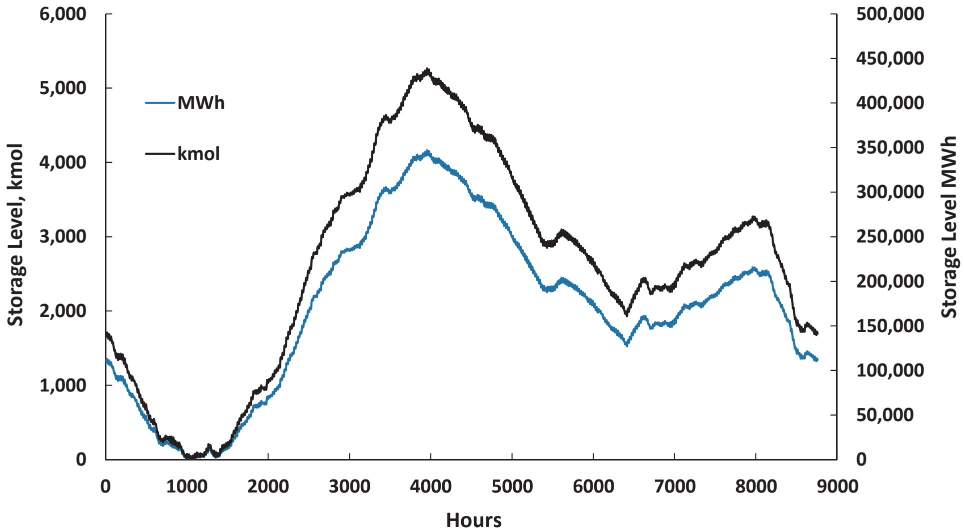

Fig. 6. Hourly variation of the energy storage level in kmol of hydrogen and kWh. Solar energy supplies 600 MW base-load power.

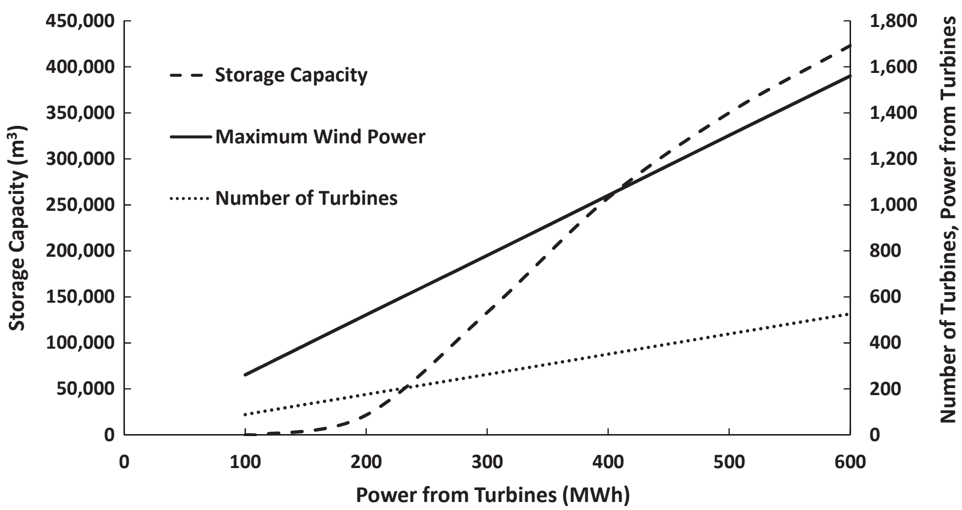

Fig. 7. Rated power of wind turbines (in MW), number of turbines (right axis) and hydrogen storage requirements (left axis) for the substitution of 100–600 MW base load power by wind turbines.

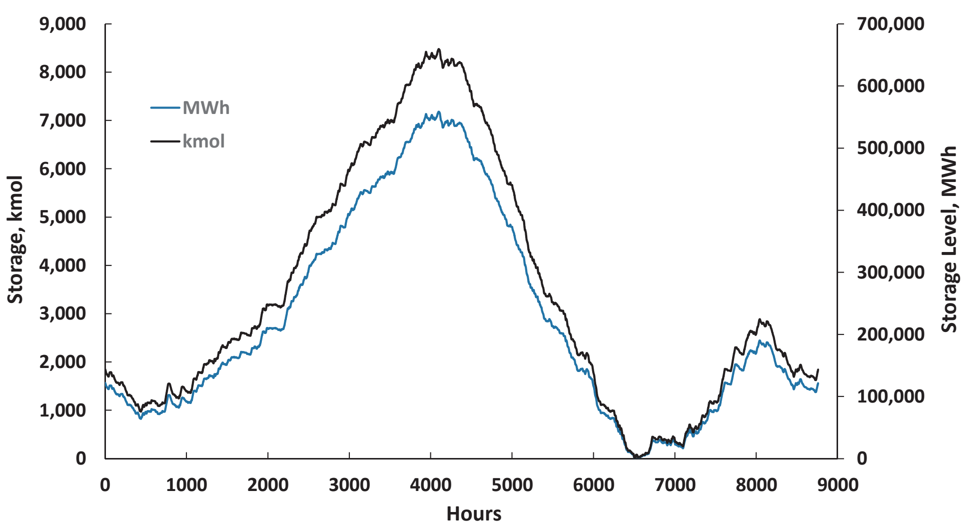

Fig. 8. Hourly variation of the energy storage level in kmol of hydrogen and kWh. Wind supplies 600 MW base-load power.

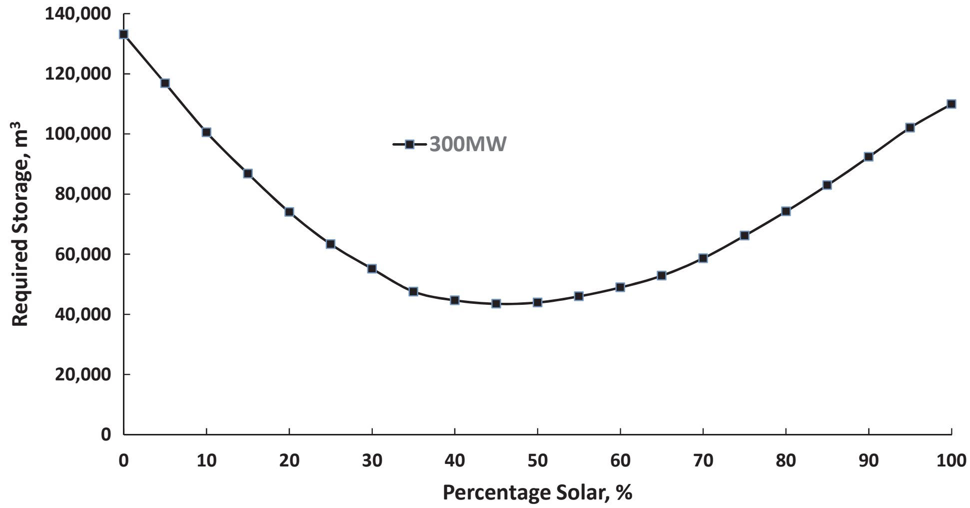

Fig. 9. Storage capacity as a percentage of solar energy. The percentage of wind energy is 100% minus that of solar.

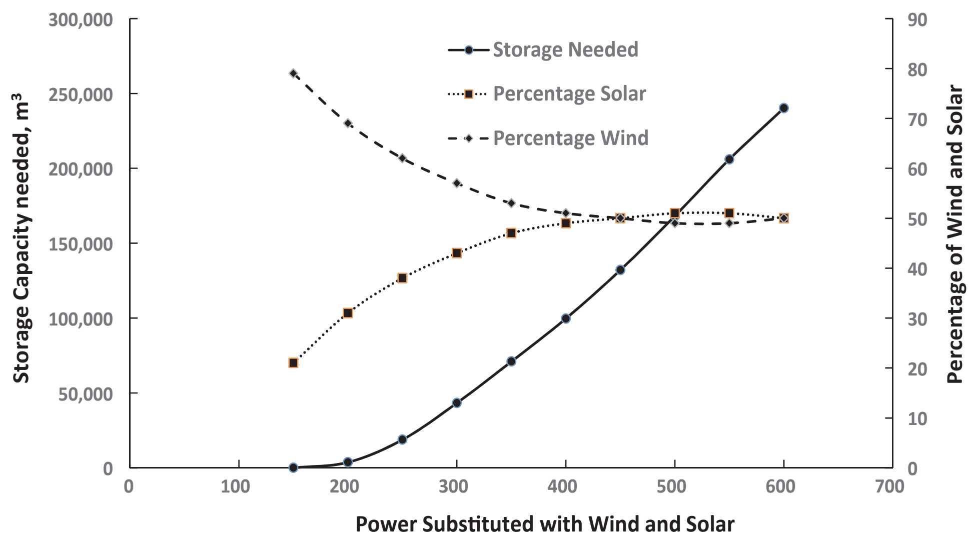

Fig. 10. Minimum storage capacity and percentage of wind and solar.

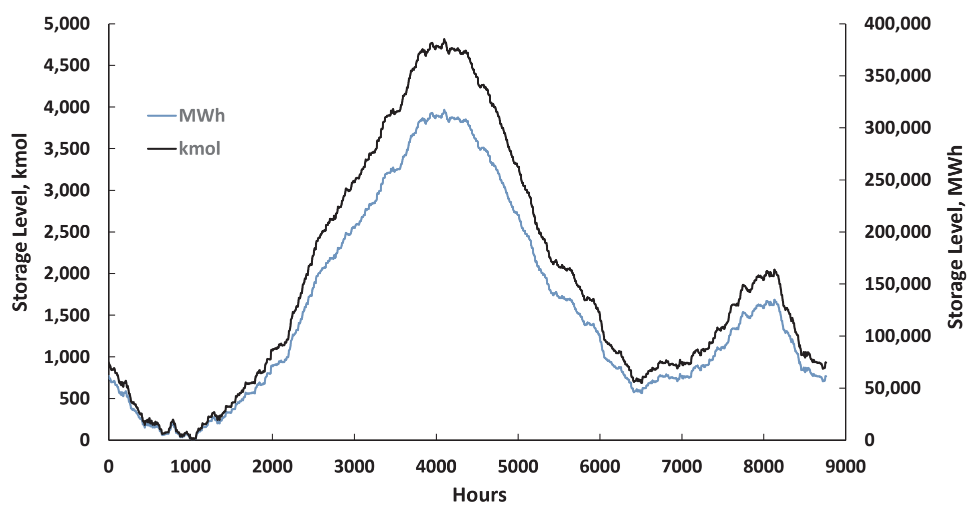

Fig. 11. Variation of the hydrogen storage level at the minimum required storage level. 300 MW of the power is supplied by solar and 300 by wind.

hydroelectric units that may provide base-load and intermediate load power [2].

7. Conclusions

A high fraction of renewable wind and solar generated electricity in a region causes the demand for the other power plants to shift significantly. This effect in combination with the inability of several types of base-load power plants to meet the diurnal fluctuations of power demand reduces substantially the flexibility of the electric grid to supply power to the region. When the annual amount of renewable energy from wind and solar exceeds approximately 25% of the total, the demand from other power plants at certain time periods during a year diminishes and may even become negative for a few time-periods, which implies that the energy produced cannot be absorbed by the consumers. In such cases energy storage becomes necessary. In areas with relatively flat topography hydrogen storage is the most favorable storage method for utility-level storage. An analysis of the hourly electricity demand data for a region in Central North Texas reveled that substantial storage capacity, of the order of 250,000 m^3 of hydrogen is required for the substitution of 600 MW base-load capacity that is now delivered by a coal power plant. The required energy storage capacity as a function of the substituted power is an S-shaped curve for both wind and solar power. Substitution of the coal-generated electricity with wind power requires significantly higher storage capacity than substitution with solar. A combination of wind- and solar-generated electricity – two weakly correlated energy sources – requires lesser storage capacity.

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