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Full length article

The effect of electric vehicle energy storage on the transition to renewable energy

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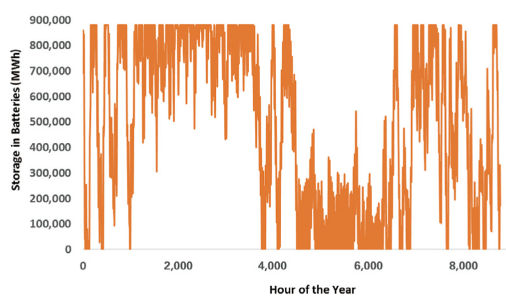
HIGHLIGHTS

- Significant storage capacity is needed for the transition to renewables.
- EVs potentially may provide 1–2% of the needed storage capacity.
- A 1% of storage in EVs significantly reduces the dissipated energy by 38%.
- A 1% storage in EVs reduces the total needed storage capacity by 50%.
- Improving by 1% the storage efficiency reduces by 0.92 TWh the needed storage.

GRAPHICAL ABSTRACT



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ABSTRACT

The most viable path to alleviate the Global Climate Change is the substitution of fossil fuel power plants for electricity generation with renewable energy units. This substitution requires the development of very large energy storage capacity, with the inherent thermodynamic irreversibility of the storage-recovery process. Currently, the world experiences a significant growth in the numbers of electric vehicles with large batteries. A fleet of electric vehicles is equivalent to an efficient storage capacity system to supplement the energy storage system of the electricity grid. Calculations based on the hourly demand-supply data of ERCOT, a very large electricity grid, show that a fleet of electric vehicles cannot provide all the needed capacity and the remaining capacity must be met by hydrogen. Even though the storage capacity of the batteries is close to 1–2% of the needed storage capacity of the grid, the superior round-trip storage efficiency of batteries reduces the energy dissipation associated with the storage and recovery processes by up to 38% and the total hydrogen storage capacity by up to 50%. The study also shows that anticipated improvements in the round-trip efficiencies of batteries are almost three times more effective than improvements in hydrogen storage systems.

1. Introduction

The unceasing fossil fuel combustion with the accompanying CO_2 emissions, the accumulated CO_2 in the atmosphere, and the resulting Global Climate Change (GCC) has become the most pressing global problem of the 21st century. Climate experts are urging the global community to adopt new CO_2 emission standards that would first stabilize and then reduce the concentration of this gas in the atmosphere. A promising method to achieve CO_2 emissions reductions is to shift a large fraction of the global energy needs from fossil fuel resources to renewable

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resources. However, the two most abundant renewable energy resources, solar energy and wind energy are periodically variable (solar) and intermittent (wind) and, oftentimes, are not available to satisfy the instantaneous power demands of the consumers. As a result, energy storage at the utility level [1] or at the consumers' level [2] becomes an integral part of the solution to the problem of decarbonization of the electricity generation sector.

It is apparent that, because the transportation sector switches to electricity, the electric energy demand increases accordingly. Even with the increase electricity demand, the fast, global growth of electric vehicle (EV) fleets, has three beneficial effects for the reduction of CO_2 emissions: First, since electricity in most OECD countries is generated using a declining fraction of fossil fuel power plants (and, especially, coal-fired plants), the substitution of IC-engine vehicles with EVs results in immediate CO_2 emissions reduction. Improvements in the well-to-wheels efficiencies of EVs will result in further CO_2 emissions avoidance in the future, even in the developing countries [3]. Second, with flexible and optimized charge–discharge schedules a higher fraction of renewable energy sources (RES) may be used in transportation. A recent study by Zhao et al. [4] proposed a set of indices and an algorithm to initiate a scheduling scheme for renewable power generation. In addition, they proposed a "particle swarm optimization algorithm" to coordinate the output of the renewable units and plug-in electric vehicles (PEVs). Third, with the availability of large batteries in EVs, a fraction of the energy stored in these batteries may be used to supplement the needed energy storage – the so-called vehicle to grid (V2G) scheme. It must be noted, however, that not all the currently marketable EVs are suitable for V2G operation. Currently (2022) only two of the fifty-five EV models marketed in the USA have V2G capability with a third having vehicle-to-home capability [5]. It is expected that with sufficient market incentives or governmental directives, most if not all of the EV models in the market will have V2G capability in the future [6]. Actually, a recent article by Costa eta al [7]. advocates a business model innovation that recognizes the changing business landscape (boundary condition) and allows the widespread V2G capability. Another economic evaluation by Liu and Zhong [8] of four V2G strategies determined that the combination of PV power supply and storage systems may become economical before the year 2025 and that V2G strategies could become economically attractive in the long.

Regarding the EV energy exchanges with the grid, Sharifi et al. [9] conducted such a study and formulated a real-time charge/discharge scheduling algorithm so that the aggregator takes advantage of real-time communication in smart grids to coordinate the EV charging schedules, wind generation forecasts, and electricity prices. Their simulations demonstrate significant increase in wind utilization, the reduction of charging costs, and lower EV battery degradation. You and Kim [10] developed an optimization model and applied it to the island of Jeju, Korea to analyze renewable energy networks using electricity, with hydrogen as the storage medium. The networks transform energy from a variety of sources to electricity, thermal energy, and hydrogen and are used to satisfy all the energy needs of the consumers. However, the high penetration of time-dependent RES – in particular, of wind power – in the electricity generation markets creates complexities in the operations of power systems. The substitution of IC-engine vehicles with EVs increases the uncertainty of electricity generation and consumption, so that an uncoordinated charging process will further complicate grid scheduling. Oldenbroek et al. [11] considered the use of hydrogen in the tanks of fuel-cell driven vehicles as potential energy storage medium in the model of a smart city, while Robledo et al. [12] presented the results of a demonstration project that included building-integrated photovoltaic solar panels, and a hydrogen fuel-cell electric vehicle for mobility and power generation, with the aim to achieve a net zero-energy residential building. A review [13] of the subject proposed the coordination of scheduling for the charging and discharging of EV fleets to maximize the integration of renewable energy in the grid, while using the EVs as part of the utility-level storage system. Another, more recent review of the subject [14] presented perspectives on the progress of PEVs to exchange electric energy with the grid.

Related to the operation of EVs Ebrahimi et al. [15] conducted a stochastic study to determine the candidate locations for installing RES units, fast charging stations, and power switches, in a way that the entire grid can be modelled and clustered as multiple and active interconnected micro-grids. Shi et al. [16] considered worst-case scenaria, introduced a dispatch interval coefficient, and proposed a strategy to improve the security and economy of microgrid systems, considering the uncertainty of wind power and the EVs' state of charge (SOC). Emrani-Rahaghi and Hashemi-Dezaki [17] introduced a probabilistic scenario-based model for residential energy hubs. This study considers the electric as well the thermal needs of households under a scenario of renewable energy sources. The authors concluded that the use of plug-in EVs would assist in decreasing the operational costs of the residential energy hubs. Han et al. [18] developed a novel method for modeling the wind turbine power curve to provide more reliable data for the support of wind power penetration and EV charging in nearby regions. Their study did not consider the EV batteries as an auxiliary system for energy storage.

Among the studies pertaining to EVs energy storage in specific regions and municipalities, Bartolini et al. [19] examined the impact of EVs in the town of Osimo, Italy as a case study. They determined the achievable degree of RES self-consumption and the CO_2 emission reductions in the city. They concluded that a 10% EV penetration with V2G capability will lower the city's emissions by 3.5% while a 30% penetration of EVs would lower these emissions by 17.6%. Ravindran et al. [20] assessed the capability of plug-in EVs to function as energy storage systems in the Mediterranean island of Menorca. They determined that the use of EVs may provide up to 375 MWh storage capacity in the island, and this would facilitate the further penetration of renewables. Pearre and Swan [21] conducted a study to determine the potential of "smart charging" of EVs in Digby, Nova Scotia, to add load to the grid so as to increase export capacity and to charge EVs using renewable energy, primarily the wind and tidal energy resources that abound in the area. Zhou and Cao [22] conducted a study using a component-based model that integrates the PV system in a Hong Kong building and EVs. Also, Bastida-Molina et al. [23] assessed the CO_2 emissions avoidance in Spain using the well-to-wheels efficiency method. They concluded that the introduction of a large number of EVs in Spain would reduce the CO_2 emissions and that, if this is combined with a 100% renewable energy generation the CO_2 avoidance will be up to 74 million tons per year.

Liu and Zhong [8] performed an economic evaluation for the coordination between electric vehicle storage and distributed renewable energy systems and identified key barriers that EVs and distributed storage are facing in China. They determined that charging the EV batteries is cost-efficient in the near term because of the low investment, but also point out some of the limitations of V2G, such as the limits of battery cycles and the acceptance of EV owners. Gong et al. [24] tackled the problem of renewable energy generation uncertainty by developing a novel model for the prediction of RES outputs. They also modelled the EV electricity demand and suggested an optimal charging protocol to minimize the effects of supply-demand volatility. Similarly, Hornammand and Jadid [25] proposed an energy management model for a microgrid that includes 200 EVs and takes into account the constraints of renewable power forecasting errors, the reserve requirements, and EVs owner satisfaction. An open question in most of the V2G studies is the possible degradation of the vehicle battery from the more frequent charging–discharging processes. While it is known that frequent charge–discharge cycles in general deteriorate the battery performance, a recent simulation study using $C_6/LiNiCoAlO_2$ batteries concluded that an optimum discharging schedule to the grid can actually reduce the lithium-ion battery degradation [26].

Three modes of vehicle–grid interactions have been presented in the literature: Home to Grid (H2G) where vehicle(s) provide power for a home. Vehicle to Vehicle (V2V) where a group of vehicles (two or more) share the energy stored in their batteries. Vehicle to Grid (V2G) where

EVs interact directly with the grid in a bidirectional flow of energy. This study pertains to the V2G category and considers the impact of renewable energy generation and the possible role of EVs using as a reference the ERCOT grid, which supplies with electric power 92% of the State of Texas. The grid annually generates electric energy that is comparable to those of large countries (in 2019 it generated more electricity than the national grids of the U.K. and Italy) and operates in a region with excellent wind and solar resources [27].

The novelty of this study is that it considers the actual hourly power demand in an entire and very large grid (ERCOT) and computations are performed for every hour of the year (8760 h). This covers all seasons and all days in the year. None of the previous studies has considered an electric grid of such size and the effect of V2G systems on the energy and power supply of the grid. The study proposes a system that meets the hourly power demand with RES alone using the required energy storage capacity with EV batteries (V2G) and hydrogen (P2G – power to gas). Such a large grid system, where air-conditioning in the summer months results in very significant power consumption/demand and imposes very large size and severe constraints in the storage system, has not been studied before. Given that batteries have significantly higher round-trip storage efficiency than other utility-level energy storage systems, the computer algorithm assigns priority to the V2G part when power is needed from the storage systems. The study determines the effects of EVs on the necessary utility-level storage capacity; the thermodynamic irreversibility (dissipation), which is associated with the energy storage-and-recovery processes, as a large fleet of EVs develops in this region; the effect of the efficiencies of the energy storage systems; and the necessary energy storage capacity for the transition of this large electricity grid to renewable energy.

2. Demand and supply mismatch – storage and the role of electric vehicles

In order to combat the GCC, several national and regional governments have adopted long-term plans for the significant reduction of CO_2 emissions. Most of the decarbonization plans include the transition to RES for the production of electric power. Electricity generation from coal entails the production of approximately 1.1 kg of CO_2 per generated kWh. Electricity generation from natural gas in combined cycles entails the production of approximately 0.41 kg/kWh [2]. For any significant reduction of national or regional CO_2 emissions, it makes sense to retire the fossil fuel power plants for the generation of electricity, starting with the coal power plants. A recent study concluded that the retirement of a single 600 MW coal power plant in North Texas and substitution of the electricity produced by renewables would result in 6,062,000 tons/year CO_2 avoidance [28].

A moment's reflection, however, proves that while the fossil fuel power plants may produce power continuously – and the natural gas power plants may be brought in line to follow an ever-changing demand for power – the most abundant renewable sources are either periodically variable (solar) or intermittent (wind) and do not follow the consumers demand for electricity. As a result of the substitution of fossil fuels with wind and solar energy, a supply-demand mismatch is expected that may only be corrected with the storage of energy. In addition, the higher penetration of wind and solar energy in the electricity markets creates the so-called *duck curve* in the electric energy supply, which also dictates utility-level electric energy storage [2,29]. Depending on the wind-solar mix for electricity generation, approximately 40 TWh storage capacity will be needed for the substitution of all fossil fuel power plants in the ERCOT region with wind, and solar energy while keeping the nuclear output at its present level [30]. The storage and recovery of electric energy to satisfy the hourly demand of the consumers causes significant energy dissipation, which must be supplied in addition to the annual electricity demand.

The high magnitude of energy storage capacity cannot solely be met with EV batteries. Hydrogen storage and pumped hydroelectric storage (PHS), in regions where the land terrain is suitable, are the only energy storage methods for utility-level storage and are capable of storing large quantities of energy at timescales that span the seasons of a year. However, when all the energy transformations and dissipation sources are taken into account, both these types of energy storage have low round-trip efficiencies: 45–60% for the hydrogen-fuel cell systems and 45–55% for the PHS systems [2]. Battery energy storage entails significantly higher round-trip efficiencies, that may approach 90% with optimum battery charging [31]. Therefore, a large number of electric cars with spare battery capacity may be used within a region supplied by an electric grid for two purposes:

a) To alleviate some of the energy storage capacity requirements; and

b) To reduce the annual total amount of dissipated energy in the storage/regeneration system.

Approximately 22 million passenger vehicles and light trucks are now registered in the State of Texas, the vast majority operating with IC engines. This fleet of vehicles consumed 331.5 million barrels of gasoline and 41.2 million barrels of diesel fuel in 2019 [32], the equivalent of $1996*10^{15}$ J of heat. For any meaningful participation of the EVs in utility-scale energy storage, a large fraction of these vehicles would be converted to EVs. If 50% of the IC-engine vehicles (11 million) are converted to EVs, an additional 55.4 TWh of electricity would be needed for transportation annually, with the corresponding reduction of 165.5 and 20.6 million barrels of gasoline and diesel fuel, respectively [32]. The additional annual amount of electricity corresponds to an increased, base-load grid capacity of 6330 MW. If the EVs are used for commuting, as it happens in most work-days, the electric energy required for the commuting trips is significantly less than the capacity of the batteries. The difference between the average battery capacity (approximately 65 kWh) and the commuting needs of the local population is 40 kWh per EV and this implies that the IC-to-EV conversion of the 11 million vehicles will also introduce in the ERCOT region approximately 440,000 MWh of storage capacity in EV batteries. Of course, whether or not such capacity will become available depends on several factors, including:

1. The prices of electricity and gasoline fuels.
2. The relative prices of EVs *vis a vis* the IC-engine vehicles.
3. Whether or not the EV batteries will be suitable for V2G operations (currently only two of fifty-five models that are marketed in the ERCOT region have V2G capability).
4. The incentives provided to the EV owners to participate in EV operations.
5. The availability and cost of the ancillary systems used in V2G operations.

Because these factors cannot be accurately quantified at present, in the computations that follow, the fraction of the vehicles converted to EVs, the available storage capacity of the EV batteries, and the corresponding electric power usage for transportation are treated as parameters that vary in the computations.

It must be noted that for the complete functioning of the system several ancillary equipment will have to be used (inverters, transformers, frequency matching equipment, etc.). In this study, we consider only the most important part of these systems, the available energy and the flow of this energy to the consumers. Simply put, in the absence of the energy to be transferred, V2G systems would not exist. Also, that there are several other uses of EVs and advantages to switching to EVs including:

- Reduction of local emissions and improvement of the local air quality.
- Reduction of noise pollution, especially in large cities.
- Higher energy efficiency.
- Integration with RES and enhancement of the available energy storage.
- Lesser maintenance and (at present) significantly lesser fuel cost.
- For most of the OECD countries, reduction of petroleum imports.

3. Governing equations

Fig. 1 is a schematic diagram of the proposed system that would replace the fossil fuel power plants in the ERCOT region. A large number of wind turbines and PV installations, which are dispersed within the ERCOT region, produce power from the wind and solar irradiance. When the current demand in the grid is less than the power generated by wind and solar, the excess power is stored either in EV batteries or is directed to electrolysis plants that generate and store hydrogen locally. When the current grid demand exceeds the current supply, the deficit is met by the system of batteries and stored hydrogen, which is converted to electricity in fuel cells. The hierarchy for the storage and discharge of energy is first to or from the EV batteries and secondly to or from the hydrogen storage facilities. This hierarchical charging-discharging enables us to take advantage of the significantly higher round trip efficiency (charging and discharging to the grid) of the batteries in comparison to the hydrogen-fuel cell storage system. It must be noted that the EV batteries are not allowed to completely discharge, because a large part of their energy is needed for the daily transportation of their owners – the average daily travel in the state per vehicle is approximately 110 km per day [32].

The timescale of the calculations is 1 h and details of the hourly electricity demand in the ERCOT region are well known [33]. During a given hour of the year, the electric energy generation from solar irradiance in the PV cells 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 is the installed PV area; η_{si} is the efficiency of the PV cells; and t the time period considered – 1 h in this case. With this choice of the time period, $t = 1$ h, when the unit of the irradiance is kW/m^2, the energy production is calculated in kWh/m^2.

The efficiency of PV cells is almost constant at temperatures below 25°C and decreases at higher temperatures. The following closure equation [34] was used for the efficiency of the PV cells in this study:

$$\eta_{si} = \eta_{sc} - k_{sc}(T - 25) \text{for } T > 25^{\circ}\text{C} \tag{2}$$

where, η_{sc} is the nominal PV cell efficiency, provided by the manufacturer; and k_{sc} is the temperature sensitivity coefficient, which is typically in the range 0.002–0.006 °C^{-1} [34]. The value $k_{sc} = 0.002$ was used in this study.

For the calculation of the electric power generated by the wind turbines, the hourly data of energy generation per MW of wind installed capacity in the entire region served by ERCOT were obtained for three years (2017 through 2019). From this set of data, the hourly wind generation in the region was calculated for the installed capacity in the future.

In the absence of fossil fuel generated electricity, the electric energy production during a given hour of the year, i, is the sum of the energy produced by all the wind turbines, all the PV installations, and the other non-carbon power plants. The other plants include four nuclear reactors and two small hydroelectric units:

$$E_{Pi} = E_{wPi} + E_{sPi} + E_{oPi} \tag{3}$$

The hydroelectric units contribute 512 MW; the nuclear power plants contribute a total of 4985 MW and are used as base load units. The hourly electric power demand was obtained from the ERCOT data [33]. The 2019 hourly demand was augmented by the additional electric power needed for the operation of the electric vehicles.

When the power generation is higher than the demand during a given hour in the calendar year, i, the excess energy produced is stored to be used at a later period, when the electricity generation is insufficient (e.g. because it is nighttime or because there is low wind). The energy stored or retrieved from the storage system during the time period, i, is equal to the difference between the power production and demand:

$$\delta E_{Si} = E_{Pi} - E_{Di} \tag{4}$$

where δE_{Si} is the change in the stored energy during the time-period, i; E_{Pi} is the electric energy generated; and E_{Di} is the energy demanded during the same time-period.

Two energy storage systems are available – the EV batteries and hydrogen. The round-trip efficiency of the EV batteries (charging and discharging) is significantly higher than that of the hydrogen systems

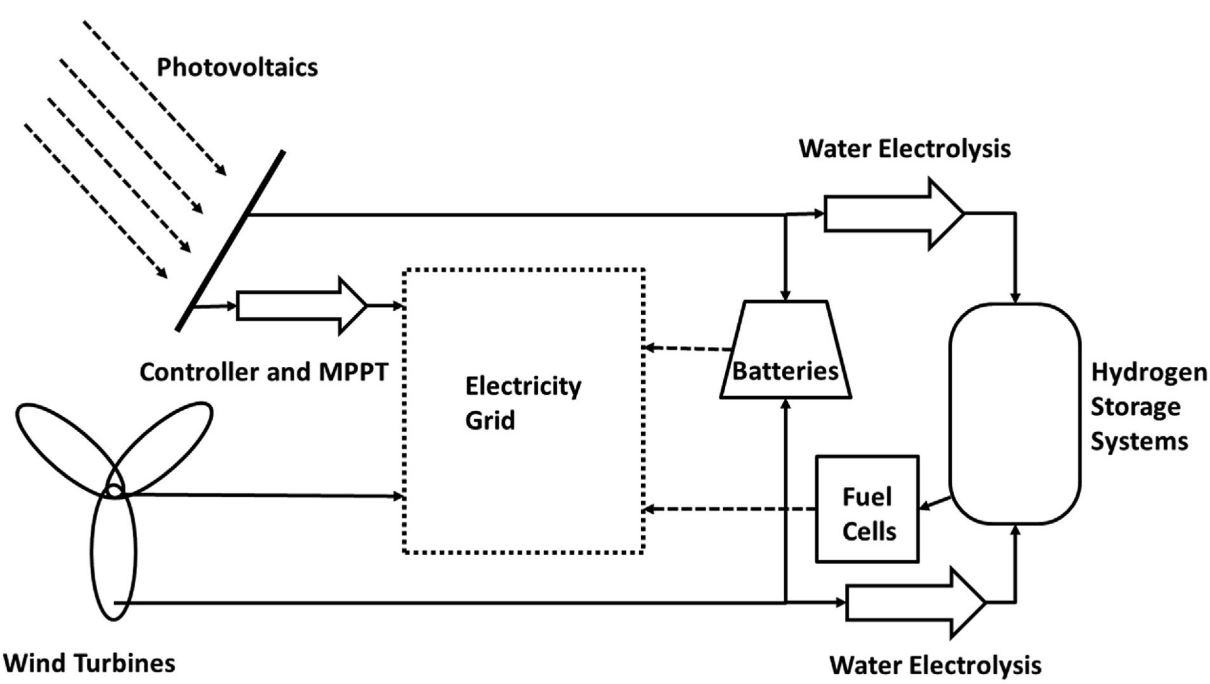

Fig. 1. A schematic diagram for the replacement of the fossil fuel power plants with renewable energy.

(hydrogen production via electrolysis followed by electricity generation in fuel cells) and entails significantly less energy dissipation [2]. Because of the higher efficiency, charging and discharging the EV batteries (subject to their capacity limits) is performed first, before any contributions from or to the hydrogen storage system. When the energy storage in the EV batteries is equal to its capacity, any excess energy generated is directed and stored in the hydrogen systems; similarly, when the available capacity of the EV batteries is exhausted, any energy needed to meet the demand is extracted from the hydrogen storage system. If the supply-demand surplus (positive) or deficit (negative) is denoted by δE_{Si} and the average efficiencies for charging and discharging the EV batteries are denoted by η_{ch} and η_{dc}, the energy added to the EV battery system (during surplus hours) or retrieved from it (during hours of deficit) is given by the expressions:

$$\begin{aligned} E_{Si+1} &= E_{Si} + |\delta E_{Si}|\eta_{ch} \text{ if } E_{Pi} \geq E_{Di} \\ E_{Si+i} &= E_{Si} - |\delta E_{Si}|/\eta_{dc} \text{ if } E_{Pi} < E_{Di} \end{aligned} \tag{5}$$

Similarly, when the average efficiency of electrolysis is η_{el} and that of the fuel cells η_{fc}, the energy storage level at the hour $i+1$ is:

$$\begin{aligned} E_{Si+1} &= E_{Si} + |\delta E_{Si}|\eta_{el} \text{ if } E_{Pi} \geq E_{Di} \\ E_{Si+i} &= E_{Si} - |\delta E_{Si}|/\eta_{fc} \text{ if } E_{Pi} < E_{Di} \end{aligned} \tag{6}$$

where E_{Si} is the energy storage level at the previous hour, i. The calculations in this study include a range of efficiencies obtained from [35–38]. For the time intervals when both battery and hydrogen storage is used, a linear combination of Eqs. (5) and (6) is used. It must be noted that there is low energy dissipation in other devices of the power generation systems, e.g. inverters, transformers and maximum power point trackers. The efficiencies of these devices are lumped together with the above four efficiencies in the calculations of the round-trip efficiencies. In the computations that follow the hourly demand from the grid was matched every hour (8760 h) of the year by supply from the RESs directly or from the two storage systems according to these governing equations.

An integral part of the mission and charter of all electric grids is that they must be reliable and capable to respond to the customers' demand for electricity at all times. However, electricity generation by wind and solar energy cannot be determined with high accuracy in the long run. For this reason, and in order to ensure the reliability of the grid, a constraint was introduced in the calculations that the two storage systems, combined, contain enough battery charge and hydrogen at all hours of the year to not only supply the instantaneous demand, but also to provide the grid with power for a minimum of fifteen days. The minimum stored energy ensures that in periods of system failures or severe adverse weather conditions (e.g. coastal hurricanes, snow blizzards, and inland tornados) that reduce the energy produced by renewables, the grid operators will have enough time to respond to the situation. Within these fifteen days, the operators will be able to perform the necessary repairs, purchase hydrogen from outside sources, and import electric energy from outside the grid to ensure an adequate supply of electricity.

Given the charging-discharging preference for batteries and the minimum storage constraint, the system of the governing equations yields 8760 linear equations (each for 1 h of the year). The equations are solved to yield, among others, the following parameters of interest:

1. The hourly energy supplied or withdrawn from the EV batteries and the H_2 system.
2. The hourly levels of energy storage in the H_2 system and the EV batteries.
3. The hourly dissipation.
4. The needed solar and wind capacity.
5. The needed total energy storage.
6. The daily and annual thermodynamic dissipation.

4. Results and discussion

Hourly calculations were performed for the additional solar and wind installed capacity to substitute all the fossil fuel power plants, while meeting the hourly power demand in the ERCOT region for the 8760 h of a given (non-leap) year. For a given EV battery storage capacity, which is treated as a parameter, the hourly and the total annual energy dissipated during the storage–recovery processes was calculated, as well as the needed storage capacity of the larger hydrogen system. For these calculations the round-trip efficiency of EV batteries, including losses in transformers is 79.2% and the round-trip efficiency of the hydrogen storage system is 52.5%. Fig. 2 shows the two quantities of interest vs. the fraction of solar and wind energy in the mix of renewables that are necessary to replace all the fossil fuel power plants in the region. The Figure is the base-case scenario and pertains to zero available battery storage capacity. It is observed in this Figure that a high quantity of the generated electricity is dissipated in the storage/recovery system. The minimum of the annually dissipated energy is approximately 38 TWh and occurs at 28% solar and 72% wind in the renewables mix. The energy dissipated increases to 48.5 TWh, when only wind is used. and 156 TWh when the renewable energy is solely generated by the solar irradiance. It is also observed in Fig. 2 that the required energy storage capacity is significantly lower (31 TWh) when all the additional electricity is produced by solar energy. This happens because the air conditioning systems in buildings demand most of the annually generated electricity and the energy supplied to air-conditioning is highly correlated with solar irradiance that causes high temperature. These results are corroborated by the results of two other studies on the elimination of coal power plants and the transition from fossil fuels to RESs [31,32].

Fig. 3 depicts the same information as Fig. 2, but includes the EV contributions with the addition of 440,000 MWh (0.44 TWh) storage capacity, which is available in the batteries of 11 million EVs (half of the 22 million vehicles that are now in use). A comparison of Figs. 2 and 3 leads to the observation that the annually dissipated energy is significantly lower at all the solar–wind combinations. The dissipated energy is 17% lower when wind supplies all the renewable energy; 38% lower when all the additional renewable energy is supplied by solar irradiance; and between the two values when the additional energy is supplied by a mix of wind and solar units. Fig. 3 also shows that the needed hydrogen storage is not significantly affected by the addition of the battery storage in the electricity generation mix. This happens because the needed hydrogen storage capacity is on the order of 40 TWh, while the battery capacity in this case is only 0.44 TWh – approximately 1% of the total.

The total available EV battery storage capacity is a parameter and its effects on the annually dissipated energy are shown in Fig. 4. The Figure depicts on the left axis the energy dissipated in the storage-recovery process when all the additional renewable energy is generated from the wind or solar irradiance, as well as the minimum dissipation – the minima of the corresponding curves, similar to the last two Figures. On the right axis the Figure depicts the total energy generated by the wind and the solar units at the points of minimum dissipation. The total energy generated is increasing with the battery capacity, because a larger number of EVs are in operation. It is observed in Fig. 4 that adding battery storage capacity has a significant and beneficial effect on the energy dissipated, under all scenarios of energy generation, despite the fact that the total energy generated increases to accommodate the EV additions. In the case of 100% solar generation, adding 880,000 MWh of battery capacity (approximately 2% of the total storage capacity) the dissipated energy drops by almost 50%. Similarly, in the scenario of 100% wind generation the dissipated energy drops by 16.5% and in the minimum dissipation scenario it drops by 12.5%. In all these scenarios the total generated energy increased to accommodate the addition of the 22 million EVs.

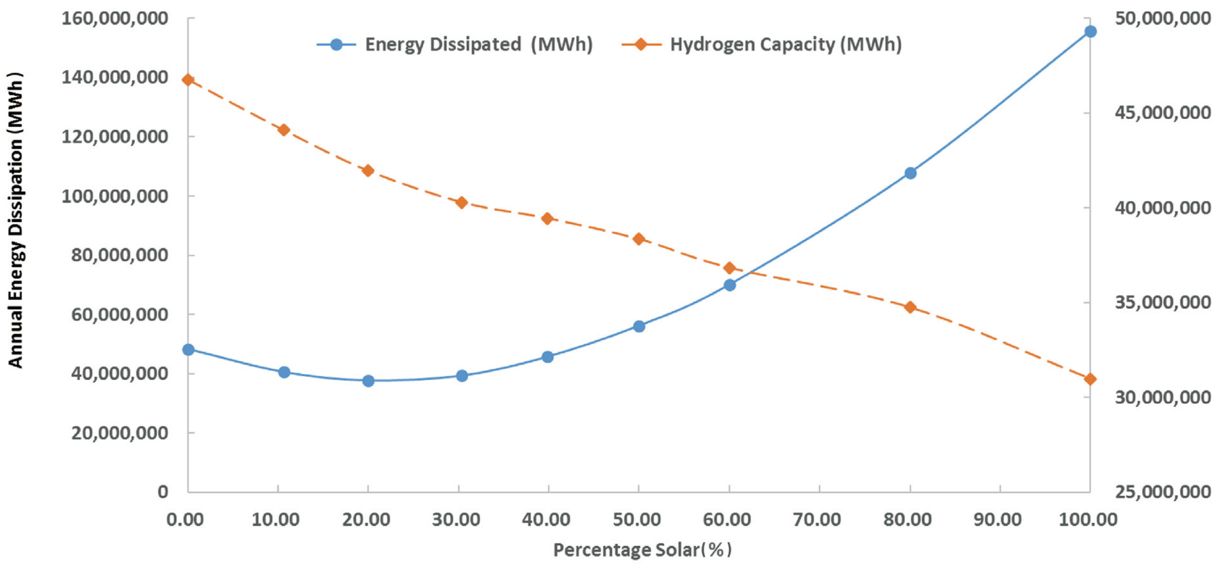

Fig. 2. Annual energy dissipation and hydrogen storage capacity when there is no available battery storage.

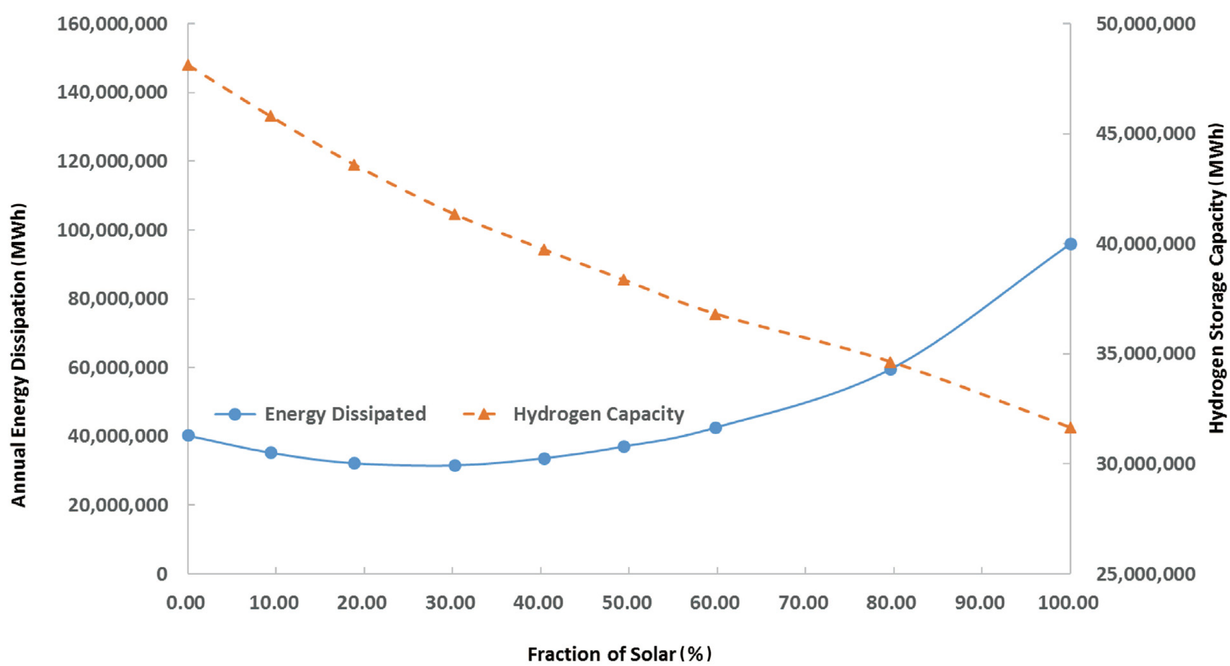

Fig. 3. Annual energy dissipation and hydrogen storage capacity with 440,000 MWh available battery storage.

Fig. 5 is a histogram that shows the energy exchanges on a summer day, when the battery storage capacity is 100,000 MWh. The Figure also shows the state of charge (SOC) of the batteries. The priority of the batteries in the charging and discharging processes is apparent in the Figure. It is also apparent that, because the magnitude of the hourly excess and deficit is high – on the order of 100,000 MWh – and the battery capacity is on the same order of magnitude, the hydrogen system, which has very high capacity contributes significantly more in the energy exchanges.

It is axiomatic that the loss of energy during the charging-regeneration process and the annually dissipated amount of energy depend on the round-trip efficiency of the energy storage system. For the two storage systems in this study the round-trip efficiencies are treated as adjustable parameters. The hydrogen storage systems entail two essential systems, the electrolysis systems whose efficiency has an upper limit 78% [35], and the fuel cells whose efficiency varies in the range 45–80% [36]. The minimum amount of the annually dissipated energy was calculated for hydrogen storage round-trip efficiencies in the range 35–60%[1] and the results are depicted in Fig. 6. It is observed in this Figure that there is an almost linear reduction of the dissipated energy with the hydrogen storage efficiency improvements. The slope of the data trendline is 0.92 TWh per 1% efficiency improvement.

The charging and discharging processes of electric batteries is inherently more efficient than that of a hydrogen storage system. Similar calculations were performed for the battery storage system and the results are depicted in Fig. 7, where the range of variation of the efficiencies is 75–85%. This Figure also shows the almost linear dependence of the

[1] The round-trip efficiencies of the alternative utility-level energy storage system, the pumped hydro system (PHS), are in the same range. Compressed air energy storage systems (CAES) have lower round-trip efficiencies [2].

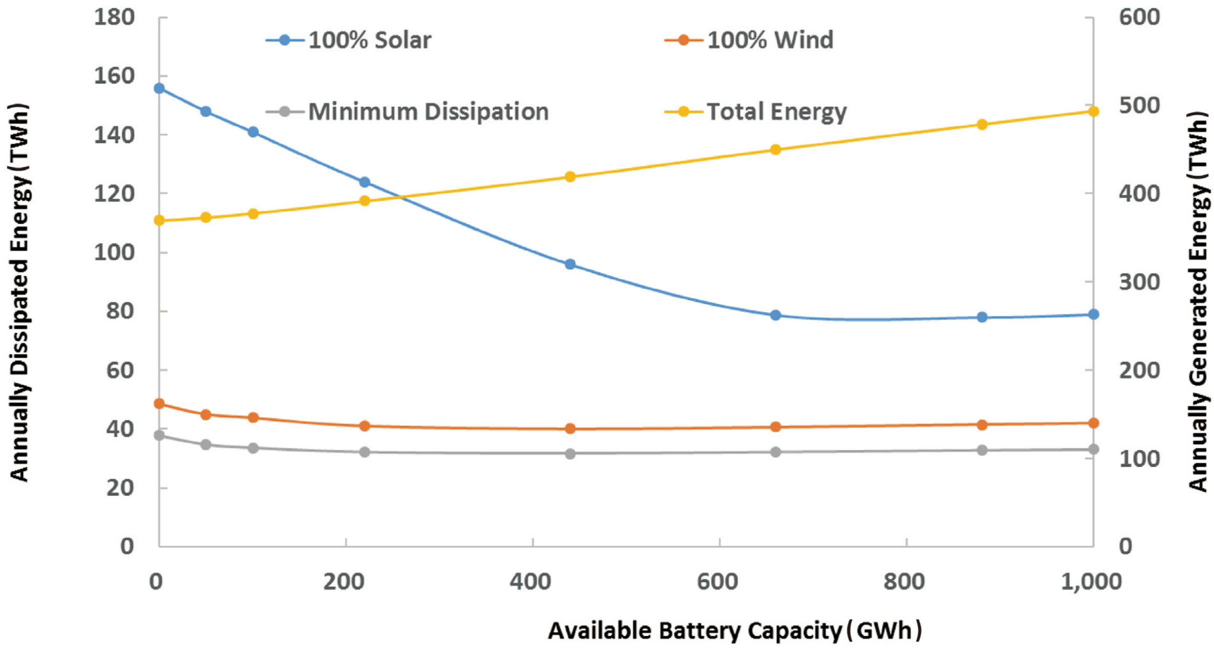

Fig. 4. The effect of available battery storage capacity on the dissipated energy and the total generated energy.

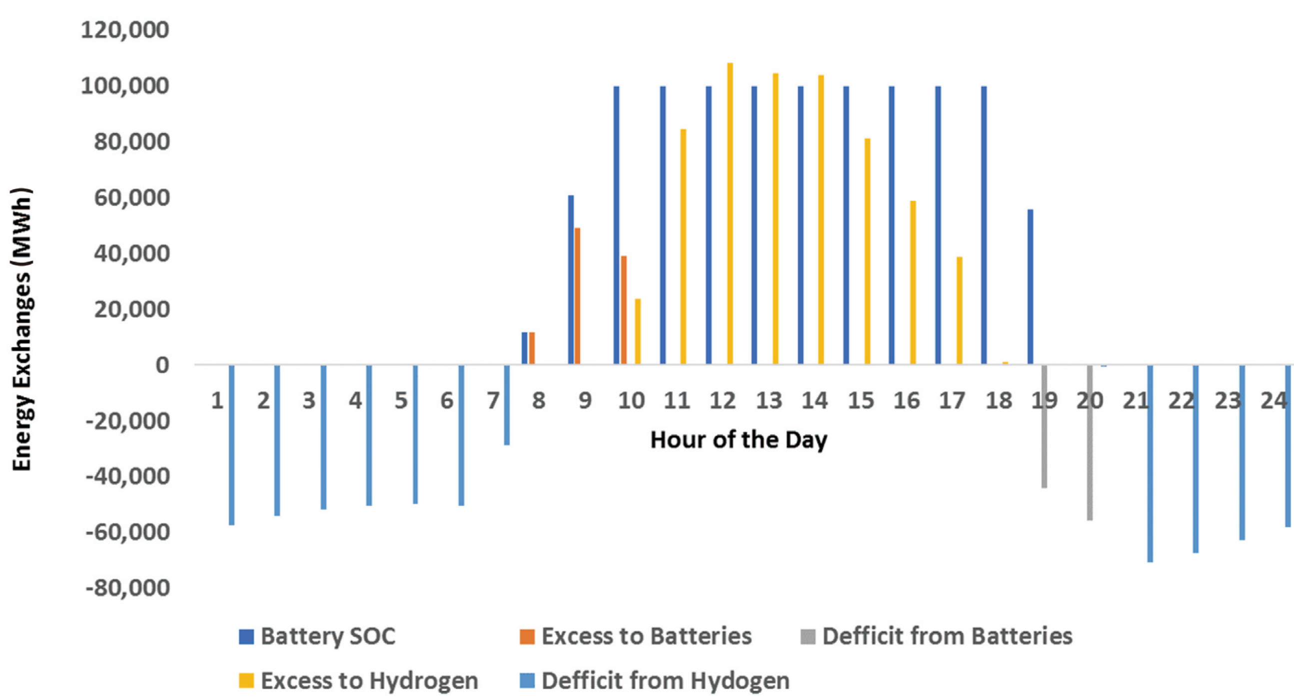

Fig. 5. Hourly energy exchanges during a summer day.

reduction dissipated energy with the round-trip efficiencies. The slope of the trendline in this case is approximately 0.3 TWh per 1% efficiency improvement. This is due to the already high round-trip efficiencies of the battery systems.

Given the variability of the electric power demand in the region and the high demand during the summer, it is expected that there are significant fluctuations in the energy level of both hydrogen and battery storage systems. With a total battery capacity of 880 GWh, Fig. 8 depicts the hourly storage level in the hydrogen system. It is observed in this Figure that energy is stored during the late winter and spring to be used in the summer, when the air-conditioning demand causes the total electric power demand to peak. The maximum energy that needs to be stored in hydrogen is 39,800 GWh. It is noted in this Figure that the stored energy in hydrogen does not vanish, because of the constraint that there should be enough energy in the two storage systems to supply the entire grid for fifteen days.

Fig. 9 shows the hourly energy fluctuations in the battery storage system, which has a maximum of 880 GWh (approximately 2.2% of the 39,800 GWh for the needed hydrogen storage). It is observed that the energy needed to be stored in the batteries actually vanishes during several hours in the year. This happens because, as explained in the section of the governing equations and because of its higher round-trip

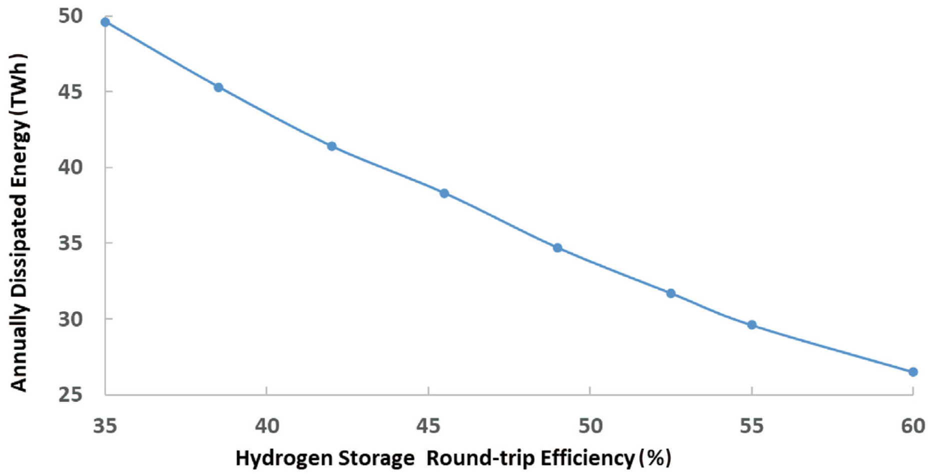

Fig. 6. The dependence of the dissipated energy on the round-trip efficiency of the hydrogen storage system.

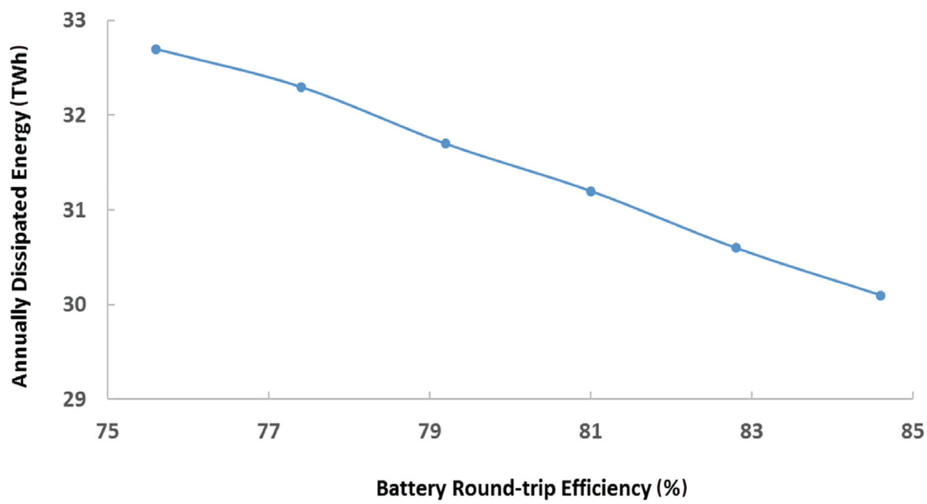

Fig. 7. Dependence of the annually dissipated energy on the round-trip efficiency of the EV battery storage system.

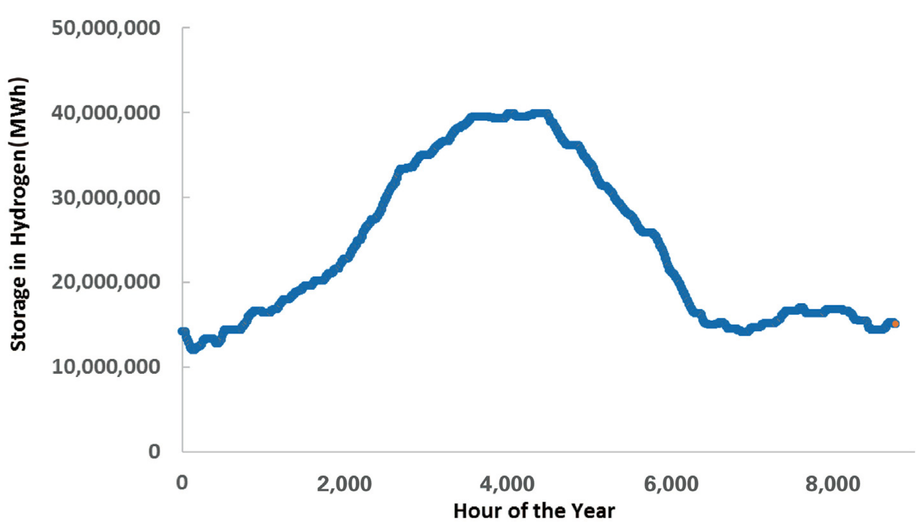

Fig. 8. Hourly level of energy stored in hydrogen for the entire year.

efficiency, the available storage in the battery system has priority in charging and discharging operations, with the hydrogen system taking over afterwards. It is emphasized that the vanishing numbers in this Figure do not imply that there is no power to run the vehicles: the Figure shows the part of the stored energy in the batteries that is assigned to the grid, rather than for vehicle transportation.

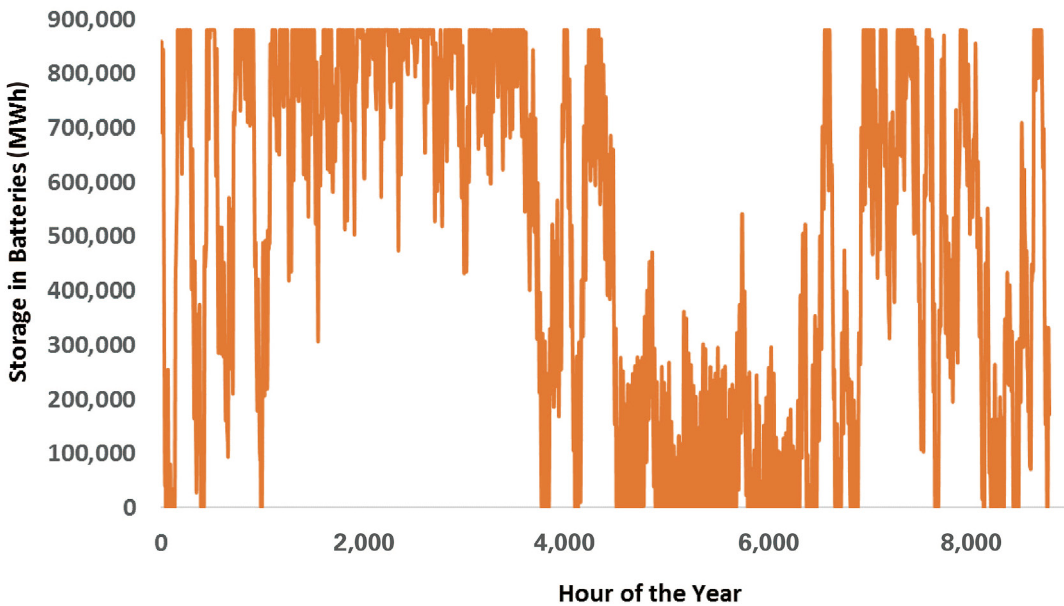

Fig. 9. Hourly level of energy stored in the batteries for the entire year.

It must be noted that, for the complete substitution of the fossil fuel electric power plants with renewable wind and solar energy units within the ERCOT region, the required utility-level storage capacity is high, in the range 30–50 TWh, depending on the fractions of wind and solar generated electricity. This region has very high density of vehicles per inhabitant (0.7 vehicles per capita), which amounts to approximately 22 million vehicles. Even if all these vehicles are to be converted to EVs, the EV battery storage capacity that may be used for grid storage would be 0.9 TWh, significantly less than the needed storage of the electricity grid. In electricity grids that serve large and highly populated areas, the EV energy storage system is only auxiliary to a higher capacity, utility-level storage. While V2G storage systems do not alleviate the need for a larger utility-level storage system, the introduction of even a small amount of battery storage significantly improves the performance of these larger storage systems.

This is an analysis on the energy conversions related to EV batteries and the general energy storage requirements of an entire electric grid. The market penetration of EVs is still very low and V2G systems are in their infancy. Actually, only two of the fifty-five EV models that are marketed in the USA have V2G capability. V2G storage technology has not been implemented within the ERCOT region. As a result, the current prices of equipment and systems for this technology are still high. Following other similar technologies (from refrigerators to laptops and cell phones), the prices of V2G equipment are expected to significantly drop as they become “everyday appliances.” Because of such ambiguities in the equipment prices and because all energy prices fluctuate significantly (with relative standard deviation higher than 50%, [39]), an economic analysis of V2G systems would be premature and will be laden with very high uncertainty. For this reason, this paper is limited to the thermodynamics (energy balances) of these systems.

It must also be noted that such results are specific to the demand in the ERCOT grid. Because of the widespread air-conditioning use, the grid experiences high electric power demand during summers. As the use of air-conditioning proliferates globally, other electricity grids will experience similar demand patterns and the general results of this paper will also apply to those grids.

5. Conclusions

Part of the energy storage capacity in the batteries of EVs may be used for the storage of renewable electricity. Large fleets of EVs in a region may contribute to utility-level energy storage as auxiliary energy storage systems, but their storage capacity is two orders of magnitude less than the storage capacity that is necessary for the substitution of fossil fuel power plants with renewable energy units. Because the round-trip efficiency of battery storage is significantly higher than that of other systems (e.g. hydrogen, PHS and CAES), even a very small fraction of battery storage availability in a large grid system results in significant reductions of the dissipated energy in the storage/recovery process. The dissipated energy reduction is up to 50% when a high fraction of solar units is used in the grid. The needed hydrogen storage is not significantly affected by the addition of the battery storage primarily because the needed hydrogen capacity is two orders magnitude higher than the available battery capacity. Because of the already high round-trip efficiencies of batteries, technological improvements of the battery charging-discharging round trip efficiencies are three times less effective as equivalent efficiency improvements in the hydrogen.

Author contributions

E. E. Michaelides conceived of the project, had the general management and wrote most of the sections. V.N.D. Nguyen wrote the computer software and performed most of the calculations. D. N. Michaelides assisted with the solution algorithm, and part of the writing.

Data availability

The data and materials used to support the findings of this study are available from the corresponding author upon a reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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