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Decarbonization of the electricity generation sector and its effects on sustainability goals

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Abstract

The substitution of fossil fuels, especially coal, with renewable energy is a crucial step for the CO_2 emissions reduction and the avoidance of Global Climate Change. The electric power generation industry is the first economic sector that will have to transition to renewable energy. However, wind and solar energy, the two most abundant renewable energy forms, are not dispatchable. The high penetration of these renewables in the energy market will create a demand–supply mismatch, which can only be alleviated with large-scale energy storage. This paper uses the case of Texas—a state that generates and consumes more electricity than several large, industrialized nations—to quantitatively examine the required infrastructure for the decarbonization of the electricity generation industry, while satisfying the current electric power demand in the State. Among the parameters that are examined are: the additional solar and wind capacity; the necessary energy storage infrastructure; the energy dissipation in the storage/regeneration process; and the effect of decarbonization on the cost of electricity and the welfare of the citizens. The computations show that the technology is available for the transition to a decarbonized electric power sector but requires significant investment in new wind and photovoltaic units as well as substantial energy storage. This would increase the electricity prices by a factor between 2.9 and 3.7 and, would have a disproportionate impact on the citizens in the lower income brackets.

Keywords Sustainability, Energy transition, Decarbonization, Energy storage, Electricity grid, ERCOT

Introduction

Thermal engines have proliferated since the dawn of the Industrial Revolution and ushered for humans a new era of prosperity, utmost convenience, and better life. However, the combustion of fossil fuels—on which thermal engines depend—has also generated very large amounts of carbon dioxide (CO_2), which accumulates in the atmosphere and has caused a sizeable increase of the concentration of the gas from 280 ppm at the end of the eighteenth century to more than 410 ppm in 2023. In addition, the emissions and accumulation of all Greenhouse Gases (GHGs) have increased the average temperature of the biosphere and have resulted in a calamitous Global Climate Change (GCC), the most significant and urgent environmental concern of the twenty-first century (IPCC, 2007). After a wide and energetic debate, the human society has come to the realization that a drastic reduction of the CO_2 emissions is absolutely necessary to avoid global environmental disasters. However,—and notwithstanding the several United Nations conferences, including the Paris conference and agreement of 2015—there is no significant progress in the reduction of GHG emissions. The annual global GHG emissions (which include the equivalent methane and nitrogen oxides) increased from 38.9 gigatons (Gt) of CO_2 equivalent to 41.2 Gt; and the CO_2 global emissions have jumped from 33.6 Gt to 36.8 Gt (International Energy Agency, 2023; International Energy Agency, 2019a). And this happened despite the global economic downturn caused by the Covid-19 pandemic in the years 2020–21 (Global Energy Review, 2021; Ritchie & Roser, 2020).

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The electricity generation industry accounts for approximately 43% of the global CO_2 emissions. It is the most significant contributor of GHG emissions with the transportation being the second contributor. Because electricity is generated in very large stationary GHG sources, it is reasonable to first tackle the electric power plants for industry directives and national regulations aimed at the significant reduction of CO_2 emissions. The Intergovernmental Panel on Climate Change (IPCC) recommended in 2014 that, to keep the average global temperature rise under 2 °C, CO_2 emissions from electric power plants should be reduced by 90% or more from their 2010 levels between the years 2040 and 2070 (IPCC, 2014). In 2018, the same organization adopted a more stringent goal for the global temperature rise, 1.5 °C (IPCC, 2019). The adoption of these goals will profoundly transform the electricity generation sector of the global economies by shifting the generation of electric energy from fossil fuels to renewable energy.

Wind and solar power are the most abundant renewable energy sources on a global scale and achieving the global CO_2 reduction goals—even partially—will result in photovoltaic (PV) cells and wind turbines generating most of the electricity for an increasing global population—expected to reach 10 billion people in 2040 (IPCC, 2019). It must be noted that a few nations have significant dispatchable renewable resources, primarily hydroelectric (e.g., Norway, Nepal) and geothermal (e.g., El Salvador, Iceland, Nicaragua) that may supply a very large fraction of their electric power demand. However, the vast majority of nations—and, more important, the larger economies and the most populous nations—will have to primarily rely on wind and solar for the decarbonization of their electricity generation sector. Decarbonization in this context denotes the complete substitution of all the fossil fuel power plants (coal, diesel, natural gas) with renewable energy units.

Solar energy is periodically variable, and wind is intermittent. Transitioning the electricity generation industry from the (always available and easily stored) fossil fuels to wind and solar energy introduces a significant problem: The demand for electric power follows well-known seasonal and diurnal patterns and is not correlated at all with the availability of the two renewable energy sources. Currently, the electric power demand fluctuations are met by increasing the power of coal power plants or bringing in line gas-turbines. Both categories of power plants as well as the nuclear power plants generate dispatchable electric power that can be relied to supply power on demand. A future society that relies on solar and wind power will have to develop energy storage infrastructure to ensure that the demand for power is matched by the supply. Development and utilization of a large energy storage network is an indispensable technological component in a future, where renewable energy sources supply a large fraction of the electric energy (Argyrou et al., 2018; Mahlia et al., 2014; Michaelides, 2021a). A second reason for the development of large-scale energy storage capacity is the high PV power generation during the early morning hours. The supply by far exceeds the demand of the grid and progresses into the *duck curve* for PV energy systems (California ISO (CAISO), 2016; Freeman et al., 2016;). A similar power overproduction (the *rattlesnake curve)* occurs with wind turbines during windy time periods, especially during spring and autumn (Michaelides, 2021b). The two effects stress the vital role of energy storage in any electricity grid that primarily relies on wind and solar energy.

The decarbonization (and its almost synonymous zero-carbon emissions) of industry sectors has become a general research area with several research teams extending the proposed solutions from the electricity generation sector to other areas of economic activity. Among the more recent research on the decarbonization of the global industries one may see the work by Griffiths et al., on the zero emissions from the cement industry and the socio-economic aspects of this type of energy transition (Griffiths, 2023); the application of carbon capture and sequestration in a power plant that utilizes the gas effluents in a landfill where urban waste is dumped (Brigagao et al., 2021); the article by Dong and He on the urban environments and the effect of reducing CO_2 emissions by optimizing the "green roofs" within large cities (Dong, 2023); and the blueprint for the development of microgrids for smaller towns and communities that are completely independent of centralized grids by generating and storing renewable energy (Sandoval Aguilar & Michaelides, 2021).

This paper aims to present a realistic scenario for the transition of the Texas electricity generation industry to zero CO_2 emissions by substituting fossil fuels with a combination of solar and wind power. The paper is based on the electric power supply–demand equilibrium at all hours of the year in the Electricity Reliability Council Of Texas (ERCOT), the independent electricity grid that supplies 92% of the State of Texas, which is of the size of electricity grids in several major industrialized economies. This grid system is almost entirely independent with very low interconnectivity to the other USA grids—in 2022 only 0.21% of the electricity consumed within the ERCOR region was imported from other grid systems. It must be noted that, even if the interconnectivity is enhanced, the surrounding states do not have the capacity to generate sufficient electric power to satisfy the very large demand in ERCOT. Hourly calculations on demand and supply determine the necessary ratings (plate capacity) of solar and wind electricity generation units in a zero-emissions scenario; the energy storage capacity that would make this scenario possible; and the energy dissipation in the energy storage/recovery systems. The paper includes cost estimates for this transition, the effect on the electric energy cost to the consumers and the associated implications on two of the United Nations sustainability goals.

The ERCOT electricity system

The ERCOT system manages the generation and distribution of electricity to more than 29 million people in the State of Texas, including 95% of industry and businesses. The region supplied by ERCOT is representative of many others in the globe, where the high summer temperatures necessitate the intense use of air-conditioning (AC) during the summers. As parts of the globe become more affluent, AC use is spread globally. The International Energy Agency estimates that the number of AC units in buildings will reach 5.6 billion by 2050, up from approximately 2 billion units in 2022 (International Energy Agency, 2018). The widespread use of AC will transform the electric power demand in other parts of the globe to the demand patterns that are currently exhibited in ERCOT.

The generating capacity of ERCOT is equivalent to the national grid of a very large economy. In 2022 the system generated and distributed 428.5 TWh of electricity, a quantity that is higher than the electricity generated in the national grids of the UK and Italy (International Energy Agency, 2021). The rated generation capacity of ERCOT is close to 86,000 MW and the maximum demand in the 2022 was slightly higher than 80 GW (at 4:00 pm on July 20th) (http://www.ercot.com/gridinfo/generation). Since 2005 of the wind generating capacity experienced high growth rates in the ERCOT region, while the coal generating capacity significantly decreased. The generating fuel mix that supplies electric power in this region includes nuclear, wind, solar, coal, gas, and hydroelectric with the electric energy generated by each energy sources depicted in Fig. 1. Sources labelled as "other" chiefly include small amounts of hydroelectric and biomass energy as well as electric energy imported from the surrounding states and Mexico. The total of all the "other" sources was less than 1 TWh.

One may conclude from the data in Fig. 1 that:

1. The contribution of coal to the total fuel mix has been continuously decreasing and dropped below the wind generated electricity since 2020. This trend is consistent with the global goals to substantially reduce and, finally, eliminate coal from the electricity generation mix.
2. The contribution of wind power generation has dramatically increased since 2006 and that of solar since 2018. In 2022, wind power generated 107.3 TWh of electricity and the PV solar installations 24.2 TWh.

The system for decarbonized electricity generation

A schematic diagram for the system that would generate, store, and distribute electric power in the ERCOT region is depicted in Fig. 2. For the servicing of such an immense electricity grid, a large number of wind and solar generating units would have to be constructed throughout Texas as well as energy storage facilities. The grid already has two nuclear power plants that operate as base-load plants and the "Other Sources," which include hydroelectric

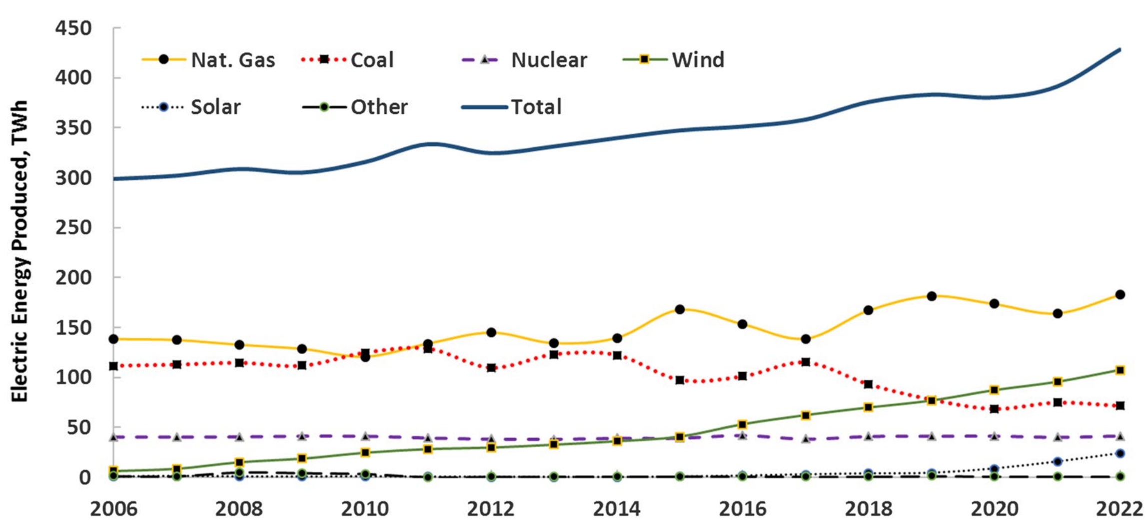

Fig. 1 Evolution of the primary energy sources for ERCOT in the period 2006–2022

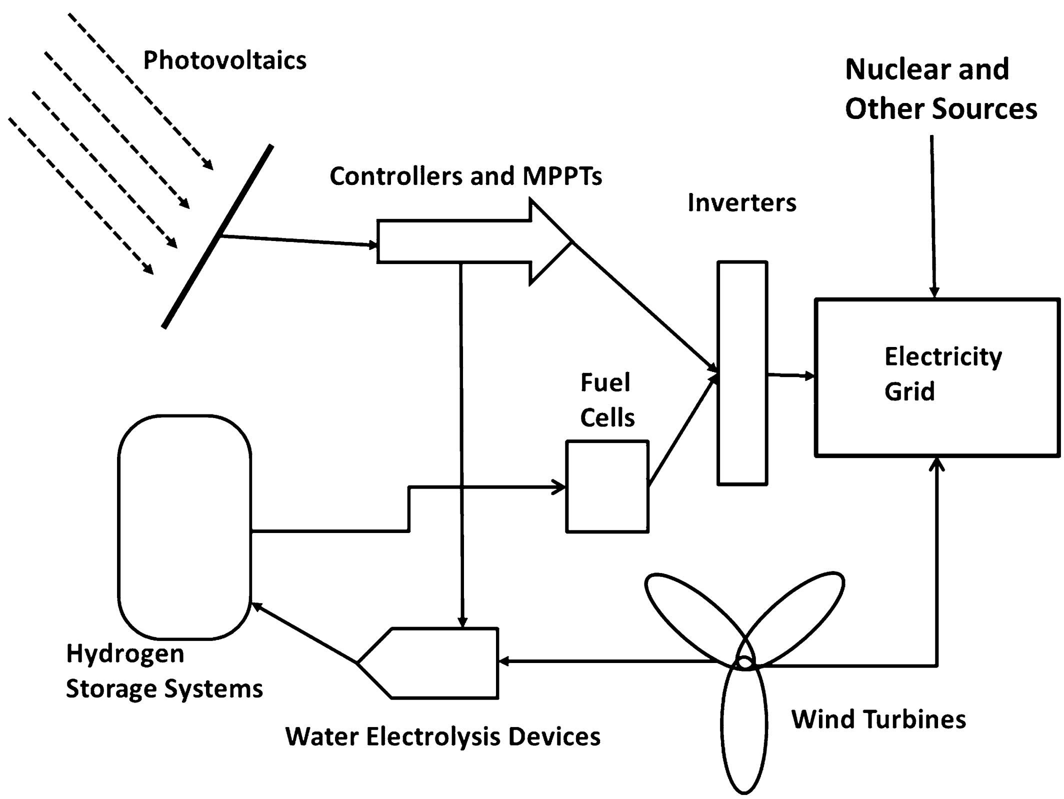

Fig. 2 Schematic diagram of the statewide system for the decarbonized electricity grid

energy and energy imports from neighboring regions, operate at will depending on the demand. Since the two renewable energy sources are diffuse (low energy density) the solar and wind farms are dispersed throughout the ERCOT region.

When there is sufficient demand in the grid to consume all the generated power, the power is directed to the grid. At low demand, any excess energy from the wind and solar farms supplies the water electrolysis systems, which produce hydrogen gas and store it under pressure. When the demand is high, hydrogen is fed to the fuel cells and supplied to the grid via dc-to-ac power inverters. The Maximum Power Point Trackers (MPPTs) and the Inverters ensure the optimum generation of power and supply to the grid.

Energy storage

The ERCOT region lies in the southwestern part of the USA between the foothills of the Rocky Mountains and the Mississippi Valley. With very small mountains and several hills, the area of the region is on a gentle slope facing east that induces the winds to flow from west to east. Because of this, the ERCOT region has excellent wind and solar resources. The region does not have the appropriate geographic characteristics (lakes at high elevation and large underground caverns) to develop pumped hydroelectric systems (PHS) and compressed air energy storage (CAES) systems (Michaelides, 2021a). The entire region has twenty-three very small hydroelectric power plants (with less than 15 MW total capacity) and the existing and potential dams are very small to facilitate significant energy storage. This leaves hydrogen and large-scale battery storage as the only options for grid-scale energy storage, which is very substantial. The use of large batteries entails supplies of vast quantities of minerals. In addition, the self-discharge issues of all batteries (Holtze, 2022) are a limiting factor, because it excludes the seasonal storage of power—e.g., storage during the high winds of the spring to be converted during the hot days of the late summer.

Since hydrogen is a stable chemical and abundant (in water), and the technology to generate and store energy is well known, hydrogen storage is very likely the only storage option in the ERCOT region. Hydrogen will be stored locally (at the dispersed generation facilities throughout the State) at the ambient temperature and approximately 50 MPa maximum pressure, in the calculations that follow. This is technologically feasible given that there are automobiles in the market with hydrogen tanks at pressures in the range of 30–70 MPa (Michaelides, 2018).

Governing equations

The energy transition model is based on the complete decarbonization of the ERCOT grid. With systems such as the one depicted in Fig. 2 distributed throughout the region, the model uses the pertinent energy balances to ensure that the hourly power demand is always satisfied. For this reason, an hour-by-hour energy balance computation was performed (for the 8760 h of the year 2022) using the hourly demand data in the ERCOT database (http://www.ercot.com/gridinfo/generation). On the supply side, the energy sources were hierarchically arranged in the following way:

A. The nuclear power plants operate continuously as base-load plants.
B. The wind and solar farms generate power during all times when this power is available. Part or all of this renewable power is instantaneously fed to the grid. Any excess power is stored.
C. Power from the "Other Sources," (which amounts to a maximum of 1,300 MW) is flexible and fed to the grid when the demand is high enough for the power from the nuclear, wind, and solar sources to be insufficient to satisfy the demand.
D. When all the power sources have been utilized, any excess demand is supplied by the stored hydrogen, using fuel cells and inverters.

For the hourly demand–supply simulation, the electric energy production/generation during the hour of the year, *i*, is:

$$E_{Pi} = E_{WPi} + E_{SPi} + E_{NPi} + E_{OPi} \tag{1}$$

where E denotes the electric energy; the subscript P denotes production; and the second subscripts $W, S, N,$ and O denote wind, solar, nuclear and others, respectively. The hourly generation of the additional wind and solar units has been calculated using the regionally averaged generation capacity, in MWh per MW installed, of the currently operational wind units and PV units in the ERCOT region.

At the same hour, i, the energy stored or recovered from storage is equal to the difference between the energy generated and the energy demanded by the grid:

$$\delta E_{Si} = E_{Pi} - E_{Di} \tag{2}$$

Energy dissipation (energy losses) is associated with the energy storage/recovery processes. The dissipation is taken into account in the computations by the efficiencies of the electrolysis process, η_{el}, and of the fuel cells, η_{fc}. The stored energy (energy storage level) in the next hour, the $(i+1)^{th}$ hour, is:

$$\begin{aligned} E_{Si+1} &= E_{Si} + (\delta E_{Si})\eta_{el} \qquad if \quad E_{Pi} \geq E_{Di} \\ E_{Si+i} &= E_{Si} - (\delta E_{Si})/\eta_{fc} \qquad if \quad E_{Pi} < E_{Di} \end{aligned} \tag{3}$$

where E_{Si} is the energy storage level at the previous hour, i. Equation (3) essentially determines the dissipation of the storage-regeneration process: Since electrolysis is an irreversible thermodynamic process, the quantity of energy stored as hydrogen energy is less than the available electric energy prior to the electrolysis. Also, since the fuel cells' operations are irreversible, more energy is extracted from the stored hydrogen than the demand–supply deficit.

The value η_{el}=75% is used in the simulations of this study (Mazloomi et al., 2012). Fuel cell efficiencies are currently in the range 60% < η_{fc} < 85% (US-DOE., 2006) and the value η_{fc}=75% is used in the simulation. The two values of the efficiencies have been chosen to be lower than the optimum efficiencies because they include the efficiencies of the auxiliary equipment, such as the maximum power point trackers (MPPTs), inverters and transformers (Haeberlin et al., 2006).

To ensure reliability, it is stipulated that the storage level in the entire system does not drop below a level that would enable the system to run on stored energy for at least ten days (240 h). If there is a generation system failure or major malfunction at any part of the grid—e.g., a summer hurricane or a severe winter storm that significantly affects or damages the renewable energy systems—then the grid operators will have the time to purchase enough hydrogen and import energy from another grid to ensure continuous electricity supply. As a result of this constraint, the minimum stored energy in the entire grid is significantly higher than zero at all hours of the year.

The following iteration process is used to solve the system of equations and constraints of this problem:

1. The additional installed wind and solar rated capacities are stipulated, in MW.
2. The storage system capacity on the first hour of the year, E_{S0}, is also stipulated, in MWh. The stipulated values in steps 1 and 2 emanate from previous experience. The results iteration converges fast enough for the first values not to be important in the overall convergence of the system.
3. The nuclear installations generate base load power at their rated capacity, 4,975 MW.
4. Based on the 2022 average wind and solar output in ERCOT (MWh/MW installed), the wind and solar energy generated is calculated for the hour *i*, using Eq. (1).
5. Based on the ERCOT 2022 hourly demand, the hourly energy surplus or deficit is calculated for the hour *i*, using Eq. (2)

6. In the case of a deficit, the "other sources" are activated.
7. If there is still an energy deficit, the deficit is supplied by stored energy.
8. Based on the results from steps 3 through 7 the quantity of the stored energy is calculated at the end of the hour i, using Eq. (3).
9. The stored energy at the end of the year, E_{S8760}, is determined and compared to E_{S0}, at the beginning of the year. If $E_{S0} < E_{S8760}$, the wind and solar generation capacity are increased, and steps 4–8 are repeated. If $E_{S0} > E_{S8760}$, the renewables generation capacity is decreased, and steps 4–8 are repeated, until $E_{S0} = E_{S8760}$. This iterative process determines the correct values of the additional wind and solar capacity.
10. A second iteration is performed to determine the correct value for previously stipulated E_{S0}. This iteration uses the constraint that, on the day of minimum energy stored, the entire system still contains enough hydrogen (stored energy) to satisfy the grid demand for the subsequent ten days.

Additional renewable capacity, storage, and dissipation

Calculations were performed to determine the additional renewable (wind and solar) generating capacity that would eliminate the primary CO_2 emission sources (coal and natural gas power plants). Given the current wind and solar energy capacity, Fig. 3 shows the additional capacity of wind and solar energy units to achieve the complete decarbonization of the ERCOT grid. Since either wind or solar energy or a combination of the two can be used for the decarbonization of the electricity sector, the algorithm presented above has infinite solutions. For this reason, a parametric study is performed to derive the combinations of the two energy sources that would achieve decarbonization: we use the solar contribution as a parameter and calculate the wind capacity that achieves this goal. Figure 3 shows the wind and solar power combinations that would substitute all the fossil fuel power plants in the ERCOR region, while keeping the nuclear capacity constant. It is observed in Fig. 3 that the addition of 98,470 MW wind power (with no additional photovoltaics), or the addition of 162,970 MW solar power (with no additional wind power), or a combination of the two (as depicted in Fig. 1) will result in the decarbonization of the energy generation sector in the ERCOT region. The combination that may be finally chosen will include both wind and solar energy and will be dictated by the minimum cost for the construction of the infrastructure. The slope of the curve is indicative of the lower average capacity factors of the solar installations (23.1%), as compared to the average capacity factor of the wind units, which is currently at 33.6%.

A glance at Fig. 3 proves that the installed capacity of solar and wind units is significantly higher than the fossil fuel capacity they would substitute. This is due to two reasons:

1. The average capacity factors of the wind and solar units are, in general, significantly lower than the capacity factors of the fossil fuel units (the latter may approach 100% if used as base-load units).

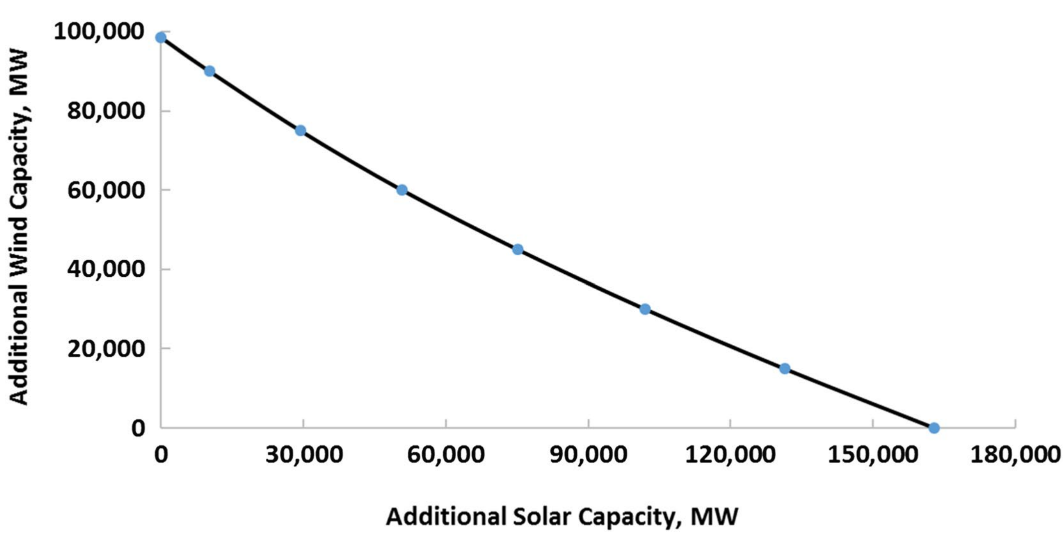

Fig. 3 Combinations of additional wind and solar energy power infrastructure needed for the decarbonization of the ERCOT system

2. The dissipation in the storage-regeneration processes, which necessitates additional energy generation.

It must be noted that the State of Texas has 695,662 km^2 of area that is prime for both wind and solar development: The northern and the coastal regions of the State experience winds with average velocities in excess of 23 km/hr (at 90 m height) and the average insolation on a horizontal surface is approximately 235 W/m^2, with some regions in the western part of the State exceeding 250 W/m^2. The addition of wind and solar power capacity, which is indicated in Fig. 3, is not going to be a problem for the region. The necessary additions to the wind and PV units become significantly lower and the needed storage is reduced if:

1. There is additional nuclear capacity by constructing more nuclear power plants in the State (in addition to the currently installed 4,975 MW) (Michaelides & Michaelides, 2020).
2. There is significant investment in conservation and higher efficiency on the part of the consumers that would reduce the demand (Michaelides, 2018).
3. Storage technologies advance and the round-trip of energy storage increases.

Figure 4 depicts the needed storage capacity (in m^3 of hydrogen at 30 °C and maximum pressure 50 MPa) as well as the expected annual energy dissipation in the storage/regeneration equipment. It is observed in Fig. 4 that the annual dissipation curve exhibits a minimum—at approximately 50 MW additional solar power and 60 MW additional wind. However, even at the minimum (calculated with $\eta_{el}=75\%$ and $\eta_{fc}=75\%$), the dissipated energy accounts for 10.1% of the total annual energy demand. The addition of the required storage capacity, indicated in Fig. 4, is currently technologically feasible, but will require significant investment for specialized storage tanks and hydrogen compressors. It must be noted that, given the highly diffused nature of wind and solar energy, the additional power and the storage capacity will have to be distributed throughout the ERCOT region and, preferably, close to the high demand sites—the cities of Dallas, Fort Worth, Austin, San Antonio and Houston—to mitigate transmission losses.

The necessary storage capacity and dissipation may be alleviated if ERCOT keeps the existing natural gas power plants (including the combined cycle plants) in operation (Leonard et al., 2019). However, this may not be an acceptable solution for the decarbonization of the electricity generating sector.

It must be noted that the CO_2 emissions avoidance from the coal-with-renewables substitution.

In the entire ERCOT grid is 125 million tons ($125*10^9$ kg of CO_2) or approximately 0.32% of the global CO_2 emissions in 2022. The substitution of all the fossil fuel power plants and the complete decarbonization of the ERCOT system will result in the avoidance of 225 million tons of CO_2 which corresponds to approximately 0.57% of the total global emissions in 2022 (Leonard et al., 2019).

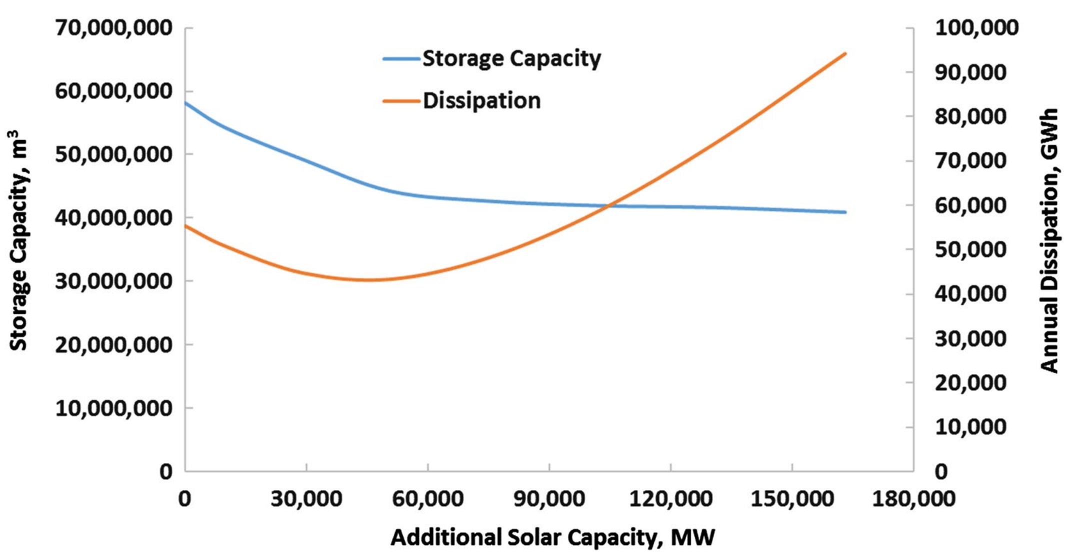

Fig. 4 Energy storage capacity and annual dissipation for the decarbonization of the ERCOT system

Necessary infrastructure

Based on results such as those in "Additional Renewable Capacity, Storage, and Dissipation" Section, it becomes apparent that significant infrastructure must be built, and additional investment must be made for the decarbonization of the power generation sector in the ERCOT electricity grid. The same also applies to all other electricity grids in the vast majority of the nations, except those with significant hydroelectric resources that may double as energy storage facilities. The following is a list of the necessary additions and investments for the decarbonization of the electricity generation sector:

1. Investment in new wind and solar units (and, perhaps, additional nuclear). As stated in "Additional Renewable Capacity, Storage, and Dissipation" Section, because of the difference in the capacity factors, the installed capacity of the wind and solar units is significantly higher than the capacity of the decommissioned fossil-fuel units.
2. Investment in the auxiliary devices and equipment that connect the renewable units to the grid, such as MPPTs, inverters, transformers, etc.
3. Investment in energy storage and regeneration equipment—electrolysis equipment, hydrogen tanks, hydrogen pressurizers, fuel cells, etc.
4. Decommissioning of most fossil fuel units and cleanup of their sites.
5. Maintaining a number of gas turbines for reliability and emergencies.
6. Securing the land to install the new solar, wind, and storage units.

Implications for energy prices and sustainability goals

Energy balances and the calculations that follow them (as in "The System for Decarbonized Electricity Generation" and "Additional Renewable Capacity, Storage, and Dissipation" Sections) are derived from the principles of thermodynamics, which are natural and immutable laws. On the other hand, prices and costs are derived using theories of economics, a social science, which is founded on empirical principles. Prices and costs are not permanent and vary significantly with time. They strongly depend on the time of observations and the type of economy: the energy pricing mechanisms are different in free-market economies, regulated economies, and centrally planned economies. As a result, the cost of energy systems, and the cost of energy to the consumers, exhibit a very high variability and are laden with significant uncertainty. The often-quoted crude oil prices and the gasoline prices paid by the consumers are examples of the cost variability (Michaelides, 2021c). For this reason, one must be cognisant that future prices and costs are simply estimates with high variability and uncertainty, rather than accurate calculations, and should be treated qualitatively.

Two complications arise when estimating future electricity prices from the current economic environment: Subsidies and unrealized costs. At present, renewable energy is subsidized in most countries. Excise taxes and carbon taxes supply the revenue for these subsidies. When the transition to renewable energy is completed, excise taxes on fossil fuels and the carbon tax revenue will disappear. The renewable energy subsidies are scheduled to phase out. This includes the ERCOT region, where the current governmental (Federal and State) subsidies are $23 per MWh and (when combined with certain private and non-profit organization subsidies) may exceed $34 per MWh. In 2025, the tax credits for wind will be replaced with technology-neutral credits for low-carbon and zero-carbon electricity generation, which in turn are slated to phase out in 2032, or when U.S. power sector greenhouse gas emissions decline to 25% of their 2022 levels (https:, , windexchange.energy.gov, projects, tax-credits. xxxx; Rhodes, 2019). The second complication is that most of the current studies on prices and costs calculate the cost of electricity from coal and natural gas by including a "social cost" or a "cost for carbon abatement," or the "environmental" costs for the clean-up of CO_2, and other pollution products (Lazard's levelized., xxxx). However, these costs are not born by the electricity generation corporations in the ERCOT region (and the entire USA). Therefore, it is not realistic to apply such costs to the balance sheets of these corporations as costs that are passed by the generators to the consumers.

Effect on electricity cost and prices

The average retail price of electric energy paid by the residential sector in the ERCOT region in 2022 was $0.1197/kWh of which approximately $0.045/kWh was the cost of distribution (U.S., 2023). The total price for the commercial sector was $0.1094/kWh and for the industrial sector the total price was $0.0825/kWh, significantly lower than the price for the residential sector. The residential average prices in ERCOT are lower than the average USA electricity prices and significantly lower than the residential prices in most of the other industrialized countries (International Energy Agency, 2019b; U.S., 2023). The low electricity prices help residents, especially those with low incomes, afford AC systems that are now necessary in all households and businesses.

A glance at "Necessary Infrastructure" section on the necessary infrastructure proves that the transition of the electricity generation sector in the ERCOT region to renewable energy entails significant costs, chief of which are the costs for generating units and energy storage (Zakeri et al., 2015). In a market-oriented economy these costs will be passed to the consumers. The complete transition of the electricity generation sector to renewables will have the following effects for the society:

1. The CO_2 emissions of the electricity generation industry in Texas will plummet—a very desirable societal effect.
2. The quantity of the generated electric energy will increase because of the dissipation in the storage-regeneration process. While not desirable, this effect can be accommodated by the society at large.
3. The price of electricity in the region will increase because of the costs associated with the infrastructure outlined in Sect. 5—a very undesirable societal effect.

If all the currently operating fossil-fuel units are decommissioned and when the renewable subsidies are faced out (in 2032), the estimates of the future electricity price for the consumers are in the range \$0.35/kWh-\$0.44/kWh (Ferreira et al., 2018; Hoffmann, 2006; Zakeri et al., 2015). Given the enormity of the undertaking for the decarbonization of the ERCOT system, this price range is reasonable and agrees with the estimates of this and other authors (Michaelides, 2021b). This estimate represents a significant increase in the current retail electricity prices in the residential sector (by a factor between 2.9 and 3.7). The estimate is also in line with the current electricity prices paid in several countries (e.g., Germany and Denmark), which generate a high fraction of their electricity by renewables and use only a limited amount of energy storage.

Effect on incomes and sustainable development goals

The principle of sustainable development is "the ability of a society to ensure that it meets the needs for the present, without compromising the ability of future generations to meet their own needs" (http://www.un-documents.net/our-common-future.pdf). Within the guidelines for sustainable development, the U.N. General Assembly approved the Sustainable Development Goals (SDGs), a set of seventeen goals that are recommended for the drafting of national developmental plans and policies (https://sdgs.un.org/goals). The goals are interconnected, and one may see the relevance of affordable and readily available energy in most of the SDGs. The following two goals are directly connected with the global electric power generation industry:

1. Ensure access to affordable, reliable, sustainable, and modern energy for all.
2. Take urgent action to combat climate change and its impacts.

Because energy availability and costs determine the broader economic development of nations, the following two goals are directly related to the affordable energy supply:

3. End poverty in all its forms everywhere.
4. Reduce inequality within and among countries.

In the case of the ERCOT region—as well as similar regions everywhere on earth—the significant rise of the residential electricity prices will have a profound effect on the population, especially during the hot summer months, when the electricity consumption peaks. If electricity prices increase by a factor between 2.9 and 3.7, residents in the low-income brackets will not be able to afford AC and this will become a health hazard for most, especially the older and the infirm. Spending more of their disposable income on electric energy will multiply the effects of poverty in this income bracket—an impediment for the achievement of the 3rd SDG. Residents in the intermediate income brackets will spend a significantly higher fraction of their incomes on electricity. This will leave them with substantially less disposable income and a fraction of them may be relegated to the poverty brackets. High-income residents will be able to afford the higher prices with a relatively small reduction of their disposable income.

The reduction of the disposable income of their residents will also have a detrimental effect on the regional and national economies of developing nations. Lesser disposable income is associated with recessions, economic contraction, and unemployment – three undesirable societal effects (Samuelson & Nordhaus, 2009). The more severe contraction of the economies in the developing nations will increase the economic gap between rich and poor nations—an impediment for the achievement of the 4th SDG, above.

Unless technological innovations and cost reductions are achieved for much cheaper wind and solar energy as well as cheaper storage systems, with a fully decarbonized electricity sector, the cost of energy will increase. It will become more difficult for the less affluent citizens to enjoy the comfort of AC at home and advanced mechanization at work. Consequently, the reduction of the poverty goal in all its forms may suffer. An additional effect on the economies of nations is that, as a result of the reduction of the disposable income of a large fraction of their populations, other economic sectors will experience contraction and national economies will shrink (Samuelson and Nordhaus, 2009).

Higher electricity prices may lead to energy conservation and demand reduction that would partly mitigate the effects of price increases. One must consider, however, that electricity as well as most energy forms are necessary goods and their price elasticities are very low. In addition, energy-saving projects—e.g., increasing the buildings' insulation and the installation of more efficient AC units—are capital intensive and are not readily afforded by citizens in the lower income brackets. As a matter of policy, societies that progress toward a "greener" mix for electricity generation, should ensure that low-interest loans and energy subsidies become available to homeowners and consumers in the lower income brackets for energy conservation measures.

The correlation of higher electricity prices with income inequalities is similar to the effect of electricity price climbing as an effect of carbon taxes. Two recent studies on this subject (Goulder et al., 2019; Williams et al., 2015) calculated the effects of a possible carbon tax on incomes in the USA assuming that all the tax revenue is returned (recycled) to the citizens in one of three ways: (a) as lump-sum payments to the lower incomes; (b) as capital tax relief; and (c) as labour tax relief. Table 1 shows these effects on the citizens that fall in five income quintiles (Goulder et al., 2019) with the 1st quintile being at the lowest income and the 5th quintile the highest income.

It is observed in Table 1 that if the carbon tax is not fully recycled back with direct payments to the lowest income citizenry, the increase of the energy prices will have a negative effect on the citizens in the lower three income quintiles. If it is recycled as capital tax rebate, only the wealthier classes benefit and, if it is recycled as labour rebate, all income quintiles suffer. The same conclusion was reached in Williams et al. (2015), whose authors determined that anything other than lump-sum rebates to the lower income citizens would have the effects of a regressive taxation. The societal effects are analogous to price increases following the substitution of fossil fuels with renewables, which is designed to promote the decarbonization of the electricity generation sector. Such price increases must be accompanied by public policy measures that protect the lifestyles of the less-affluent citizens. At the international level, it must be ensured that the decarbonization of the electricity sectors will not increase the gap between affluent and developing countries.

Table 1 Effect of a carbon tax with three kinds of tax recycling in the USA (Goulder et al., 2019)

Quintile	1st	2nd	3rd	4th	5th
Lump-Sum rebate	3.36	1.29	0.3	−0.46	−1.93
Capital tax rebate	−0.87	−0.73	−0.57	−0.43	0.14
Labour rebate	−0.28	−0.15	−0.18	−0.21	−0.45

Conclusions

The ERCOT region in Texas is a large region that, if it were independent, it would have been ranked 7th globally in electric energy generation and consumption. Any system that may be employed for decarbonization in this big market may be applied to other electricity markets around the world. The state is very rich in wind and solar power resources. For this reason, a generation system that derives energy from the wind and solar resources has been proposed for the decarbonization of the electricity sector. This transition is technologically feasible but would require significant capital investment for new wind and solar units (and probably nuclear units too). In addition, investment for energy storage and regeneration—two expensive and irreversible processes—is needed. The effect of this type of investment in a free-market economy is to increase the cost of electricity for the generation corporations by a factor between 2.9 and 3.7. Since in a free-market economy this cost will be passed to the consumers as a price hike, decarbonization will have a disproportionate effect on the less affluent part of the population, which will have less disposable income, thus increasing the poverty and the inequalities among the citizens in the region. To reduce inequality within the State in accordance with U.N. sustainability goals, together with the investments in renewable power generation, energy subsidies for lower-income citizens should also be introduced as public policy measures.

Nomenclature

Symbols

E	Energy
δE	Energy surplus or deficit
η	Efficiency

Subscripts

el	Electrolysis
fc	Fuel cell
i	Pertains to hour *i*
NP	Nuclear production
S	Storage
SP	Solar (photovoltaic) production
WP	Wind production

Abbreviations

AC	Air conditioning
ERCOT	Electricity Reliability Council of Texas.
GCC	Global Climate Change
GHG	Green House Gases
MPPT	Maximum Power Point Tracker
PV	Photovoltaics

SDG Sustainable Development Goal

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