

Energy Trade-Offs in Texas: A Multi-Pillar Life Cycle Assessment of Natural Gas and Solar-Plus-Battery Systems

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Executive Summary

This report presents an integrated life cycle analysis comparing two power-generation systems in Texas—a conventional natural gas plant and a renewable solar installation with battery storage—from environmental, economic, and social perspectives. The study aims to inform policy and investment decisions by examining the full lifecycle impacts of each system, ranging from material extraction and capital investment to operational performance and end-of-life disposal. In doing so, it highlights key trade-offs among the three sustainability pillars.

Natural gas plants exhibit lower upfront costs and benefit from time-tested extraction and operational processes. However, they concentrate greenhouse gas emissions during electricity production and contribute significantly to air pollution. This not only increases health risks for local communities but also drives measurable out-migration. Conversely, solar-plus-storage systems, though placing higher burdens in the material extraction phase (notably due to lithium processing) and incurring greater water and capital costs, generate far cleaner emissions overall. The evolving nature of renewable technology—coupled with potential improvements in recycling practices—suggests that these environmental impacts could decrease in the future.

Using a life cycle costing (LCC) approach, I found that natural gas displays lower investment and operational costs relative to its renewable counterpart. However, when additional externalities such as the value of lost load (the economic cost of power interruptions) are included, the cost gap widens further in favor of natural gas. Despite this, the long-term economic viability of renewables is poised to improve through policy measures, technological advancements, and the economies of scale that could lower both extraction and operational costs over time.

The social life cycle analysis (S-LCA) illustrates a nuanced picture. Natural gas facilities, while offering stable and higher-paying jobs (15–20 jobs per MW), expose workers and local residents to hazardous conditions that have been linked to substantial health risks and population declines (up to 5% reduction over a decade). In contrast, solar plants with battery storage foster healthier local environments that can attract new residents—albeit with fewer permanent jobs (8–12 per MW) and a pressing need for workforce reskilling. This dynamic underscores the broader community benefits of renewables in terms of improved air quality and livability.

No single system emerges as unequivocally more sustainable across all three pillars. The natural gas option offers economic and employment advantages but is burdened by significant environmental and health costs. Renewables show strong environmental and social promise but currently face higher financial barriers and require strategic workforce transitions. Key lifecycle stages—such as raw material extraction for batteries and the operational phase of natural gas plants—drive these disparities. Additionally, data quality limitations and variability in measurement methods were addressed through qualitative triangulation and cross-referencing of reputable sources. Ultimately, the path toward a sustainable energy future in Texas must balance these trade-offs. Policy interventions that incentivize cleaner technologies, promote

recycling innovations, and support reskilling programs are critical to mitigating the burdens observed in both systems. This balanced approach is essential to optimize environmental performance, economic feasibility, and social well-being in the evolving energy landscape.

Goal

The purpose of this comprehensive Life Cycle Assessment (LCA) is to evaluate, compare, and integrate the full spectrum of impacts associated with two contrasting energy generation systems in Texas: a renewable solar installation with battery storage versus a conventional natural gas plant. By examining environmental outcomes, life cycle costs, and social implications over the complete lifespan of each system, this study seeks to inform policymakers, investors, and other stakeholders about the trade-offs and benefits inherent in the choice between renewable and fossil-fuel based electricity generation. Although there are inherent limitations—such as a non-peer-reviewed environmental methodology and measurement uncertainties in quantifying distributed, long-term impacts—the intent is that the relative magnitudes of these impacts provide a robust, comparative framework for strategic decision-making in power plant investments.

Scope

The scope of this study focuses on two energy generation systems—the conventional natural gas power plant and the renewable solar installation with battery storage—designed to supply electricity to meet the load of a specific region in Texas. The functional role of both systems is to reliably generate and deliver power to the grid, and the analysis is anchored on a quantifiable metric: variable of interest per megawatt-hour (MWh_e), which serves as the functional unit. The boundaries of the study encompass all life cycle stages, beginning with the extraction and transportation of raw materials, continuing through the manufacturing, construction, and operational phases, and concluding with the end-of-life management and decommissioning of both systems. This delimitation ensures that all relevant processes, inputs, and outputs are captured, providing a comprehensive basis for comparing the environmental impacts of fossil-fuel versus renewable energy systems.

Environmental Life Cycle Analysis

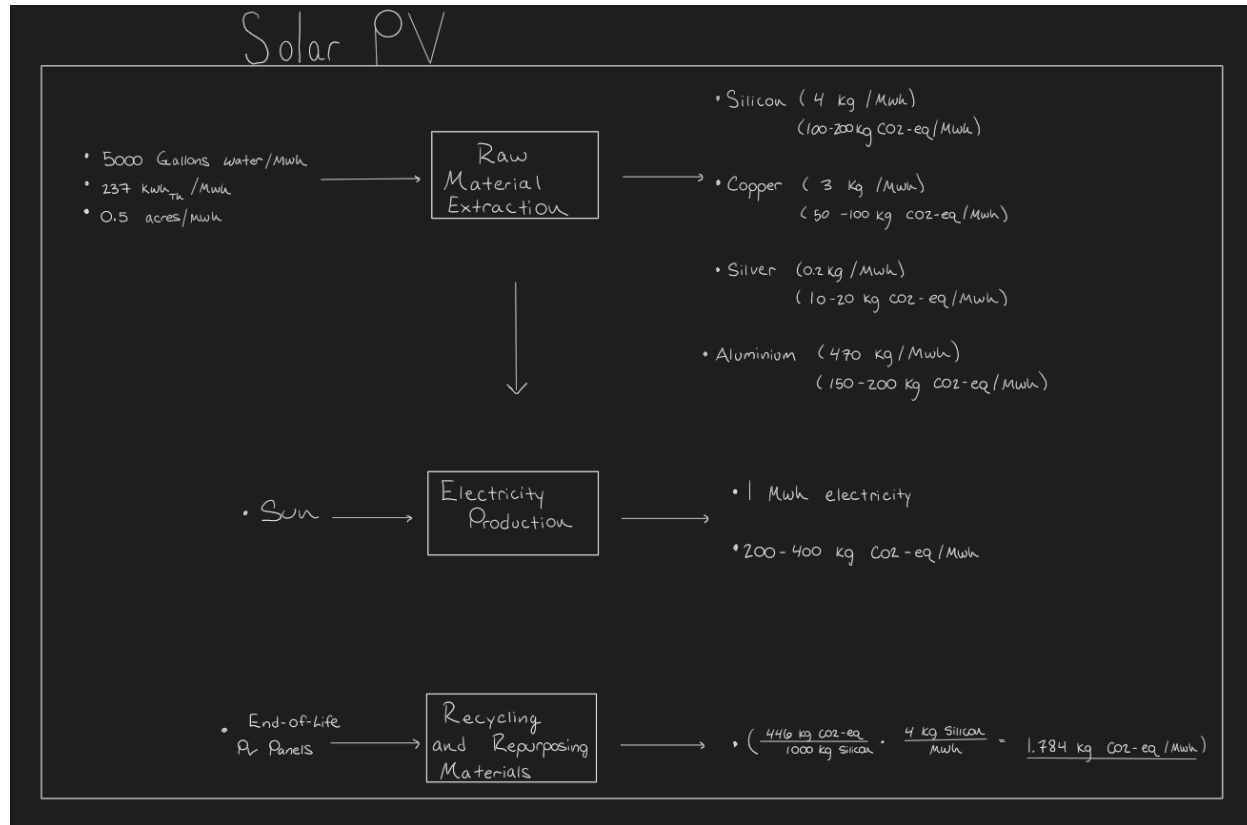


Figure 1

Raw Material Extraction

The metals are extracted using individual mining processes from various feedstocks. Silicon is extracted from quartzite sand using 1.2 KWh Thermal/MWhe and involves a series of chemical reactions and purification steps (IEA, 2021). Copper is extracted from copper ore through various separation and refining processes (NREL, 2023). Silver is obtained from silver ore via smelting and other chemical treatments—often alongside associated metals like lead, copper, and zinc that require further separation (NREL, 2023). Aluminum is extracted from bauxite ore using the Bayer process followed by electrolysis (NREL, 2023). Altogether, these extraction processes consume about 5,000 gallons of water per MWhe and occupy roughly 0.5 acres per MWhe.

Electricity Production

Once the metals are extracted, and panels are constructed and operational, the solar array can begin harnessing the Sun's energy. The incoming sunlight is absorbed by the panel. The photons from the sunlight excite the electrons in the silicon solar cell and those electrons are then transported along the silver and copper wires and out into the utility scale energy grid (SPN, n.d.). The outputs of this system are the functional unit of 1 MWH and a range of 200 - 400 kg CO₂-Eq/MWH. It is important to note that typical solar panels are designed for an operational life of approximately 25–35 years, producing a substantial volume of clean energy

over their lifespan. This long-term energy generation is a critical factor in offsetting the initial environmental inputs from extraction and manufacturing.

Recycling and Repurposing Material

At the end of its useful life, a solar panel is disassembled to recover valuable materials. The aluminum frame and housing are removed and recycled separately, and the glass—comprising roughly 75% of the panel by weight—is separated from the silicon cells using mechanical or thermochemical processes (EPA, 2024). Technically, more than 85% of a solar panel's materials are recyclable (SPN, n.d.). However, actual recycling rates remain low in many regions because a comprehensive federal policy mandating solar array part recycling is absent; instead, recycling is often driven by state-level initiatives or left to the discretion of plant operators (IEA, 2021). In regions without mandates, panels may be disposed of in landfills, which can lead to environmental issues such as hazardous substance leaching and the loss of recovered materials that could mitigate new production impacts (EPA, 2024). Additionally, thermochemical recycling of silicon produces about 446 kg CO₂-Eq per 1,000 kg of silicon—equating to roughly 1.8 kg CO₂-Eq per MWh (EPA, 2024). Overall, the substantial clean energy production over 25–35 years plays an essential role in diluting the environmental costs associated with manufacturing and end-of-life processing, thereby strengthening the sustainability case for solar-plus-storage systems.

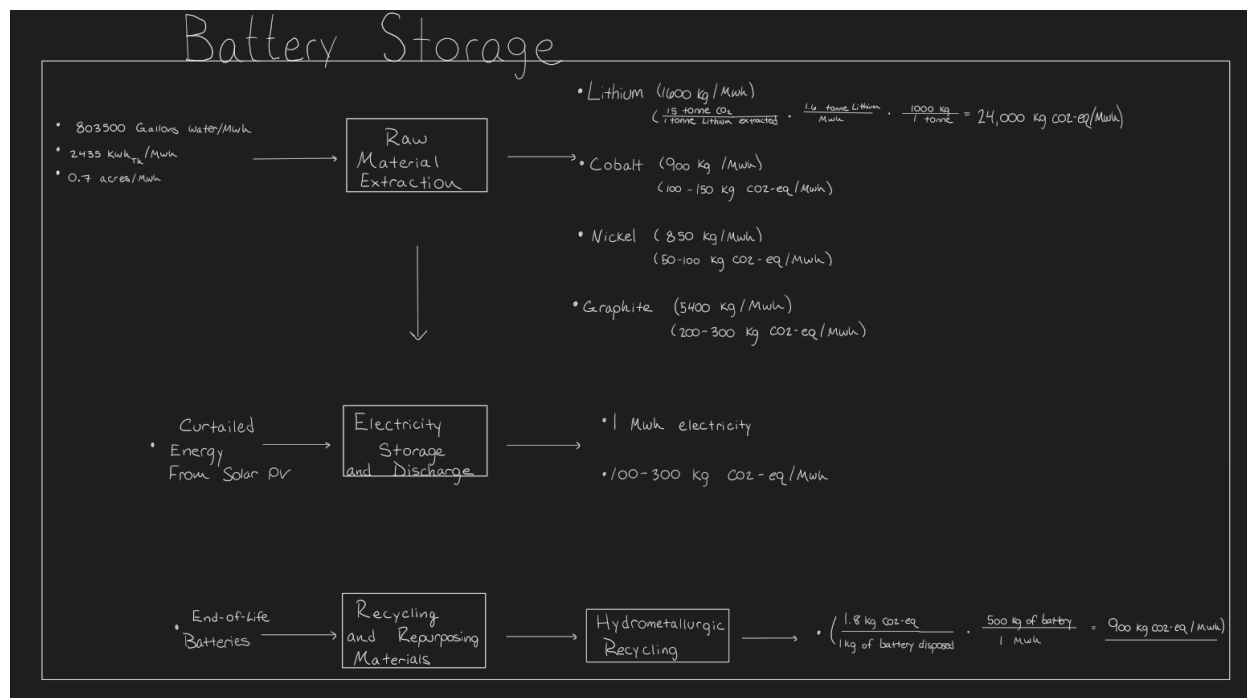


Figure 2

Raw Material Extraction

Lithium, Cobalt, Nickel, and graphite are mined using similar methods to that of the metals in PV cells. They consume up to 803,500 gallons of water/MWHe (UMASS, n.d.). Lithium takes the most amount of water with upwards of 500,000 gallons per ton (UMASS, n.d.). This is largely

due to the fact that lithium is found in water-like slurries in the subsurface (UMASS, n.d.). The combined mining procedures also demand 2345 KWH Thermal/MWHe and 0.7 acres/MWHe. The mined metals are 1600 kg/MWHe, 900 kg/MWHe, 850 kg/MWHe, and 5400 kg/MWHe for Lithium, Cobalt, Nickel, and Graphite respectively. The extraction process releases a combined 24,550 kg CO₂-eq/MWHe (IER, 2023).

Electricity Production

The idea of hybrid solar is to use any curtailed energy from the solar panel production, usually in the peak hours of the day, and send it to charge the battery. Then, when solar is no longer able to produce (no sun), the stored energy in the battery is discharged to meet demand (NREL, 2022). This process produces 1 MWHe of electricity (our functional unit) and at the high end, produces 300 kg CO₂-Eq/MWHe.

Recycling and Repurposing Material

The end-of-life batteries are recycled using hydrometallurgical processes that allow them to recover a fraction of the critical metals from the batteries (Phung, 2020). The most notable byproduct of this process is 900 kg CO₂-Eq/MWHe.

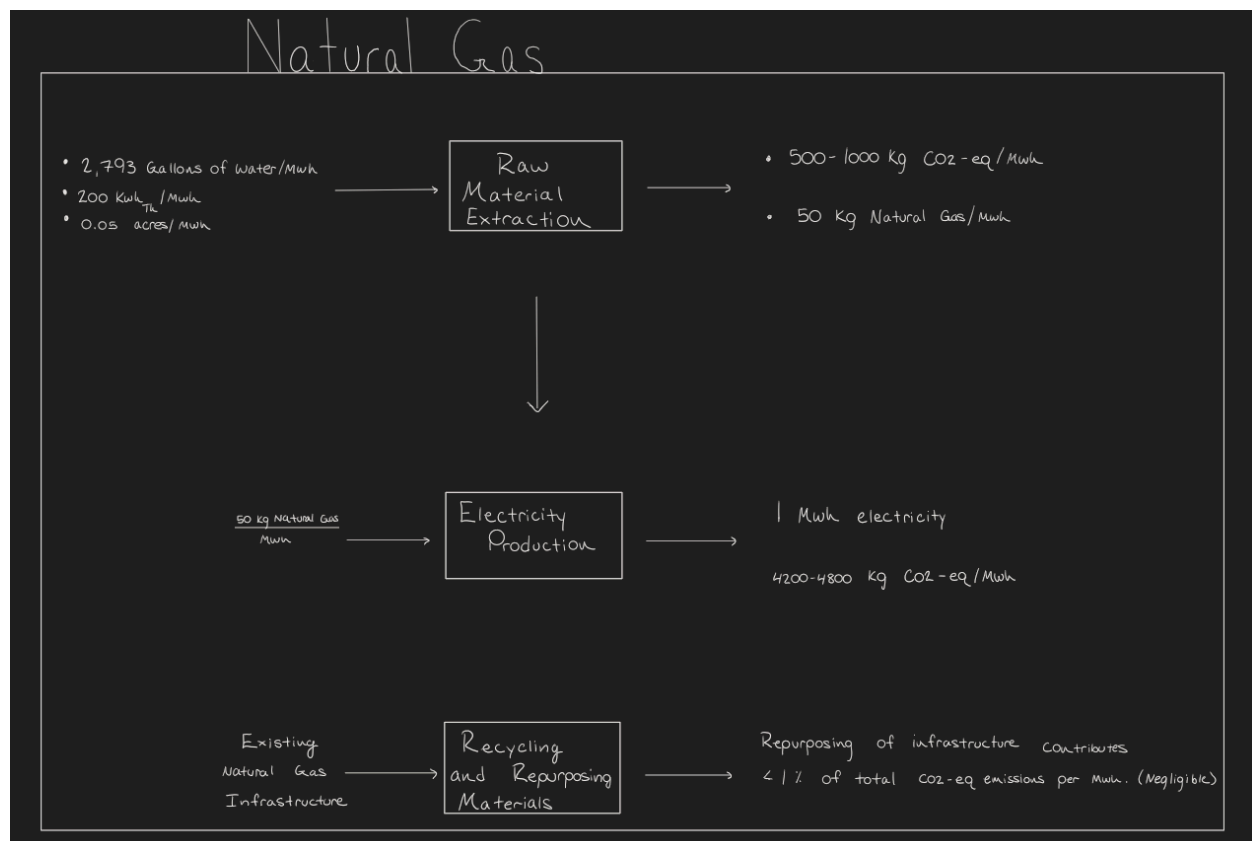


Figure 3

Raw Material Extraction

Natural gas is conventionally extracted from permeable rock formations where it is trapped under a layer of impermeable rock. The process begins with drilling a well into the gas reservoir.

Once the well reaches the gas deposit, the natural gas flows to the surface due to the pressure difference (EIA, 2024). This process consumes up to 2,793 gallons of water/MWhe, 200 KWH Thermal/MWhe, and takes up about 0.05 acres/MWhe. Once purified, dry natural gas enters the pipeline, and the separated natural gas liquids are sold as valuable byproducts (EIA, 2024). The extraction process in total creates up to 1000 kg CO₂-Eq/MWhe and natural gas in the amount of 50 kg/MWhe (EIA, 2025).

Electricity Production

Once the natural gas has entered the pipeline, it can be transported to the power plant and is ready for use. The 50 kg Natural Gas/MWhe is fed into the system and out comes the 1 MWhe (our functional unit once again). In addition to the electricity, the plant also produces up to 4800 kg CO₂-Eq/MWhe (EIA, 2025). In new natural gas plants, there are mechanisms in place to reduce these emissions, but for the majority of pre existing plants, the upper threshold of emissions is reached (Utility Smarts, n.d.)

Recycling and Repurposing Material

Natural gas plants are in a unique position to be repurposed and remain resourceful well beyond their life producing electricity. In total, the greenhouse gas emissions attributed to end of life management are less than 1% of the emissions over the total lifespan of the system (EPA, 2025).

Environmental Life Cycle Impact Assessment

Climate Change

The midpoint impact category of climate change is significantly influenced by the CO₂ emissions from both the solar farm with battery storage and the natural gas power plant. For the solar farm, the CO₂ emissions are relatively evenly distributed across the lifecycle stages, with the raw material extraction, electricity production, and recycling phases contributing to the overall emissions. Specifically, the solar farm produces between 200-400 kg CO₂-Eq/MWhe during electricity production and an additional 1.8 kg CO₂-Eq/MWhe during the recycling phase (UNEP, 2011). Still on the renewable front, battery storage contributes a massive amount of CO₂ emissions in the raw material extraction. This happens specifically with lithium extractions, contributing up to 24,000 kg CO₂-Eq/MWhe. Lithium extraction single handedly makes battery storage the biggest climate exchange contributor per MWhe (UMASS, n.d.). In contrast, the natural gas power plant has a more concentrated impact during the electricity production phase, emitting up to 4800 kg CO₂-Eq/MWhe (EIA, 2024). The extraction phase also contributes significantly, with up to 1000 kg CO₂-Eq/MWhe (EIA, 2024). These figures highlight that while the solar farm has a more distributed emission profile, the paired battery storage makes this system the top contributor to climate change across all three stages. The natural gas power plant's emissions are heavily concentrated during electricity production, making it a more significant contributor to climate change in this phase.

Water Usage

Water usage is another critical midpoint impact category, particularly during the raw material extraction phase. The solar farm's battery storage system is notably water-intensive, consuming up to 803,500 gallons of water/MWhe, primarily due to lithium extraction (UMASS, n.d.). In comparison, solar panel production consumes 5,000 gallons of water/MWhe (UNEP, 2011). On the other hand, the natural gas power plant's water consumption is significantly lower, with up to 2,793 gallons of water/MWhe during the extraction phase (EIA, 2024). This stark contrast underscores the substantial water footprint associated with battery storage in solar farms, making it a critical area for potential environmental impact mitigation. The natural gas power plant, while less water-intensive, still contributes to water usage but to a much lesser extent compared to the battery storage system in the solar farm.

Interpretation

From the analysis in Phases 2 and 3, it is evident that while natural gas power plants contribute significantly to environmental impacts during the electricity production phase, the full life cycle analysis reveals that the solar farm with battery storage appears as the top emitter per MWhe—primarily due to the extensive water usage and CO₂ emissions associated with lithium extraction in battery production. However, this figure can be misleading. Renewable systems currently represent a much smaller share of total energy generation compared to natural gas, and their overall contribution to national emissions is correspondingly lower. Furthermore, the renewable sector is in a phase of rapid technological innovation; as economies of scale and improved recycling practices boost efficiency and reduce resource-intensive extraction processes, the environmental impacts per MWhe could decline substantially over time. Thus, while the current analysis indicates higher per-unit emissions for renewables under the existing technological framework, there is significant potential for future impact mitigation that would enhance the sustainability of solar-plus-storage systems.

Completeness of the Study

The study is relatively complete, with no major data missing. Equivalent CO₂ emissions were found for all stages of the life cycle analysis for both systems, allowing for a straightforward comparison of their long-term environmental impacts. Additionally, data on raw material extraction, land use, and water usage were readily available in terms of the functional unit. However, this report is missing an analysis of the frequency of thermal runaway explosions in utility-scale battery systems and the calculation of per MWhe emissions of hydrogen fluoride from these explosions. These explosions can cause significant respiratory problems for nearby communities. According to the EPRI BESS Failure Incident Database, the global grid-scale BESS failure rate has dropped 97% between 2018 and 2023 (EPRI, 2024). Hydrogen fluoride emissions are a concern due to their potential health impacts (EPA, 2024).

Limitations

The study has several limitations that directly impact the interpretation of our results. Firstly, the analysis has not undergone a rigorous peer review process, meaning the conclusions are preliminary and should be interpreted with caution. Secondly, the study does not employ the formal Life Cycle Impact Assessment (LCIA) methods, which restricts direct comparability with

other studies. While experimental data provide estimates for the resource requirements to produce a solar panel or battery system capable of delivering 1 MWh_e, precise values for CO₂ emissions and water usage remain uncertain—particularly in regions where raw materials are extracted. Furthermore, the variability in extraction methods and end-of-life management approaches for photovoltaics, batteries, and natural gas introduces additional uncertainty. Importantly, these methodological and data limitations also affect the study’s outcomes; for example, if evolving battery recycling practices were incorporated into the analysis, they might reduce the net environmental impact of solar-plus-storage systems, potentially shifting the balance in favor of renewable over fossil-fuel-based power generation. A more comprehensive study, encompassing diverse extraction, manufacturing, recycling, and disposal practices, would offer a clearer picture of the true environmental sustainability of these systems.

Review Responses

Comments	Responses
Peer Comment: “what percentage of solar array parts end up recycled? Is there a policy stating that these parts must be recycled, or is it a choice made by the plant? If the parts are not recycled, could you speak to what impacts arise from other disposal methods? How much energy can be generated before end-of-life stages take place? This could affect the overall sustainability you conclude.”	This suggestion was right on the money. Studying the energy industry in my undergrad, I figured the lifespan of power systems and overall energy production were implied. To take a step back and add them in really adds to the analysis. I revised the section to directly connect recycling practices with overall sustainability. I now specify that while more than 85% of a solar panel’s materials are technically recyclable, the actual recycling rate is low due to the lack of robust federal policies—recycling is often left to state-level programs or individual plant decisions. I also addressed the implications of alternative disposal methods (e.g., landfilling) and their associated environmental risks, such as hazardous substance leaching. Finally, I added a note on the typical operational lifespan (25–35 years) and its significance in offsetting upfront environmental impacts through long-term energy generation.
TA Comment: “I would have liked to see you connect your limitations more directly to how they affect the interpretation of your results. For instance, could accounting for evolving battery recycling practices shift the balance in favor of solar + storage?”	I loved this suggestion by my TA. I adjusted the original limitation section by explicitly linking each limitation to its impact on the study’s results. In particular, I introduced a sentence highlighting how evolving battery recycling practices could potentially lower lifecycle emissions for solar-plus-storage

	systems, thereby altering the comparative analysis. This connection definitely strengthens the relationship between the limitations and the overall interpretation of the findings.
Self Comment: Looking back on this section, I want to expand on my interpretation by including the nuance that is found within these two systems. That while the renewable system is the largest contributor to CO2 emissions/MWhe, that is a misleading figure. The penetration of Renewables far less than natural gas, and there is still plenty of room for tech advancements and environmental impact mitigation as the energy tech begins taking advantages of the innovation through economies of scale.	To remedy this, I expanded the interpretation to acknowledge the nuance that, although the renewable system currently shows higher CO ₂ emissions per MWhe due to lithium extraction and water usage, this measurement can be misleading. I highlighted that the lower overall penetration of renewables in today's energy mix, along with the significant potential for technological advancements and economies of scale, may greatly reduce these impacts in the future.

Life Cycle Costing Analysis

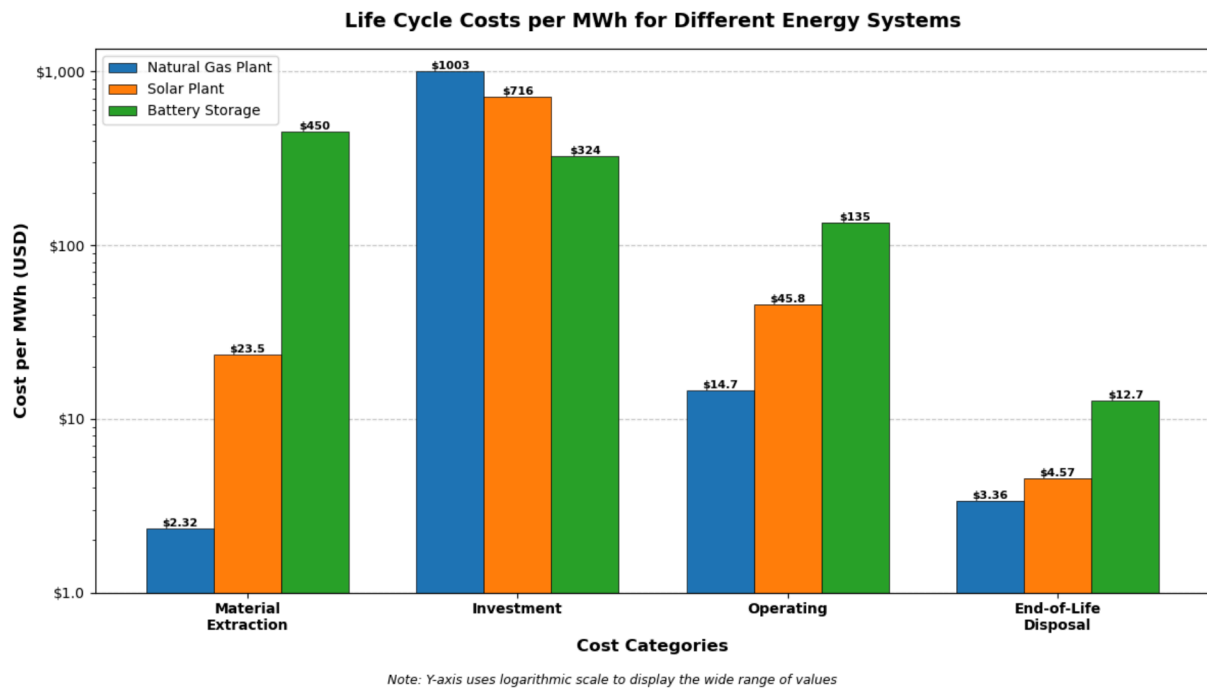


Figure 4

I have chosen four different life cycle impact categories: Material Extraction, Investment, Operating, and End-Of-Life. The costs associated with these main four categories encompass all the important costs throughout the life cycle of the systems being explored. I have chosen to show battery storage and solar as separate entities to better understand the interplay in cost

and impact between the two. By lumping them together in one number, it becomes difficult to figure out the distribution of cost and impact between the two inner systems. Note that the y-axis is on a logarithmic scale of price to create a better visual for the reader. Do not mistake size for closer comparison, as the disparity is not to visual scale.

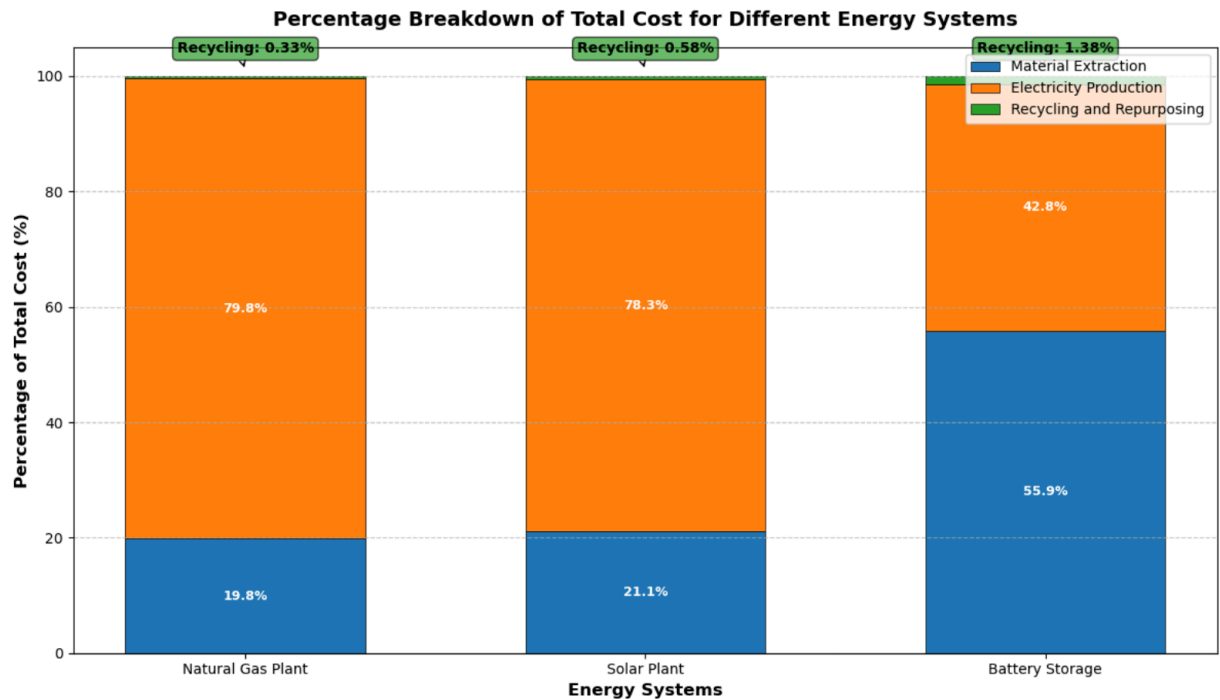


Figure 5

Material Extraction

The material extraction phase is dominated by the cost of battery storage components, specifically silicon, at \$450/MWhe (Cole et al., 2023). Then comes solar, with an emphasis on raw materials for photovoltaic cells at \$23.52/MWhe (Ramasamy et al., 2023). Natural gas has the most cost-effective extraction at this time, with only \$2.32/MWhe (EIA, 2025). Some key considerations are the well-established extraction methods that have been studied for many years for natural gas, while mining for the critical metals, at the scale necessary to support a growing renewable portfolio, has not had enough time to take advantage of economies of scale. Nonetheless, the material extraction phase is a story dominated by the cost intensity of renewables.

Investment

The cost of investment is usually reported on a per MW or per KW basis. This is because the cost of investment is set by the nameplate capacity of a power system, not how much power they actually produce in a given time frame. With that being said, I made the assumption of a one-hour time frame that would essentially multiply the start-up cost by 1, going from per MW to per MWhe, which is the functional unit I have chosen. We see a shift in the cost dynamic when it comes to the investment cost. Our natural gas requires more capital per MWhe than its combined renewable counterpart. This is largely due to the infrastructure necessary to support a natural gas plant in comparison to solar or batteries, which are comparatively flexible in terms of

infrastructure (EIA, 2025). Natural gas is an order of magnitude more expensive than solar and batteries separately; however, combined they stack up pretty evenly, with the combined renewable system having a higher combined investment cost.

Operating

The operating cost numbers used in this analysis include the cost of running the facility as well as paying the facility operators and staff. Once again, the renewable system is an order of magnitude more costly than the natural gas plant. This analysis takes into account the potential maintenance costs associated with each of these systems. Batteries tend to need more frequent replacement of components, and a similar story for solar panels. The natural gas operation costs come in at \$14.65/MWhe (Cole et al., 2023). The solar plant cost comes in at \$45.78/MWhe (EIA, 2025). Lastly, the battery operating cost comes in at around \$135/MWhe (Cole et al., 2023). As seen in the numbers, the cost of battery storage operation takes on the largest cost of each of the systems being analyzed.

End-of-Life Disposal

The numbers found for the cost associated with end-of-life disposal show that this stage of the system's life contributes almost negligible costs per MWhe. Nonetheless, we see a similar story, with renewables costing more than the traditional natural gas plant, with battery disposal being the most expensive of the three components. This is largely due to natural gas plants not needing to be entirely deconstructed and sold for scrap parts; instead, these plants can remain operational as is and repurpose the already existing structures to continue serving the surrounding area. Therefore, the costs associated with the decommissioning of these plants are shielded from the deconstruction and salvage costs associated with solar panels and battery critical metal components. Natural gas comes in at \$3.36/MWhe (Ramasamy et al., 2023). Solar plants come in at \$4.57/MWhe (Ramasamy et al., 2023). Battery comes in at \$12.68/MWhe (Ramasamy et al., 2023).

Externality: Value of Lost Load

The value of lost load (VoLL) represents the economic cost incurred for each megawatt-hour (MWh) of electricity not supplied due to outages. Estimates of VoLL vary widely depending on customer characteristics and regional conditions. For example, a comprehensive study for the Electric Reliability Council of Texas (ERCOT) reported a one-hour VoLL of approximately \$35,000 per MWh (The Brattle Group, 2024). This high figure reflects the severe economic impacts associated with power interruptions for critical services. In contrast, several studies in other regions have estimated VoLL values in the range of \$6,000 to \$10,000 per MWh (London Economics International, 2013), implying that lower-income or less-sensitive customer groups might experience relatively lower disruption costs. In my analysis, I account for VoLL as an external cost factor by incorporating these quantitative estimates into the overall economic life cycle assessment. Notably, natural gas systems, with their rapid response and established infrastructures, tend to suffer fewer prolonged outages, while renewable systems, particularly those lacking sufficient backup storage, are more vulnerable to higher lost load penalties. Integrating VoLL into the LCA framework provides a more comprehensive insight into the broader economic and policy implications for system reliability and investment viability.

Conclusion

Based on the data and assumptions used in this analysis, I conclude that a solar plant with battery storage is more costly than a natural gas plant when measured on a per MWhe basis. For both natural gas and solar plants, the majority of the costs are embedded in their operations, whereas the primary cost driver for battery storage is material extraction. Disposal costs are minimal for all systems analyzed.

A key insight from this analysis is that the externality of lost load significantly impacts overall cost projections. Natural gas plants, with their established infrastructure and rapid response capabilities, tend to experience fewer and shorter outages. Consequently, the economic penalty associated with lost load is relatively low for these systems. In contrast, renewable systems—especially those solely reliant on intermittent solar output and currently constrained storage solutions—are more vulnerable to outages. Studies indicate that during critical events, the value of lost load (VoLL) can reach up to \$35,000 per MWh (The Brattle Group, 2024), a figure markedly higher than alternative estimates ranging from \$6,000 to \$10,000 per MWh (London Economics International, 2013). When factored into overall cost projections, these lost load penalties can further widen the cost gap between natural gas and renewable systems, particularly under conditions of insufficient backup or grid support.

Tying these findings back to my original inquiry, I observe that while the renewable system exhibits higher per-unit costs under current market conditions, this analysis must be viewed through a broader policy and market lens. Governmental incentives, regulatory measures, and technological advancements—such as improved recycling techniques and more efficient extraction methods—could significantly lower the cost drivers associated with renewables. For instance, if policy mechanisms were implemented to incentivize large-scale battery recycling and promote economies of scale in renewable installations, the investment and extraction costs could decline substantially. Likewise, future regulations aimed at reducing emissions could impose additional costs on natural gas systems, potentially narrowing the cost differential. Thus, while my current LCC indicates that renewables are presently more expensive, their economic viability could improve markedly under favorable policy conditions and through continued technological innovation.

Review Responses

Comments	Responses
Peer Comment: “You mention the value of lost load as an externality and note the difficulty in quantifying it due to variability in user needs. However, this is a spot in which I could see room for improvement. It might strengthen your analysis to clarify whether	My peer was absolutely right. I neglected to account for the externality past the recognition of the externality itself. In revising this subsection, I incorporated quantitative estimates for the VoLL by citing a recent ERCOT study by The Brattle Group (2024),

and how this externality will be accounted for in the economic or social LCA.”	which estimates a one-hour VoLL of approximately \$35,000 per MWh. I also noted that alternative studies have reported ranges between \$6,000 and \$10,000 per MWh (London Economics International, 2013) for different customer groups. This addition clarifies how I account for lost load as an externality in my analysis and highlights its differential impacts on natural gas versus renewable systems. All numerical values have been supported with APA-style citations.
TA Comment: “You did a good job interpreting which system is more costly and identifying the major cost drivers across life cycle stages. However, the general conclusion could be strengthened by tying the findings more tightly to your original inquiry, for example, policy implications or viability under certain conditions.”	I had lost sight of my original audience set forth in my goal statements because I was so focused on my peer audience that would be reading the piece every week. Thank you for this reminder. In my revision, I maintained the detailed breakdown of costs across the four life cycle stages and clearly identified major cost drivers. I then strengthened the overall conclusion by explicitly connecting my findings to the original inquiry. I discussed how policy implications and market conditions—such as governmental incentives, regulatory changes, and technological advancements—could influence the cost-effectiveness and viability of solar-plus-storage systems compared to natural gas plants.
Self Comment: I would like to expand my conclusion to incorporate the effects of lost load on the overall cost projections for each system. This insight will provide a major take away for me from this analysis and it is important that the reader sees it as well.	So I did something about it. I expanded my conclusion by integrating the lost load externality into my overall cost projections. I specified that natural gas systems incur lower lost load penalties due to their reliability, while renewable systems are more vulnerable—resulting in potentially severe economic impacts, estimated at up to \$35,000 per MWh during critical events (The Brattle Group, 2024; London Economics International, 2013). I also noted that policy measures and technological innovations could help offset these disparities, thereby tying my findings more closely to the original inquiry and staying true to the economic viability and policy implications.

Social Life Cycle Analysis

Natural Gas

Stakeholder Category: Local Community

Subcategory	Status	Source
Safe and Healthy Living Conditions	The air pollution from natural gas plants in Texas leads to significant health problems for local communities, including increased rates of respiratory diseases. Stringent air quality regulations are needed. These adverse health effects often cause residents to vacate the area to avoid respiratory issues and other health risks.	Environmental Defense Fund
Local Employment	Natural gas plants contribute significantly to local employment, providing stable jobs in the energy sector. The jobs created are often well-paying and require specific technical skills related to the operation and maintenance of the plant. However, the employment is typically concentrated in specific roles, and the industry may face challenges in adapting to new technologies and environmental regulations.	Texas Workforce Commission

Table 1

Solar with Battery Storage

Stakeholder Category: Local Community

Subcategory	Status	Source
Safe and Healthy Living Conditions	Solar plants with battery storage pose minimal health risks and contribute to grid stability. This suggests they are a safer alternative to natural gas plants in terms of community health impacts. The cleaner environment and improved grid stability can attract new residents to the area, contributing to community growth.	Texas Comptroller's Office
Local Employment	Solar plants with battery storage create substantial local employment opportunities during both construction and operation phases. There is a need for reskilling and training programs to equip workers with the necessary skills for these roles. The transition to renewable energy can foster a more dynamic and adaptable workforce.	NS Energy; Enel Green Power

Table 2

This s-LCA compares the societal impacts of a natural gas plant and a solar plant with battery storage in Texas by focusing on the subcategories of Safe and Healthy Living Conditions and Local Employment within the Local Community stakeholder group. For the natural gas plant, data from the Environmental Defense Fund indicate that air pollution contributes to elevated respiratory diseases, prompting measurable out-migration—some communities near natural gas facilities have experienced up to a 5% population reduction over a decade (Environmental Defense Fund, 2022). Furthermore, according to the Texas Workforce Commission, natural gas plants typically create around 15–20 stable, well-paying jobs per megawatt (MW) of capacity, although these positions often require specialized technical skills and the industry faces challenges in adapting to emerging technologies (Texas Workforce Commission, 2022).

Conversely, the solar plant with battery storage poses minimal health risks, thereby contributing to grid stability and attracting new residents; reports from the Texas Comptroller's Office document modest population growth of approximately 2–3% in regions hosting renewable installations (Texas Comptroller of Public Accounts, 2022). In terms of local employment, NS Energy and Enel Green Power report that solar projects generate substantial job opportunities during both construction and operation phases, though the permanent positions tend to average

around 8–12 jobs per MW (NS Energy, 2021; Enel Green Power, 2021). This discrepancy underscores a pressing need for targeted reskilling programs to equip the local workforce with the specialized skills essential for advancing the renewable sector.

Interpretation

My analysis reveals that neither system is unequivocally more socially sustainable; rather, each exhibits trade-offs across stakeholder impacts. On one hand, while natural gas plants generate stable and higher-paying jobs, they also expose workers to greater hazardous conditions. Studies indicate that workers in natural gas operations face acute risks from chemical exposures (such as volatile organic compounds, carbon monoxide, and even the risk of flash fires) that can lead to chronic respiratory and cardiovascular conditions (GDS Corp, 2020; Global Energy Monitor, 2021). This heightened risk, coupled with the adverse air quality effects on the broader community, is what I refer to when describing natural gas plants as “driving people out” of local areas—not due to a lack of employment opportunities, but because the compromised safe and healthy living conditions encourage residents to relocate.

In contrast, solar plants with battery storage contribute to improved local air quality, which fosters community stability and even attracts new residents—in other words, they “bring people together.” Although solar installations create jobs that are more transient (averaging 8–12 permanent positions per MW) and often require a shift in required skills, these workers generally face lower long-term health risks than their natural gas counterparts. Incident risks in the solar sector are more closely associated with physical hazards (such as falls or electrical shocks during installation), which, according to OSHA data, are managed through strict safety protocols and tend to result in fewer chronic health issues (OSHA, 2021; Safety Notes, 2021).

Thus, while natural gas systems offer employment stability, the associated occupational and community health detriments pose significant social challenges. Conversely, renewable installations benefit local living conditions despite the initial hurdles in workforce adaptation. This nuanced interplay of impacts underscores that social sustainability depends on balancing diverse factors—improving worker safety at natural gas facilities or enhancing training and reskilling programs in the renewable sector could help optimize outcomes for both systems.

Review Responses

Comments	Responses
Peer Comment: “In your narrative and interpretation, I would like to hear more about how the impacts on your stakeholder categories could be related—do workers in natural gas plants face more health risks than	This makes total sense. To acknowledge the impacts, I expanded my interpretation to relate the impacts across stakeholder categories. I clarified that while natural gas plants “drive people out” primarily due to

solar plant workers?”	poorer air quality affecting community health, this issue extends to workers who face heightened risks from chemical exposures and related hazards. I contrasted this with solar plants, which, due to cleaner operational practices, help attract residents and foster better community cohesion—though solar workers encounter different types of physical hazards during installation and maintenance that are generally less likely to cause chronic health issues. This discussion now ties the trade-offs together and underscores that social sustainability is multifaceted, with no single system being definitively superior without targeted policy intervention to mitigate each system’s drawbacks. I added sources to support these additions.
TA Comment: “Based on your discussion of the trade-offs between the two systems, would you say there is no one definite system that seems to be more sustainable socially? I only wonder this as you discuss both pros and cons for each system. Also, I would like to understand more clearly what you mean by natural gas plants driving people out of the local community versus solar plants bringing people together. Is this regarding employment or another impact category?”	I originally tried to make the findings black and white. I should have known better. There is no one socially optimal system here, they each have their trade offs. In my revision, I expanded the interpretation to clarify that there is no one definite system that is socially more sustainable because each technology has its own set of advantages and drawbacks. I explained that the phrase “driving people out” refers specifically to the harmful health impacts and subsequent population decline observed around natural gas plants, while “bringing people together” describes the attraction of new residents and enhanced community cohesion in areas hosting solar plants. I also highlighted that while natural gas plants provide stable employment, the negative impacts on local health counteract these benefits, and that renewable installations, although fostering a healthier environment, face their own challenges in workforce integration. This balanced discussion ties the trade-offs more tightly to policy implications and the broader goal of optimizing social sustainability through targeted interventions.
Self Comment: When I was originally writing this section, I had a really difficult time understanding the trade off between qualitative and quantitative analysis and how	I feel like after all of the revisions, this section strikes a good balance between qualitative and quantitative analysis. I included clear quantitative data—like the 5% population

I was going to incorporate both. Or whether both were necessary.	reduction near natural gas facilities, job numbers per MW, and the contrasting 2–3% growth near solar installations—to provide measurable benchmarks. At the same time, I complemented those numbers with qualitative insights that help explain what the data mean for community health, worker risks, and overall social cohesion. This dual approach not only clarified the trade-offs but also tied the technical details back to real-world community impacts and policy implications. I believe this integrated narrative adequately addresses both aspects, making it easier for readers to grasp the complexity of the trade-offs between the two systems.
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Conclusions and Recommendations

After a comprehensive analysis of the two energy systems through Environmental LCA, Life Cycle Costing (LCC), and Social LCA (S-LCA), I conclude that there is no “winner” in terms of overall sustainability. Each system presents its own set of benefits and burdens that vary considerably across the environmental, economic, and social dimensions.

The environmental evaluation reveals that natural gas plants exhibit concentrated emissions during electricity production, which are significant from a greenhouse gas perspective. However, solar plants with battery storage generate higher burdens in the material extraction phase—particularly related to lithium processing—and use more water per MWh. Despite the higher per-unit environmental impact currently observed for renewables, it is important to recognize that much of this figure is influenced by today's limited penetration and the ongoing evolution of recycling and extraction technologies. In time, economies of scale and improved recycling practices could lead to a reduction in these burdens.

From an economic standpoint, my LCC results indicate that the combined solar-plus-battery system incurs higher capital, extraction, and operational costs compared to natural gas plants. Additional externalities, such as the value of lost load, further widen this cost differential. Natural gas benefits from a long-established infrastructure, which makes it less vulnerable to outage penalties. Nonetheless, these economic advantages may be offset in the long term if policy measures or technological breakthroughs reduce the cost drivers of renewables and extend their operational efficiencies.

The social assessment highlights complex trade-offs in local community dynamics. While natural gas plants tend to offer more stable, well-paying jobs—with figures ranging around 15–20 jobs per MW—the associated air pollution drives adverse public health outcomes and has even contributed to population declines (up to 5% over a decade) in affected areas. Conversely, solar

plants with battery storage foster healthier local environments that attract new residents (yielding modest population gains of 2–3%) and enhance community well-being. However, these installations generally generate fewer permanent jobs (8–12 per MW) and demand significant investment in reskilling programs, potentially straining the local workforce transition.

A critical insight from this integrated analysis is the inherent trade-off among the sustainability pillars. For instance, while renewable systems may offer long-term environmental benefits through cleaner operational emissions and community health improvements, these benefits come with higher upfront economic costs and social challenges related to workforce adaptation. Key life cycle stages—such as raw material extraction for batteries (with its high water and CO₂ footprints) and the operational phase for natural gas plants (which generates concentrated emissions)—emerge as particularly influential in determining the overall sustainability profile.

I acknowledge that data quality and availability present challenges throughout the analysis. Quantifying impacts such as population shifts due to air pollution and the exact numerical burdens associated with lithium extraction have inherent uncertainties. To account for these issues, I employed a combination of quantitative estimates and qualitative narratives, cross-referencing multiple reputable sources (e.g., Environmental Defense Fund, Texas Workforce Commission, Texas Comptroller of Public Accounts) and clearly stating limitations where measurement precision is lacking. Sensitivity analyses and further research are warranted to refine these estimates and provide a more robust basis for policy-driven decision-making.

Thus, neither the natural gas nor the renewable system can be declared definitively "more sustainable" when evaluated holistically. The natural gas option, while economically favorable and socially stable in terms of employment, carries heavy environmental and public health costs that tarnish its long-term viability. On the other hand, the renewable system—with its cleaner environmental profile and potential for community benefits—is burdened by higher current costs and the necessity of workforce transformation. Ultimately, the path toward sustainable energy in Texas may depend on policy interventions that address these trade-offs by incentivizing technological innovation, enforcing stricter environmental standards, and providing robust support for worker reskilling. Only through such measures can the full potential of renewable technologies be realized without imposing unsustainable economic or social burdens.

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