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Strategies to Achieve Deep Decarbonization in Power Generation: A Review

Abdullah Alotaiq

***Abstract*—**The transition to low-carbon power generation is essential for mitigating climate change and achieving sustainability. This process, however, entails considerable costs, and understanding the factors influencing these costs is critical. This is necessary to cater to the increasing demand for low-carbon electricity across heating, industry, and transportation sectors. A crucial aspect of this transition is identifying cost-effective and feasible paths for decarbonization, which is integral to global climate mitigation efforts. It is concluded that hybrid solutions, combining different low-carbon technologies, are optimal for minimizing costs and enhancing flexibility. These solutions also address the challenges associated with phasing out existing fossil fuel-based power plants and broadening the spectrum of low-carbon power generation options.

***Keywords*—**Review, power generation, energy transition, decarbonization.

I. Introduction

IN this review, we aim to provide an in-depth analysis of the literature on cost-effective strategies for deep decarbonization in power generation, emphasizing the impacts of pace and scale. We have meticulously reviewed 30 studies published since the Paris Agreement, encompassing modeling approaches, empirical analyses, and regional or global case studies. Our objective is to identify recurring themes, discrepancies, or conflicting results, and highlight gaps in current research. Our ultimate goal is to enhance understanding of the factors influencing decarbonization costs and provide guidance on optimizing the transition to low-carbon power generation.

The Paris Agreement targets limiting the global mean surface temperature increase to well below 2°C, ideally to 1.5°C, above pre-industrial levels. To meet these targets, it is estimated that the global carbon budget from 2017 to 2100 is capped at 1000 $GtCO_2$ for a 66% chance of staying below a 2°C rise, and 850 $GtCO_2$ for a 33% chance or 420 $GtCO_2$ for a 66% chance of limiting the increase to 1.5°C [1]. Achieving these targets mandates the power sector to not only fully decarbonize but also contribute to negative emissions by 2050.

The power sector, a significant contributor to global emissions, must undergo a transformation to meet these objectives. Globally, the power sector is responsible for approximately 40% of CO_2 emissions, predominantly from fossil fuel combustion in coal, oil, and gas power plants. Transitioning to low- or zero-carbon power systems is technically feasible, as evidenced by expanding literature [2]. These systems are expected to rely more on intermittent renewable sources, such as wind and solar, complemented by large-scale low-carbon sources like nuclear power and fossil fuel plants with carbon capture and storage (CCS) to ensure a reliable electricity supply [2], [35]. However, achieving a 100% renewable or low-carbon power system poses challenges, including the need for backup and storage capacity [3]-[34].

The literature consistently emphasizes the formidable task of achieving near-zero emissions in the power sector, as opposed to modest emission reductions [2]-[35]. Effective planning and policy must therefore focus on long-term goals to avoid the costly lock-in of suboptimal resources. Short-term choices can lead to long-term challenges and higher costs in transitioning to an optimal resource mix [15]. A diversified mix of low-carbon generation resources is highlighted as critical for affordable deep decarbonization [4], [6], [9], [11], [13], [24], [28], [34]-[36]. Incorporating dispatchable low-carbon resources, like nuclear energy or fossil energy with CCS, can alleviate the costs and technical challenges associated with deep decarbonization. This aligns with a growing consensus that a holistic approach to decarbonization, rather than reliance on a specific set of technologies, is necessary.

We begin our review by examining the current state and challenges of the power sector in achieving deep decarbonization. We explore various pathways and strategies, analyzing the costs and benefits of each, including the roles of different technologies and resources, and the importance of diversified low-carbon generation resources. We assess the trade-offs between speed and cost, and their impact on the overall cost of decarbonization. We conclude by summarizing our key findings and providing recommendations for policymakers and researchers on optimizing the pace and scale of the transition to low-carbon power generation. This review offers a comprehensive examination of the literature on decarbonizing power generation costs, aiming to clarify the factors influencing these costs and the trade-offs involved.

II. Methods

The systematic review methodology employed in this literature review aims to provide a comprehensive overview of the literature on the costs of decarbonizing power generation, with a focus on the impact of pace and scale. The methodology is based on the systematic quantitative review introduced by Pickering and Byrne [37] and Pickering et al. [36], and has been applied in several energy-related studies such as Kang et al.

Abdullah Alotaiq is with the Energy and Power Group, Engineering Science Department, University of Oxford and Energy C Environmental Informatics, Engineering Science Department, University of Oxford, United Kingdom (e-mail: abdullah.alotaiq@eng.ox.ac.uk).

[38], Mosavi et al. [39] , Munro and Cairny [40] and Qazi et al. [41].

The methodology for conducting a systematic quantitative review was divided into four phases. The first phase consisted of defining the topic and research questions, including identifying the implications of the pace and scale of power generation decarbonization on system costs and forming four specific research questions pertaining to the current state of knowledge, variations in system costs across different levels of decarbonization, primary obstacles encountered in the decarbonization of power generation, and recommendations for future research.

The second phase involved identifying relevant studies through the use of keyword search strings and initial evaluations of the titles and abstracts. A comprehensive search strategy was employed utilizing a combination of keywords and phrases such as "climate," "decarbonization," "low-carbon," "renewable," "power," "generation," "costs," and "investments," “scenarios”. The search was conducted across three major databases: Google Scholar, Scopus, and the Web of Science, which are known for their comprehensive coverage across various academic disciplines. The search was limited to literature published between January 2017 and January 2023, to ensure that the studies included are current and reflective of recent technological and policy developments.

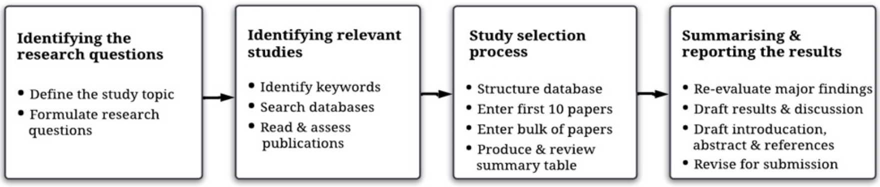

Fig. 1 The systematic quantitative review strategy used in this study; modified from [37]

TABLE I
SYSTEMATIC REVIEW STRATEGY FOR IDENTIFICATION AND SELECTION OF RELEVANT PAPERS

No.	Item	Description
1	Define topic	Cost-effective strategies for achieving deep decarbonization in power generation
2	Formulate research questions	*Research Aim* To review the implications of the pace and scale of deep power generation decarbonization on system costs *Research questions* • What is the state-of-art in the literature on the cost-effectiveness of • deep decarbonization in power generation? • How does the system cost of power generation changes across different levels of decarbonization? • What are the main challenges in deep decarbonization scenarios with relation to costs? • What recommendations can be derived to deeply decarbonize power generation at the lowest costs?
3	Keyword search string	climate OR decarbonization OR low-carbon OR renewable OR net zero AND power OR electricity AND costs OR investments AND scenarios OR pathways OR outlook
4	Online database	Web of Science, Scopus, Google Scholar
5	Inclusion criteria	*Period* 2016–2022 (since the Paris Agreement) *Type of study* Peer-reviewed literature published in English focused on holistic power generation decarbonization (i.e., including supply and storage but excluding demand and transmission). *Geography* Global or regional level. *Evidence* Qualitative and quantitative findings on implications of the pace and scale of power generation decarbonization on system costs by 2050 or until complete decarbonization. If multiple scenarios present, we choose the most ambitious for decarbonizations for our review matrix.

The study selection process was carried out in the third phase, where the articles were thoroughly evaluated, and a structured database was created. A snowball technique was utilized to further identify relevant literature from the list of references in the studies that were initially identified. This resulted in a total of 223 studies from ScienceDirect, 354 studies from the Web of Science, and 2,256 studies from Google Scholar being imported into the reference management software, Zotero. The study selection process was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram [42] and was depicted in Fig. 2. The titles and abstracts of the articles were subsequently screened and evaluated for eligibility based on the inclusion criteria outlined in Table I.

In the fourth phase, the extracted data was re-evaluated, summarized, and results were prepared. The data retrieval procedure and analysis were designed to address the four research questions formulated in the first phase. The data were analyzed and evaluated to provide a comprehensive understanding of the current state of knowledge on the effects of pace and scale on system costs of decarbonization in power generation, variations in system costs across different levels of decarbonization, the primary obstacles encountered in the decarbonization of power generation, and recommendations for future research.

A total of 169 studies were ultimately included in the final analysis, after applying the inclusion criteria and eliminating duplicate studies. These studies were analyzed and evaluated in detail, with a focus on their contribution to the research questions outlined in Table I. The data extraction process was carried out using a structured database, which was created for the purpose of organizing and summarizing the information extracted from the studies. The extracted data were re-evaluated, summarized, and prepared for analysis.

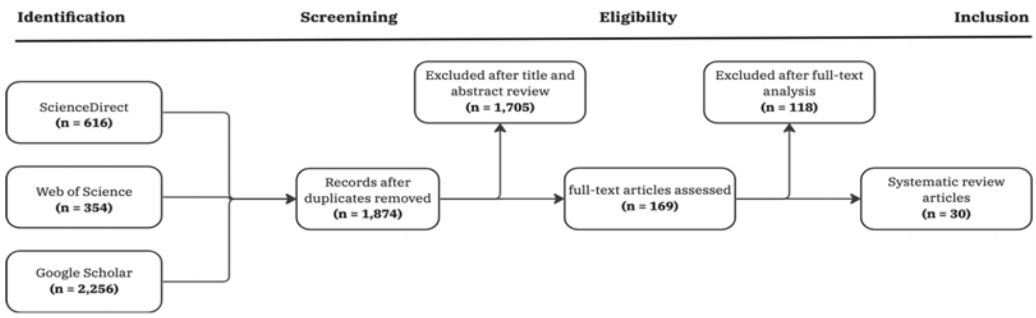

Fig. 2 The PRISMA flow diagram of the systematic quantitative literature review showing an illustration of the process for identifying, screening, and including eligible articles

In total, we identified and evaluated over 30 studies that addressed our research question. These studies represented a range of research approaches, including modeling, empirical analysis, and case studies. We included studies from variety of regional and global levels and time periods, in order to provide a broad and comprehensive overview of the literature. The literature excluded after full-text analysis are due to unavailability of document, non-English studies or out-of-scope.

The data analysis involved a qualitative analysis of the studies, which aimed to identify patterns and trends in the literature and to provide a comprehensive overview of the current state of knowledge on the topic. This analysis was carried out using a thematic analysis approach, which involved identifying key themes and sub-themes from the studies and grouping them accordingly. The results of the literature review were then used to draw conclusions and make recommendations for future research on the topic. The results were presented in a clear and concise manner and were organized according to the research questions outlined in Table I.

In summary, the systematic quantitative review methodology applied in this review paper provides a comprehensive and rigorous approach to analyzing and evaluating the existing literature on electricity deep decarbonization studies, with a specific focus on the impact of pace and scale on the costs of decarbonizing power generation. The methodology follows a systematic and systematic process, which includes a comprehensive search strategy, thorough study selection, and structured data analysis. This approach ensures that the literature review is comprehensive, reliable, and valid. The results of the literature review provide valuable insights into the current state of knowledge on the topic of deep decarbonization of electricity and highlight the importance of considering the pace and scale of decarbonization when evaluating the costs of decarbonizing power generation.

III. Results and Discussion

The results from the scholarly literature recognizes the vital part that the power sector plays in mitigating greenhouse gas emissions [2]-[35]. It underscores the significance of decarbonizing the sector at an accelerated rate, reaching near-zero emissions by 2050 to meet the increasing demand for low-carbon electricity in heating, industry, and transportation. The literature stresses the requirement for economically feasible and cost-effective decarbonization paths as a critical aspect of global climate change mitigation efforts and notes that while faster transitions may entail higher costs, the costs of delay can also be substantial [15], [27], [43], [44]. The review advocates for hybrid solutions that incorporate both renewable energy sources and low-carbon resources to minimize costs and enhance flexibility while addressing the challenges of transitioning existing fossil fuel power plants and increasing the range of available low-carbon resources. In this article, we summarize and condense the findings from 30 studies that have been published since the 2015 Paris Agreement. The results of these studies are presented in Table II.

It is widely acknowledged that the power sector must play a key role in achieving economy-wide greenhouse gas reduction goals, and that it must decarbonize at a faster rate than other sectors [35], [15]. This is due to the fact that decarbonizing electricity is technically less complex and less expensive compared to other sectors. As a result, most studies that consider economy-wide GHG reduction goals envision the power sector reaching close to zero (or net negative) emissions by 2050 [3], [9]-[16], [18]-[22], [24], [26], [28], [29], [32], [45]. Additionally, in order to meet the increased demand for heating, industry, and transportation, a greater proportion of carbon-free electricity must be generated. Across global decarbonization scenarios, electricity demand is projected to increase by 20-120% by 2050, and 120-440% by 2100 [35]. Furthermore, electricity is expected to supply 25-45% of total energy demand by mid-century, and potentially up to 70% by 2100 [35].

TABLE II
CLASSIFICATION OF THE REVIEWED EMPIRICAL STUDIES

	Author	Year	Title	Journal	Geographic Scope	Model	Target	Decarbonization	Cost Structure	Dispatchable Sources	Storage
1	Jacobson et al. [3]	2017	100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World	Joule	Global	GATOR-GCMOM	2050	80% decarbonization by 2030 and 100% by 2050	Capital, Levelized	CSP, Hydro, Geo	N
2	Barasa et al. [5]	2018	A cost optimal resolution for Sub-Saharan Africa powered by 100% renewables in 2030	Renewable and Sustainable Energy Reviews	Regional	LUT ESTM	2030	100% renewable electricity	Levelized	Gas, CSP, Geo, Bio	BS, PHS, CAES, GS, TS
3	Heuberger et al. [6]	2017	A systems approach to quantifying the value of power generation and energy storage technologies in future electricity networks	Computers & Chemical Engineering	Global	IEAGHG	2035	80-100% reduced emission levels	Capital	Coal CCS, Gas, Gas CCS, Nuc	H2S
4	Aghahosseini et al. [7]	2017	A Techno-Economic Study of an Entirely Renewable Energy-Based Power Supply for North America for 2030 Conditions	Energies	Regional	LUT ESTM	2030	100% renewable electricity	Levelised	Gas, CSP, Hydro, Geo, Bio	BS, PHS, CAES, GS, TS
5	Gupta et al. [9]	2021	An integrated assessment framework for the decarbonization of the electricity generation sector	Applied Energy	Global	LEAP-Canada	2050	49% reduction in current policy scenario	Emissions	Gas, Gas CCS, Nuc, Bio, Hydro	BS
6	Davis et al. [10]	2020	Assessment of renewable energy transition pathways for a fossil fuel-dependent electricity-producing jurisdiction	Energy for Sustainable Development	Global	LEAP	2050	90% reduction from 2005 emission levels	Emissions	Gas, Gas CCS, Bio	N
7	Wendling [11]	2019	Bridges beyond renewable energy: Decarbonizing the global electricity sector under uncertainty	Energy Research & Social Science	Global	Analytical	2050	80%-100% emissions reduction	Capital	Coal CCS, Gas, Gas CCS, Nuc	N
8	Schlachtberger et al. [12]	2018	Cost optimal scenarios of a future highly renewable European electricity system: Exploring the influence of weather data, cost parameters and policy constraints	Energy	Regional	PyPSA	2050	80% to 95% in 2050 compared to 1990 values	Levelized	Gas, Hydro, H2	BS, PHS
9	van Zuijlen et al. [13]	2019	Cost-optimal reliable power generation in a deep decarbonization future	Applied Energy	Regional	PLEXOS®	2050	70% renewable electricity	Capital	Gas, Gas CCS, Nuc, H2	PHS
10	Hrnčić et al. [14]	2021	Different investment dynamics in energy transition towards a 100% renewable energy system	Energy	Regional	OSeMOSYS / Markal/ TIMES	2050	100% renewable electricity	Capital	Gas, Hydro	N
11	Way et al. [15]	2022	Empirically grounded technology forecasts and the energy transition	Joule	Global	PCF	2050	100% reduction in emission levels	Levelized	H2	BS
12	Gerbaulet et al. [16]	2019	European electricity sector decarbonization under different levels of foresight	Renewable Energy	Regional	dynELMOD	2050	98% reduction of the 1990 carbon dioxide (CO_2)-emissions	Capital	Gas, Bio, Hydro	BS
13	Child et al. [18]	2019	Flexible electricity generation, grid exchange and storage for	Renewable Energy	Regional	LUT ESTM	2050	100% renewable energy	Levelized	Bio, Hydro	BS, PHS

	Author	Year	Title	Journal	Geographic Scope	Model	Target	Decarbonization	Cost Structure	Dispatchable Sources	Storage
			the transition to a 100% renewable energy system in Europe								
14	Pleßmann & Blechinger [19]	2017	How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050	Energy Strategy Reviews	Regional	Elesplan-m	2050	80-95% reduction in emission levels	Capital, Levelized	Gas	BS, H2S
15	Zappa et al. [20]	2019	Is a 100% renewable European power system feasible by 2050?	Applied Energy	Regional	PLEXOS	2050	100% renewable electricity	Capital	CSP, Hydro, Geo, Bio	PHS
16	Bogdanov et al. [21]	2021	Low-cost renewable electricity as the key driver of the global energy transition towards sustainability	Energy	Global	LUT ESTM	2050	100% renewable energy	Capital, Levelized	Gas, Hydro, Bio, Geo, CSP	GS, TS
17	Lehtveer & Fridahl [22]	2020	Managing variable renewables with biomass in the European electricity system: Emission targets and investment preferences	Energy	Regional	ELINEPOD	2050	90% reduction from 1990 emission levels	Levelized	Coal CCS, Hydro, Bio	BS
18	Poncelet et al. [24]	2016	Myopic optimization models for simulation of investment decisions in the electric power sector	2016 13th International Conference on the European Energy Market (EEM)	Global	LUSYM	2050	100% reduction in emission levels	Fixed	Coal CCS, Gas, Gas CCS, Nuc	N
19	Bogdanov & Breyer [25]	2016	North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options	Energy Conversion and Management	Regional	LUT ESTM	2030	100% renewable energy	Levelized	Gas, Hydro, CSP	BS, PHS, TS
22	Pleßmann & Blechinger [26]	2017	Outlook on South-East European power system until 2050: Least-cost decarbonization pathway meeting EU mitigation targets	Energy	Regional	Elesplan-m	2050	100% reduction in emission levels	Capital, Levelized	Gas, Hydro	BS, PHS, GS
23	Heuberger et al. [45]	2017	Power capacity expansion planning considering endogenous technology cost learning	Applied Energy	Regional	ESO-XEL	2050	100% reduction in emission levels	Capital	Coal CCS, Gas, Nuc , Bio	BS
24	Mileva et al. [28]	2016	Power system balancing for deep decarbonization of the electricity sector	Applied Energy	Global	SWITCH	2050	85% below 1990 levels	Capital, Levelized	Gas, Nuc, Bio, Geo, CSP	BS
25	Duan et al. [29]	2022	Stylized least-cost analysis of flexible nuclear power in deeply decarbonized electricity systems considering wind and solar resources worldwide	Nature Energy	Global	MEM	2050	80% emissions reduction	Capital	Gas CCS, Nuc	BS
26	Ziyaei et al. [30]	2022	Sustainable power generation through decarbonization in the power generation industry	Environmental Monitoring and Assessment	Global	OSeMOSYS /LEAP	2030	80-100% reduced emission levels	Capital, Levelized	Gas CCS, Nuc	N
27	Sepulveda et al. [32]	2018	The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation	Joule	Global	GenX	2050	100% reduction in emission levels	Levelized	Gas CCS	BS
28	Aghahosseini et al. [34]	2020	Towards sustainable development in the MENA region: Analyzing the feasibility of a 100% renewable	Energy Strategy Reviews	Regional	LUT ESTM	2030	100% renewable electricity	Levelized	Gas, Bio, Geo, Hydro, CSP	BS

	Author	Year	Title	Journal	Geographic Scope	Model	Target	Decarbonization	Cost Structure	Dispatchable Sources	Storage
			electricity system in 2030								
29	Gaffney et al. [4]	2018	A comparative analysis of deep decarbonization scenarios for the European power system	Joule	Regional	PLEXOS	2050	85-90% emission reduction compared to 1990 levels	Capital, Emissions	Coal CCS, Gas CCS, Nuc, Bio	N
30	Farzaneh et al. [33]	2016	Toward a CO_2 zero emissions energy system in the Middle East region	Green Energy	Regional	OM	2100	100% reduction in emission levels	Capital	Gas CCS, Nuc	N

Abbreviations: Capital, capital costs for transitioning either a lumpsum or ratio per technology type; levelized, concluding findings use levelized cost of electricity to estimate the system costs; Emissions, the cost of emission mitigation; CCS, Carbon Capture and Storage; Nuc, nuclear power; Hydro, hydropower whether run-over river or a dam; Bio, bioenergy in all forms including waste, biofuels, biomass etc.; Geo, geothermal power; CSP, concentrating solar power; H2, hydrogen; BS, battery storage; PHS, pumped hydro storage; GS, gas storage; H2S, hydrogen storage; TS, thermal storage; CAES, compressed air energy storage. This is not a comprehensive list of all studies on the topic but covers a diverse range of research and aims to provide a comprehensive overview of key findings from recent studies.

Scholars concur that the electricity sector must not only decarbonize, but also steadily increase its market share [4]-[8], [13], [17], [20], [23], [24], [26]-[30], [32]. Failure to do so would impede efforts to mitigate climate change across the broader economy. Additionally, if decarbonization is too costly and results in a substantial increase in the price of electricity, it would make low-carbon electricity less appealing as a substitute for fossil fuels in transportation, heating and industry [9]. Therefore, identifying cost-effective and feasible routes to decarbonize the power sector is crucial to global climate mitigation efforts.

The literature is in strong agreement that reaching near-zero emissions is more difficult than achieving more modest emissions reductions, such as a 50% to 70% reduction in CO_2 emissions [4], [4], [13], [28], [29], [32]. This is because reaching near-zero emissions requires a different set of low-carbon resources and technologies, rather than being able to rely on natural gas-fired power plants as firm resources. To achieve near-zero emissions, it would require a significant replacement or retrofitting of existing fossil fuel power plants with carbon capture and storage technology [4], [9], [10], [11], [13], [22], [24].

Given the long lifespan of power sector infrastructure and the extended period required for R&D, it is essential to assess the specific obstacles associated with deep decarbonization [13]. A passive approach is unlikely to yield optimal results. The existing literature suggests potential solutions to decarbonization, but also highlights a number of challenges that must be surmounted along the path towards a zero-carbon electricity system. Given these challenges and the significant technological uncertainty, it is more likely to achieve deep decarbonization in an affordable manner by adopting a strategy that focuses on enhancing and expanding the range of available low-carbon resources, rather than limiting it.

The literature collectively outlines and evaluates two main approaches to reducing carbon emissions in the electricity sector: one that primarily or entirely relies on variable renewable energy (VRE) sources, such as wind and solar power, with support from energy storage [3], [5], [8], [14], [17], [18], [20], [25], [34]. The other approach relies on a wider range of low-carbon resources, such as wind and solar power, as well as more consistent resources, such as fossil fuels with carbon capture and storage, as well as nuclear, geothermal, and biomass [3]. These different approaches carry varying costs and should be evaluated based on the specific context of the region or country. Additionally, it is important to consider the potential for hybrid solutions that could combine elements of both paths to minimize costs and maximize flexibility.

Several studies have found that achieving significant levels of decarbonization through the use of VRE sources, such as wind and solar, is technically feasible [4], [9]-[11], [13], [22], [24]. Despite the diversity of contexts and analytical methods used in these studies, there is a high degree of agreement on several key characteristics that must be in place for this decarbonization pathway to be both feasible and affordable. Importantly, the challenges associated with the variability of these sources increase non-linearly as their share of energy generation increases. As such, issues that may be manageable at lower penetration levels can quickly become significant barriers as the share of VRE approaches 100% [8].

The integration of high levels of VRE sources such as wind and solar power is crucial for achieving deep decarbonization of the power sector. However, the intrinsic variability of these sources poses significant challenges for ensuring a stable and reliable energy supply. To overcome this, an excessive amount of installed capacity must be built to provide sufficient energy during periods of low output. The excess energy generated during periods of high output must then be stored or discarded, which can become increasingly difficult as the share of VRE increases. A number of studies have shown that the challenges associated with overgeneration, and curtailment rise nonlinearly as the penetration of wind and solar increases [3], [5], [8], [18]. At high penetration levels, the amount of wasted energy can be substantial. Furthermore, as the penetration of VRE increases, the need for energy storage infrastructure also increases in order to ensure a reliable and stable power supply.

The utilization of wind and solar energy sources in deep decarbonization pathways is constrained by the need to overbuild capacity and the resulting curtailment of a significant proportion of generated energy. This results in a significant reduction in the capacity factor of wind and solar energy sources, particularly for the marginal capacity installed to achieve greater than 80% renewable energy shares [17]. Additionally, total system costs tend to increase as the proportion of renewable energy in the generation mix approaches 100% [12]. To mitigate these cost escalations and maintain the affordability of decarbonization pathways dependent on a high penetration of VRE, there is a need for further reductions in the capital costs associated with wind and solar energy sources worldwide.

In these systems with a high penetration of VRE such as wind and solar, the need for reliable, firm capacity becomes paramount. This is particularly crucial during prolonged periods of low wind or solar production, which can last for days or weeks, making it difficult for short-duration energy storage to bridge the gap. To mitigate this challenge, VRE-dominant systems must have sufficient capacity from dispatchable sources, such as bioenergy, hydropower with large reservoirs, geothermal, natural gas plants, or nuclear power [4], [10], [11], [13], [22], [32], [36], [45]. However, in such scenarios, these firm resources tend to have a lower utilization rate, thus, low capex and high opex sources costs, such as bioenergy, hydrogen, or natural gas-fired power plants, are economically more suitable to pair with high wind and solar shares [32].

The feasibility and affordability of deep decarbonization utilizing VRE sources such as wind and solar is contingent on the availability of energy storage systems capable of sustained output over prolonged periods. Currently, no such storage options exist on a large scale and the cost of implementing them remains uncertain [6], [18], [23], [46]. This necessitates the incorporation of other forms of firm, low-carbon generation or the exploration of alternative storage methods such as thermal energy storage or hydrogen production and storage. However, the scalability, cost- effectiveness, and feasibility of these options are yet to be determined [46].

The utilization of a diverse range of low-carbon resources, in addition to VRE sources, can mitigate many of the challenges that arise with high penetration of wind and solar power. These scenarios that include a mix of firm low-carbon generation resources such as nuclear, coal or natural gas plants with carbon capture and storage, and greater shares of dispatchable renewable resources such as geothermal or bioenergy, result in a more closely sized installed capacity relative to peak demand, higher utilization of resources, and minimal curtailment of renewable energy output. Furthermore, these scenarios do not require the implementation of long-duration "seasonal" storage technologies making the overall cost of decarbonization in comparison more affordable in technology-diversified scenarios.

The majority of studies surveyed, which utilize techniques such as techno-economic optimization and integrated assessment modeling, have determined that a balanced portfolio of resources is essential for achieving deep decarbonization at an affordable cost [9]-[13], [16], [19], [22], [24], [26]-[32]. These studies identify the inclusion of scalable, reliable low-carbon generation sources as a crucial aspect of the most cost-effective pathways to decarbonization. This is evidenced by the fact that all of these studies include a significant proportion of these firm low-carbon resources in their optimal resource portfolios. Despite their potential, these resources also face significant challenges that may impede their widespread adoption. Nuclear power is struggling to keep pace with retirements, while carbon capture technologies are still in the demonstration phase [29], [47]. Additionally, while biomass use is increasing, there are concerns about its net life-cycle greenhouse gas benefits [48]. Furthermore, hydroelectric power is geographically limited and carries environmental impacts, and conventional geothermal energy is restricted to certain locations [49]. Enhanced or engineered geothermal systems, which have the potential to unlock widespread resources, are not yet commercially available [50].

It would be unwise for policymakers, socially responsible businesses, and research endeavors to place all their bets solely on the current front-runners, such as solar, wind, and battery energy storage, due to the obstacles that existing firm low-carbon resources are currently facing. The pursuit of deep decarbonization in the power sector is a complex and multifaceted endeavor that requires addressing a variety of challenges. A diversified portfolio of resources that includes a combination of variable renewables and firm low-carbon generation is crucial for avoiding obstacles such as public opposition, limitations in transmission network infrastructure, and the need for large-scale, long- term energy storage solutions [32], [51]. It is important to acknowledge that these challenges may not be easily surmountable and to consider the potential barriers that could impede the cost-effective decarbonization of electricity.

In summary, achieving deep decarbonization in a cost-effective manner requires enhancing and expanding the range of available low-carbon resources, rather than limiting it. A diversified approach to decarbonizing the power sector, which includes the development of a wide range of clean energy resources, is crucial in ensuring that there is a reliable and cost-effective means of providing low-carbon electricity. Nuclear power, carbon capture and storage, bioenergy, and enhanced geothermal energy are all viable options that have the potential to fill the role of firm, low-carbon power sources in case other technologies prove insufficient. While the probability of each resource becoming affordable and scalable within the next two decades may be low, the odds of success in decarbonizing electricity increase significantly when multiple options are pursued simultaneously. Adopting a diversified approach to decarbonization significantly increases the chances of identifying cost-effective pathways, as supported by a range of studies in the field [9]-[13], [16], [19], [22], [24], [26]-[32]. By taking a flexible and adaptive approach, it will be possible to minimize costs and maximize flexibility while still achieving deeply decarbonized power generation.

IV. Conclusions

In conclusion, the transition to low-carbon electricity is a paramount step in ameliorating the effects of climate change and realizing a sustainable future. However, the process of decarbonizing the power sector can be costly, and it is imperative to comprehend the factors that influence the costs of this transition.

First, the literature highlights the pivotal role that the power sector plays in achieving economy-wide greenhouse gas reduction goals, and the need for it to decarbonize at a faster rate than other sectors. It is acknowledged that decarbonizing electricity is technically less complex and less expensive than other sectors and most studies envision the power sector reaching close to zero emissions by 2050. In order to meet the increased demand for heating, industry, and transportation, a greater proportion of carbon-free electricity must be generated. The literature highlights the importance of identifying cost-effective and feasible routes to decarbonize the power sector as a crucial factor in global climate mitigation efforts. The failure to do so would impede efforts to mitigate climate change across the broader economy and make low-carbon electricity less appealing as a substitute for fossil fuels.

Second, the review of the literature on the costs of decarbonizing the power sector suggests that the pace and scale of decarbonization can have a substantial impact on the costs of transitioning the power sector. In general, faster transitions tend to be more costly in the short term, as they necessitate the deployment of new technologies and infrastructure at a quicker rate. However, the costs of delay can also be significant, as the negative impacts of climate change and the opportunity costs of waiting can accumulate over time.

Finally, the literature on power sector decarbonization highlights two main approaches to reducing carbon emissions in the electricity sector: one that primarily relies on VRE sources such as wind and solar power, and one that utilizes a wide range of low-carbon resources including nuclear, geothermal, biomass, and fossil fuels with carbon capture and storage. These disparate approaches carry varying costs and should be evaluated based on the specific context of the region or country. It is also crucial to consider hybrid solutions that integrate elements of both paths to minimize costs and maximize flexibility. The literature also highlights other challenges including the need for significant replacement or retrofitting of existing fossil fuel power plants and a focus on enhancing and expanding the range of available low-carbon resources.

Overall, our review emphasizes the importance of optimizing the pace and scale of decarbonization in order to minimize costs and maximize benefits. By carefully considering the trade-offs between speed and cost, and by considering the range of factors that influence the costs of decarbonization, policymakers can design policies that are both efficacious and cost-effective.

Author Contributions

The main author, Abdullah Alotaiq, was responsible for all aspects of the paper, including formulating the research question, conducting the literature search, evaluating the studies, synthesizing the results, and writing the manuscript.

The other authors, Katherine A Collette, David Wallom and Malcolm McCulloch provided feedback on the manuscript and offered suggestions for improvement.

Declaration of Interests

The authors declare no competing interest.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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