




Muhammad Farqan Maqsood<sup>1</sup> & Abre-Rehmat Qurat-ul-Ann<sup>2</sup>

<sup>1</sup>Assistant Professor, Department of Economics, Government Allama Iqbal College, Sialkot, Pakistan

<sup>2</sup>Assistant Professor, Department of Economics, University of Gujrat, Gujrat, Punjab, Pakistan

KEYWORDS	ABSTRACT
Carbon Lock-in, Path Dependency, Decarbonization, Fossil Fuels, Committed Emissions, Climate Change	Carbon lock-in refers to the self-reinforcing inertia that keeps the process of decarbonization restricted. The literature on carbon lock-in has rapidly grown but remains fragmented in terms of methodological approaches and regional focus. This study aims to fulfill the requirement of a systematic review to synthesize this fragmented literature. It considers hundred peer-reviewed papers from Scopus and Web of Science to synthesize conceptual evolution, the standard method of measurement, regional distribution and future research prospects in this area. The findings revealed that carbon lock-in emerged as a multidimensional phenomenon. Both qualitative and quantitatively analysis have been used to explore concept of carbon lock-in. A specific type of carbon lock-in defines mechanism over which different dimensions perpetuate lock-in. Research is geographically focused around high-income and upper-middle-income countries, with zero concentration on low-income countries. In addition, policy mix, financial redirection and technological innovations are categorized as lock-out elements to hasten decarbonization. The planning for decarbonization and management of the climate risks requires comprehensive strategy in order to handle political, economic and social factors. This study proposed a comprehensive future research agenda.
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<b>Correspondence</b>	<b>Abre-Rehmat Qurat-ul-Ann</b>
<b>Email:</b>	<a href="mailto:abre.rehmat@uog.edu.pk">abre.rehmat@uog.edu.pk</a>
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## INTRODUCTION

The climate change is the fundamental transformation that has entered the world into a new era of global policy shift. Rapid decarbonization is mandatory to meet the targets established under the Paris Agreement and consecutive warnings through evaluation reports by the Intergovernmental Panel on Climate Change (IPCC) have pointed out the importance of rapid decarbonization. The

world has made substantial technological progress towards green products such as solar panels and electric vehicles, but greenhouse gas emissions have remained consistently high during this process. The carbon emissions from fossil fuel consumption reached 38.1 billion tons in 2025. Still after a decade of adopting ambitious goals under Paris Agreement, fossil fuel energy fulfills almost 80% of global energy needs (Energy Institute, 2025). Research on carbon lock-in has expanded noticeably over the past two decades, but the focus of research remains fragmented conceptually, empirically, and regionally. The consistency of emissions indicates institutional, technological, and structural embeddedness of the fossil energy creating systematic barriers which restrict the transition towards renewable energy.

The carbon lock-in is the framework that explains these systematic barriers. Unruh (2000, 2002) introduced the concept of carbon lock-in based upon the path dependency theory of development (Arthur, 1989), and defined it as techno-institutional complex that restricts the process of transition and sticks to fossil fuels due to increasing returns to scale. Carbon Lock-in refers to infrastructure and technological investment with longer lifespans (Erickson, Kartha, Lazarus & Tempest, 2015). Seto, Davis, Mitchell, Stokes, Unruh and Ürge (2016) described it as the self-perpetuating inertia that keeps path dependency due to mutually reinforcing economic, social and physical limitations. Carbon lock-in emerges through these channels, that create choice while quantifying it. Similarly, the geographical focus also varies amid the researchers, including developed and underdeveloped countries. Heavy dependence on carbon intensive technologies also restricts transition, despite the availability of superior options (Niu & Liu, 2021; Trencher, Rinscheid, Duygan, Truong & Asuka, 2020). Hence, carbon lock-in is a path dependent mechanism that stabilizes the carbon intensive technologies, institutions, social behaviors and resource bequests that make transition politically hostile and expensive.

### LITERATURE REVIEW

Carbon lock-in is categorized into sub-fields including technological carbon lock-in, institutional carbon lock-in, resource endowment carbon lock-in, social behavioral carbon lock-in, and political carbon lock-in. Technological carbon lock-in continues due to infrastructure durability, capital with extended lifespans, and fossil fuel-based technologies (Unruh, 2000). It usually exists due to heavy investments in capital intensive infrastructure with an average lifetime of 30 to 50 years. Power plants, pipelines, boilers, urban infrastructure, and personal cars are common examples of this lock-in (Unruh, 2000; Seto et al., 2016; Fisch, Guivarch, Creutzig, Minx & Callaghan, 2021; Li, Shen, Zhong, Elshkaki, Li & Li, 2026; Kotilainen, Aalto, Valta, Rautiainen, Kojo & Sovacool, 2019; Rentier, Lelieveldt & Kramer, 2019; Liu, Guo, Wagner, Liu, Cui & Mauzerall, 2024; Roth, Adams, Jaramillo & Muller, 2022). Institutional or political carbon lock-in is embedding of institutional framework is with carbon intensive technologies due to increasing returns (Unruh, 2000; Seto et al., 2016; Malz et al., 2023; Hu & Xu, 2025; Nacke et al., 2022; Rentier et al., 2019; Chou & Liou, 2023; Cho et al., 2023).

The coexistence of carbon intensive technologies as well as institutional structure keeps the path dependency and policy inertia. Subsidizing fossil energies and tax exemptions on brown products are its classic example. Resource endowment carbon lock-in arises due to abundance of resources

that naturally establish resource based industrial structures and economic dependence that keep these locked in around high carbon intensity (Chen, Liu, Ni & Chen, 2023). Abundant resources are cheaper and readily available materials that keep production process smooth and less costly. Power generation, steel industry and refineries are examples of resource endowment carbon lock-in. Social behavioral carbon lock-in encompasses social practices like high carbon severe lifestyle, cultural rigidities & energy intensive consumption, creating hurdles in transition toward fossil fuel alternatives (Chen et al., 2023; Seto, 2016; Niu & Liu, 2021; Mi, Sun, Qiao, Jia, Yang & Lv, 2021; Kotilainen, Aalto, Valta, Kojo & Sovacool, 2019; Bauer & Fontenit, 2021; Haarstad, Sareen, Kandt, Coenen & Cook, 2022).

Driving personal cars instead of using public transport, the use of air conditioners, and unplanned urban stretches are social behaviors co-evolved with the techno-institutional complex and further deepen the carbon lock-in. The conceptual emphasis ranges from technological carbon lock-in to resource endowment carbon lock-in, industrial carbon lock-in, social behavioral carbon lock-in, and institutional carbon lock-in. Numerous measurement methods and diverse range of variables have been used to quantify the carbon lock-in. Some scholars used a single variable as a proxy of the carbon lock-in (Mattauch et al., 2015; Meijden & Smulders, 2017; Erickson, Kartha, Lazarus & Tempest, 2015; Pofoura, Sun, Antwi & Antwi, 2020) while others developed a inclusive index considering different dimensions (Chen et al., 2023; Liu et al., 2023; Niu & Liu, 2021; Zhao, Zhong, Liu & Xing, 2024a, 2024b). In a broader sense, econometric models, composite index construction, capital stock-based approaches and structural decomposition methods have been employed to measure carbon lock-in. The emergence of a variety of measurement methods owed to multiple sources of carbon lock-in, such as technological inertia, institutional rigidity, consumption patterns, & life of infrastructure.

For sustainable development, a green transition and decarbonization policy is extremely important to address the ambiguities and measurement inconsistencies (Chen, Liu, Ni & Chen, 2023). The conceptual clarity and a common measurement method are required for a clear understanding with respect to sustainable development and policy formulation (Pofoura, Sun, Antwi & Antwi, 2020). Given the importance of carbon lock-in, this study aims to synthesize the theoretical foundations for conceptual clarity, map its manifestations across regions, classify and critically assess measurement methods, identify research gaps in the literature, and generate implications for future research and policy formulation for carbon lock-out. In this linking, this study addresses the following research questions and objectives; How has carbon lock-in evolved conceptually over time? How is carbon lock-in measured in the literature, and what are its limitations? What are the implications of the carbon lock-in for decarbonization, and what research gaps remain in the literature? The rest of the paper is structured as follows. Section 2 elaborates the methodology for the systematic literature review. Section 3 synthesizes the literature, and Section 4 provides the conclusion with appropriate recommendations.

## RESEARCH METHODOLOGY

This study employs a systematic qualitative review design to synthesize the available literature to understand the theoretical foundations, measurement methods, and implications of carbon lock-in.

The choice amid review methods depends on available data, specific research questions, objectives of research review and characteristics of review methodology. Systematic review minimizes bias and provides a reliable summary of existing literature. The method is highly structured, transparent, and rigorous (Gentles et al., 2016; Grant & Booth, 2009; Aromataris & Pearson, 2014). The review follows Preferred Reporting Items for Systematic Reviews & Meta-Analysis (PRISMA) 2020 plans for the identification, evaluation, inclusion, exclusion, reporting as well as synthesizing the literature (Haddaway et al., 2022).

### Search Strategy and Identification

The study uses electronic databases 'Web of Science' and 'Scopus' to search literature for review. The search queries included terms carbon lock-in, fossil fuel lock-in, and carbon path dependency. Moreover, the study considers the research articles published in the English language between 2000 and 2025 for the review process. The subject areas are energy, social sciences, environmental science, and economics have been chosen to select the desired peer reviewed literature for analysis. In this connection, from the existing accessible and available literature, the titles and abstracts of the individual research articles on the research issues had been evaluated, and irrelevant ones have been excluded.

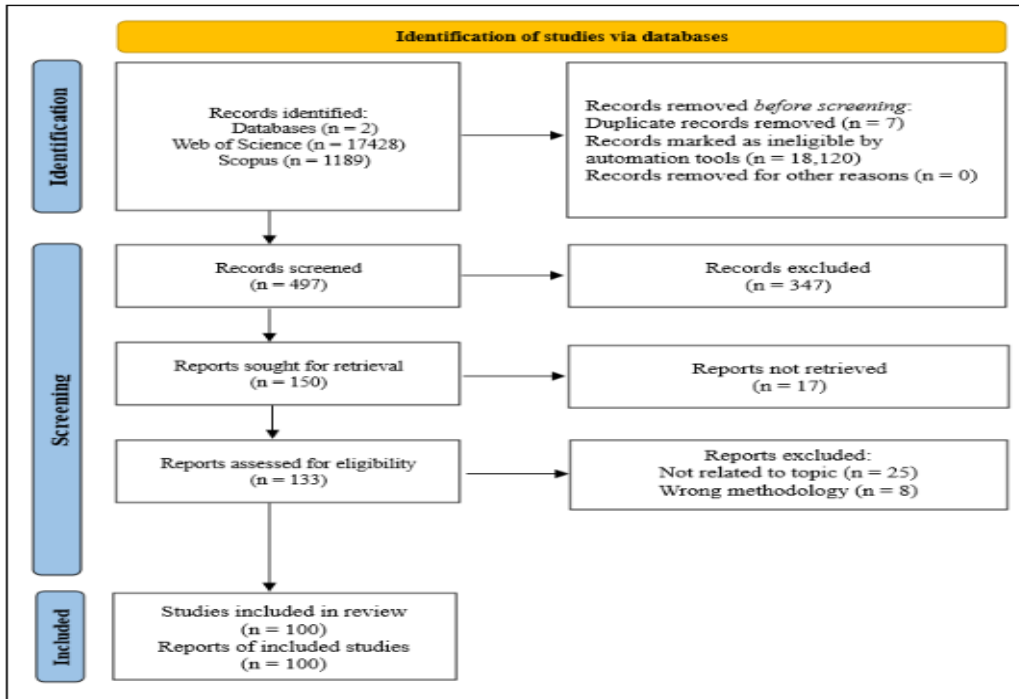
### Inclusion and Exclusion Criteria

The criteria used for inclusion in the review process is that only published articles are included and book chapters, books, research reports and proceedings of conferences are excluded, and the study includes articles that are more relevant to the research questions. Furthermore, the basic criteria for inclusion are as follows; i), the studies must have theoretical or empirical contribution regarding quantification of carbon lock-in, ii) the year of article publication should be between year 2000 to 2025, iii) publication language should be English, iv) broader area of research must fall within energy, economics or social science, and v) source of publication must be peer-reviewed for desired extraction of information. Any study that did not fulfill the inclusion criteria has been excluded from the analysis.

### Screening and Selection Procedure PRISMA

Two databases i.e. Scopus and Web of Science are explored for the identification of relevant studies, where initial search identified 17,428 articles from Web of Science and 1189 articles from Scopus. After careful screening through automation tools, 497 papers were included for detailed screening. Out of these 497 articles, this study carried out a detailed screening of titles and abstracts of 234 papers from Web of Science and 263 from Scopus. 347 studies were excluded based on the title and abstract scrutiny process, while the remaining 150 papers were shortlisted for retrieval for further analysis. From 150 studies, 17 could not be included due to no significant conceptual or measurement contribution. Finally, after thorough investigation of 133 studies, 25 studies were dropped due to non-relevance to research questions and 8 were excluded due to methodology weaknesses. Lastly, 100 studies have been finalized, selected and included for this literature review analysis of carbon lock-in. Figure 1 presents process of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) using flow diagram encompassing identification, screening & inclusion processes (Haddaway et al., 2022).

Figure 1 PRISMA flow Diagram for Identification, Screening & Inclusion of Studies



Source: Haddaway et al. (2022)

## ANALYSIS & DISCUSSION

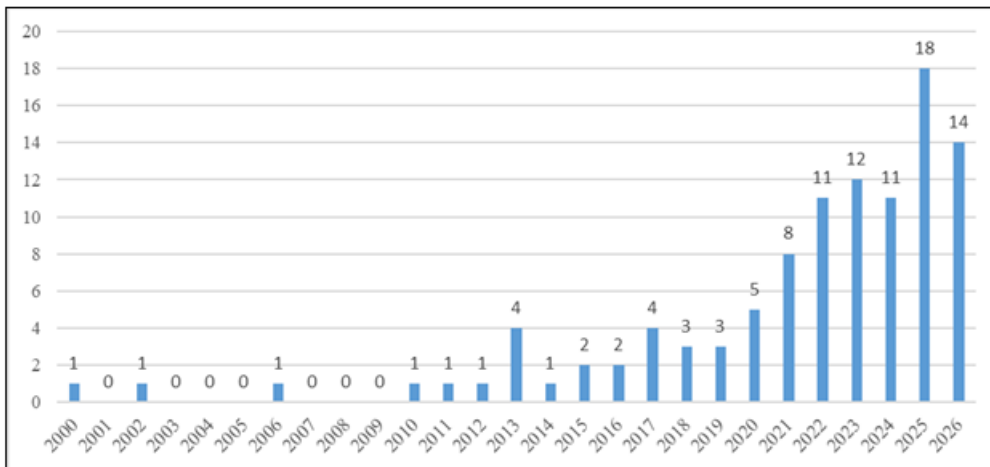
The study synthesizes literature on carbon lock-in by seeing 100 peer reviewed papers from WOS & Scopus databases.

### Conceptual Evolution of Carbon Lock-in

The study explores conceptual evolution of concept, critical assessment of measurement methods, geographical distribution of studies and implications for decarbonization. The foundational work of Unruh (2000) introduced the concept of carbon lock-in and defined it as the path dependency of industrial economies due to techno-institutional co-evolution. Unruh (2002) extended that carbon lock-in phenomenon is persistent & cannot be escaped without external forces. Erickson et al. (2015) and Mattauch et al. (2015) added economic factors and market inefficiencies along with techno-institutional factors that hinder the transition towards renewable fossil fuels. Seto et al. (2016) also identified social constraints and declared carbon lock-in a multidimensional problem. The roots of carbon lock-in originated in theory of path dependence, which states that historical development of institutions, technology, and decision-making shapes current arrangements. Once path is chosen, it is difficult to change due to high switching costs. In addition to high switching costs, increasing the returns, sunk costs, and network externalities lead to the creation of lock-in with the persistent inefficiencies & suboptimal technologies, which provide basis for long-term dependence on carbon-intensive structures.

The concept of carbon lock-in emerged in 2000 in climate change and energy economics literature to explain carbon intensive energy systems. Earlier contributions by Unruh (2000, 2002), Unruh and Carrillo (2006), Erickson et al. (2015), Mattauch et al. (2015), and Seto et al. (2016) emphasize how infrastructure, institutions & technology are making transition difficult from path dependency. Carbon lock-in gained popularity among researchers over the last ten years. Figure 2 explains the history of publications on carbon lock-in. Till 2009, there were only three publications written by Unruh (2000, 2002) and Unruh and Carrillo (2006). After 2013, the number of publications each year substantially improved and reached 18 in 2025 and 14 in 2026. This positive trend supports the earlier argument of the conceptual evolution of carbon lock-in. The inclusion of institutions, economic and social dimensions, led to a multidimensional understanding of carbon lock-in. For instance, power plants, a network of gas pipelines, building structures, high-value technologies, and technologies that support increasing returns to scale have been identified as factors that perpetuate carbon lock-in in long run (Fisch et al., 2021; Li et al., 2026; Kotilainen et al., 2019; S. Liu et al., 2024; Roth et al., 2022).

Figure 2 Number of Publications Each Year on Carbon Lock-in in WOS & Scopus



Source: Authors' work.

Table 1 shows selective references that explain the conceptual evolution and maturity of the carbon lock-in. It synthesized the key definitions from foundational studies to reveal different phases of the conceptual development. The first phase is establishment of carbon lock-in as techno-institutional complex (Unruh, 2000), which was later extended to the self-referential inertia (Unruh, 2002). The focus of the definition during this phase is on origins and persistence of carbon lock-in. The second phase extends the discussion beyond the techno-institutional complex to infrastructure and social behaviors. The focus of the concept during second phase also shifted from origins and persistence to lock-out (Erickson et al., 2015), economic inefficiencies (Mattauch et al., 2015), multidimensionality (Seto et al., 2016), and political disruption (Bernstein & Hoffmann, 2018). The recent literature has shifted the focus to policy relevance of carbon lock-in and its application in specific sectors. Bauer and Fontenit (2021) applied the concept to petrochemical and plastic industries while connecting

infrastructural lock-in with institutional and behavioral lock-in and defined it as "the continued expansion of plastics production all over the world which entrenches modern societies in necessity on fossil resources".

Chou and Liou (2023) discussed the policy failures regarding carbon tax under the high-carbon industrial structure combined with techno-institutional lock-ins. Tan and Chen (2025) and C. Zhao et al. (2023b) defined lock-in as a state of high carbon path dependence that hinders the low-carbon transition. The citation counts in column (4) of table 1 explains how many times each paper has been cited by other studies (Scopus, 2026). The number of citations serve as an indication of scholarly influence of the study, where high citation count indicates more influence. Unruh (2000) is at the top with 2242 citations, which is a recognition of its seminal work in this field. The second paper by Unruh (2002) has also been cited 774 times, but Seto et al. (2016) takes the second place with 847 citations. The high number of citations of Seto et al. (2016) following Unruh (2000) shows a shift towards multidimensional framework. Though various dimensions explain underlying drivers of carbon lock-ins, but detailed classification into diverse types captures the mechanism over which these lock-ins persist.

The table 2 provides a summary of the types of carbon lock-in identified in the literature. The types identified in literature are technological carbon lock-in, institutional carbon lock, social behavior carbon lock-in, industrial carbon lock-in & economic or financial carbon lock-in. The technological lock-in is identified by Unruh (2000), Seto et al. (2016), Fisch-Romito et al. (2021), Li et al. (2026), Kotilainen et al. (2019), Rentier et al. (2019), Liu et al. (2024), and Roth et al. (2022). The conceptual clarity and a common measurement method are required for a clear understanding with respect to sustainable development and policy formulation (Pofoura, Sun, Antwi & Antwi, 2020). This lock-in is primarily based on carbon-intensive infrastructure, fossil fuel-based energy systems, and long-lived capital. Infrastructure and long-lived capital include buildings, dams, industrial structures, power plants, and pipelines that live for longer period of time & make transition difficult. Similarly, heavy dependence on oil, gas & coal also creates path dependency despite the availability of low-carbon alternatives.

**Table 1 Definition & Evolution of Carbon Lock-In**

Author(s) (Year)	Definition of Carbon Lock-in	Key Focus of Definition	Citation
Unruh G.C. (2000)	"Industrial economies have been locked into fossil fuel-based energy systems through process of technological & institutional co-evolution driven by path-dependent increasing returns to scale."	Origins: Techno-institutional co-evolution, path dependence.	2,242
Unruh G.C. (2002)	A state resulting from a "techno-institutional complex" (TIC), where large technological systems and governing institutions become intertwined, making escape unlikely without external forces.	Persistence: The self-referential nature of the TIC.	774
Erickson et al. (2015)	"Tendency for certain carbon-intensive technological systems to persist over time, 'locking out' lower-carbon alternatives, and owing to a combination of linked technical, economic, and institutional factors."	Lock-out Effect: The active exclusion of alternatives.	185
Mattauch et al.	A market condition where fossil fuel-based ("dirty")	Economic Inefficiency:	96

(2015)	technologies dominate despite carbon-free ("clean") alternatives being dynamically more efficient.	Market failure due to path dependency.	
Seto et al. (2016)	"The inertia of carbon emissions due to... mutually reinforcing physical, economic, and social constraints." Authors identify 3 types: infrastructural/technological, institutional, and behavioral.	Multi-dimensionality: A systematic review synthesizing types and causes.	847
Bernstein & Hoffmann (2018)	Discusses "carbon lock-in" as the entrenched system that the Paris Agreement's catalytic mechanism aims to disrupt through diverse, decentralized responses like subnational climate experiments.	Political Disruption: Focuses on mechanisms (normalization, capacity building) to overcome lock-in.	189
Rentier et al. (2019)	"Institutional carbon lock-in processes as significantly affect the phase-out of the use of coal." In Coordinated Market Economies (CMEs), this translates in protection of uncompetitive domestic coal activities through subsidies and veto power.	Institutional Persistence: Comparative political economy of coal phase-out.	115
Gürsan & de Gooyert (2021)	Warns that natural gas, while a "transition fuel," can create negative long-term effects (carbon lock-in) that outweigh its short-term benefits if not carefully managed.	Systemic Risk: The unintended, delayed consequences of transition fuels.	220
Bauer & Fontenit (2021)	"The continued expansion of plastics production all over the world entrenches modern societies in dependence on fossil resources." Connects infrastructural lock-in to institutional and behavioral lock-in in the plastics industry.	Sectoral Application: Applying lock-in theory to the petrochemical and plastics sector.	49
Chou & Liou (2023)	In Taiwan, "high-carbon industrial structure" combined with government, industry, and business federations generated "institutional, cognitive, techno-institutional complex lock-ins," hindering the adoption of a carbon tax.	Policy Failure: Analyzing why carbon pricing fails due to a "high-carbon regime."	15
Zhao C. et al. (2023b)	A pressing environmental issue in Chinese cities, representing a state of high-carbon path dependence that hinders low-carbon transition.	Contextual Application: Urban and industrial challenge in a national context.	69
Tan, Chen Y. (2025)	"A state of high carbon path dependence, which hinders low-carbon transition of industrial economies under a carbon-neutral vision."	Barrier to Neutrality: An obstacle to achieving long-term climate goals.	6

Source: Authors' Work.

The behaviours also give rise to a certain carbon lock-in. Consumption patterns, cultural norms, and consumer habits form the social behavior (Seto et al., 2016; Mi et al., 2021; Y. Chen et al., 2023; Kotilainen et al., 2019; Bauer & Fontenit 2021; Haarstad et al., 2022), Energy-intensive behaviors that create pressure through the high energy demand through mobility and transport, cooling and heating systems, and energy-inefficient buildings are such behaviors which create social rigidities that restrict the change. Thus, governance, institutional or political carbon lock-in is the result of governance structures, policies, regulations, and political interests (Unruh, 2000; Seto et al., 2016; Malz et al., 2023; Hu & Xu, 2025; Nacke et al., 2022; Rentier et al., 2019; Chou & Liou, 2023; Cho

et al. 2023). Formulation of policies and regulations that support the use of fossil fuels and political structures which work in favor of the vested interests that further make the transition harder and create policy inertia.

Along with technological carbon lock-in, industrial lock-in is a specific type of lock-in where a specific sector or industry is locked into a high-carbon production process and supply chains. Steel, chemicals and power sectors are prime examples of industrial lock-in. Zhao et al. (2023), Wang et al. (2020), Tu et al. (2025), Chen X. et al. (2021), Wachtmeister & Höök (2020), and Stewart (2022) provide evidence of specific industrial carbon lock-in which are the result of a specific production process which is difficult to change due to higher replacement cost and increasing returns to scale. Erickson et al. (2015), Chen et al. (2021), Bourdin & Perrot (2026), Wachtmeister & Höök (2020), and Stewart (2022) defined type of carbon lock-in named as financial or economic carbon lock-in. It is a system where financial decisions, such as investment patterns, market structures, and financial developments favor high usage of fossil fuels & support industries that create bulk of stranded assets and carbon traps.

**Table 2 Summary of Types of Carbon Lock-in Identified in Literature**

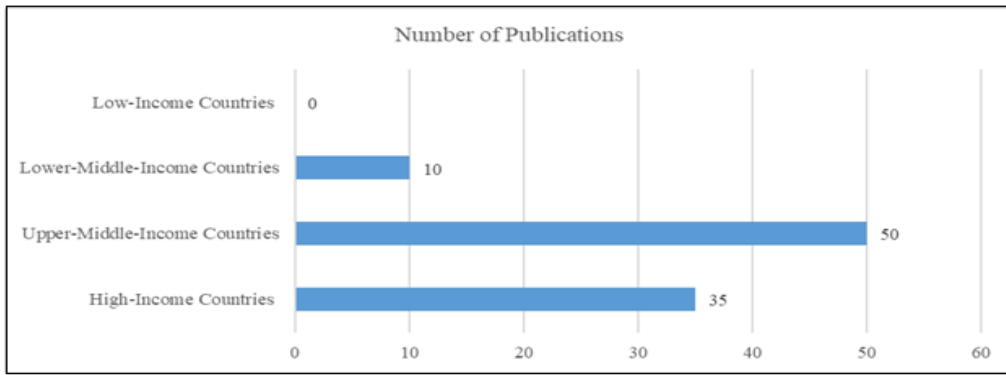
Lock-in Type	Description / Mechanism	References
Infrastructural & Technological	Long-lived physical capital (power plants, pipelines, buildings) and dominant technologies create high switching costs & long-term emission commitments.	Unruh (2000); Seto et al. (2016); Fisch-Romito et al. (2021); D. Li et al. (2026); Kotilainen et al. (2019); Rentier et al. (2019); S. Liu et al. (2024); Roth et al. (2022)
Institutional & Political	Governance structures, laws, regulations, and political interests co-evolve with and reinforce the existing technological system, creating policy inertia.	Unruh (2000); Seto et al. (2016); Malz et al. (2023); Hu & Xu (2025); Nacke et al. (2022); Rentier et al. (2019); Chou & Liou (2023); Cho et al. (2023)
Behavioral / Social	Social norms, consumer habits, and cultural expectations (for mobility or consumption) become normalized and difficult to change, reinforcing demand for carbon-intensive services.	Seto et al. (2016); Mi et al. (2021); Chen Y. et al. (2023); Kotilainen et al. (2019); Bauer & Fontenit (2021); Haarstad et al. (2022)
Industrial	Specific industrial sectors (e.g., steel, chemicals, power) are locked into high-carbon production processes and supply chains.	F. Zhao et al. (2023); X. Wang et al. (2020); Tu C. et al. (2025); X. Chen et al. (2021); Wachtmeister & Höök (2020); Stewart (2022)
Economic / Financial	Financial systems, investment patterns, and market structures favor incumbent carbon-intensive industries, creating a "carbon trap" and risk of stranded assets.	Erickson et al. (2015); X. Chen et al. (2021); Bourdin & Perrot (2026); Wachtmeister & Höök (2020); Stewart (2022)

Source: Authors' Work.

The dimensions of carbon lock-in provide specific category of variables that perpetuate the lock-in, whereas a specific type of carbon lock-in defines the mechanism over which different dimensions perpetuate carbon lock-in. The inclusion of these types and dimensions provides a comprehensive analytical framework for the better understanding of carbon lock-in. These types create reinforcing mechanism. Thus, interdependence of these types allows inclusion and formation of comprehensive carbon lock-in index. Besides, emphasis of literature on multidimensionality, such as technological,

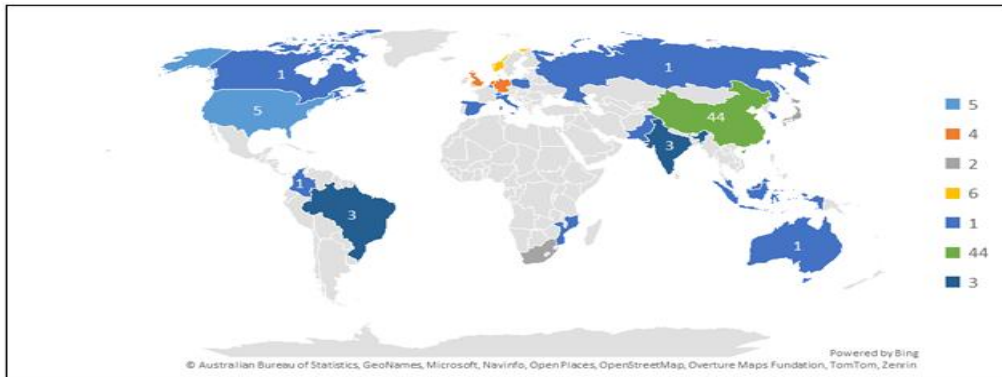
institutional, behavioral, and industrial, is justified by interconnection amid them. Figure 3 presents number of publications with respect to countries within different income levels. The data shows that high-income countries have 37% share in literature on carbon lock-in, followed by upper middle-income countries with 53% share, lower middle-income countries have 10% share, and low-income countries have 0% share. A major portion of literature on carbon lock-in originates from two high-income groups, where energy transition and climate policies are more advanced than in bottom two income groups. The disparities with respect to literature are the result of disparities in capacity and data availability. This imbalance provides a clear and significant research gap with respect to low-income countries.

**Figure 3 Distribution of Literature on Carbon Lock-in across Different Income Groups**



Source: Authors' Work

**Figure 4 Geographical Distribution of Studies on Carbon Lock-in**



Source: Authors' Own Work.

The figure 4 provides a country-wise geographic mapping of the literature for an in-depth analysis. Among high-income countries US, Germany, UK, Netherlands and Nordic states (Norway, Sweden, Finland, Denmark) have dominant share with 5, 4, 4, 4, 6 research papers respectively. Whereas, China is leading with the highest number of research papers on the carbon lock-in among upper-middle-income countries, followed by the Brazil, with only 3 studies. From lower-middle-income countries, there are 3 studies on India. Uneven distribution is clear among different income groups

as well as within income groups. The research in developed regions is focused on lock-out strategies, institutional lock-in, just transition. However, in developing regions, it is more focused on carbon-exacerbating factors and strategies to avoid the carbon lock-in. The underrepresentation of lower-middle and low-income countries is an indication of underreporting of the carbon lock-in dynamics around the globe.

**Synthesis of Measurement Methods of Carbon Lock-in**

Literature covers both quantitative and qualitative measurement methods to estimate and assess the level of carbon lock-in. Only 14 studies have constructed an index or a model for quantification of carbon lock-in, whereas 35 studies used case studies, structured interviews, theories, or reviews only. 51 papers used a single variable proxy and quality assessment through mixed methods. The clear disproportion amid use of measurement techniques of carbon lock-in indicates that literature remains largely diverse in terms of the quantification. Specifically, quantification of carbon lock-in encompasses two approaches that are unidimensional & multidimensional. Measurement methods such as forecasted life of plants and infrastructure (Edianto et al., 2023) fall under the first category, but this type of index is used to measure specific industrial carbon lock-in, such as for the coal-fired power plants. Elasticity of substitution of factors of production amid clear & dirty sectors of economy (Mattauch et al., 2015), elasticity of switch amid fossil fuel and other factors of production (Meijden & Smulders, 2017), equipment lifetime, ratio of increase in carbon emissions & financial barriers to replace high carbon emitters with low carbon alternatives are used as tools to count carbon lock-in (Erickson et al., 2015).

Similarly, CO2 emissions directly represent carbon lock-in (Pofoura et al., 2020), but trajectory of CO2 emitted per unit of energy spent or energy used per unit of economic activity is considered a better measure of carbon lock-in than CO2 emissions (Bertram et al., 2015; Seto et al., 2016; Steckel et al., 2015; Zheng et al., 2018). Literature uses diverse methods to quantify carbon lock-in, namely, installed capacity of electricity generation (Bertram et al., 2015), age of electricity infrastructure stock (Zheng et al., 2018), devoted emissions, operation life of plant (Erickson et al., 2015), stranded assets (Cui et al., 2019), carbon overload– difference amid carbon sink and CO2 emissions (Xu et al., 2022) ratio of fossil fuel consumption to total energy consumption (Mi et al., 2021; Steckel et al., 2015) and carbon emissions coefficient (Wang et al., 2022). Multidimensional categories include technological, institutional & social behavioral dimensions to construct a composite index (Chen et al., 2023; Liu et al., 2023; Niu & Liu, 2021; C. Zhao et al., 2024a, 2024b). This method calculates a separate index for each dimension and then calculates an index. Multiple approaches like entropy method, principal component analysis, projection pursuit models exist to calculate index with their unique characteristics.

**Table 3 Summary of Measurement Approaches in Carbon Lock-in Literature**

M- Methods	Description	Application	References
Committed Emissions	Cumulative CO2 emissions that would occur over the remaining operational lifetime of existing capital (power plants, vehicles).	Assessing emissions from steel plants (Vogl et al., 2021) or overseas financed power plants (Chen X. et al., 2021).	Davis & Socolow (2014); Erickson et al. (2015); Fisch-Romito et al. (2021)
Stranded Assets	The value of assets (such as coal	Evaluating financial risk of coal	Erickson et al. (2015);

	plants) that are retired early or become under-utilized due to climate policy or economic shifts.	power in China (Wang Y.-H. et al., 2022).	Fisch-Romito et al. (2021); Kemfert et al. (2022)
Composite Index	A multi-dimensional index combining indicators across technological, institutional, economic, and social dimensions into a single score.	Measuring provincial and urban carbon lock-in levels in numerous Chinese studies.	Niu & Liu (2021); Chen et al. (2023); C. Song et al. (2025); C. Zhao et al. (2023a, 2024b)
Qualitative/ Case Study Analysis	In-depth analysis of historical, political, and social processes that lead to lock-in in a specific context.	Analyzing the perpetuation of coal power in Japan (Trencher et al., 2020) or the CCS-hydrogen nexus in Europe (Faber et al., 2025), Comparing coal phase-out in Germany, Poland, Spain, and the UK (Rentier et al., 2019); analyzing carbon tax failure in Taiwan (Chou & Liou, 2023).	Unruh (2000); Seto et al. (2016); Corral-Montoya et al. (2022); Kotilainen et al. (2019); Haarstad et al. (2022); Janipour et al. (2021, 2020)
Agent-Based Modeling (ABM)	Modeling heterogeneous actors with bounded rationality to see how their investment decisions and interactions can lead to path-dependent outcomes.	Showing how historic path-dependency and competitor imitation affect the low-carbon transition in the UK, German, and Italian electricity sectors (Barazza & Strachan, 2021).	Barazza & Strachan (2021)
System Dynamics (SD)	Using causal loop diagrams and stock-and-flow models to understand the feedback mechanisms that create and reinforce lock-in.	Analyzing contrasting narratives on CCS in the Netherlands (Janipour et al., 2021); creating a deliberation platform for energy transition policies in Latvia (Blumberga, Gravelins & Blumberga, 2022).	Janipour et al. (2021); Gürsan & Gooyert (2021)
Energy System Modeling (e.g., TIMES, IMACLIM)	Using large-scale energy-economy models to simulate the impact of policies and technologies on long-term decarbonization pathways and potential lock-in.	Analyzing policy spillovers and technology lock-in in the U.S. (Roth et al., 2022); overarching vs. transport-specific EU targets (Gherzi, McDonnell & Sassi, 2013).	Fais et al. (2016); Nikas et al. (2024)

Source: Authors' Own Work.

The limited adoption of composite or multidimensional indices suggests challenges related to data availability, complexity of quantification methods, as well as the non-availability of standardized measurement techniques. Alternatively, this disproportion indicates a clear methodological gap and indicates the shortcomings of existing methodologies to capture the multidimensional nature of carbon lock-in. Thus, methodological improvement is particularly important to bridge the gap between the evolving conceptualization of carbon lock-in and its quantification while considering multiple dimensions like technological, institutional, social behavior, resource endowment and industrial. Hence, the use and application of the comprehensive index is an important direction for future research. Thus, table 3 extends the explanation on methodological distribution of reviewed

studies using a summary of Carbon lock-in measurement approaches and their classification in the sample literature.

Table 3 illustrates methodological evolution of measurement mechanism. Despite the emergence of various measurement methods, the challenge of measuring “invisible” still exists. These “invisibles” are quantification of institutional and behavioral lock-in. Both lock-ins are qualitative in nature and there does not exist any method that can directly quantify these lock-ins. Number of studies like [Niu and Liu \(2021\)](#), [Chen et al. \(2023\)](#), [Song et al. \(2025\)](#), [Song & Zachariadis \(2019\)](#) and [Zhao et al. \(2023, 2024\)](#) have used composite indices to quantify the entire set of carbon lock-in. [Chen et al. \(2023\)](#), [Song et al. \(2025\)](#) and [Zhao et al. \(2023,2024\)](#) employed entropy method to calculate the final value of carbon lock-in while [Niu and Liu \(2021\)](#) used Projection Pursuit with Real coded genetic algorithms. [Barazza and Strachan \(2021\)](#) used emerging method of agent-based modeling, [Janipour et al. \(2021\)](#) applied system dynamics, [Zhu and Rao \(2024\)](#) employed machine learning method. ABM, SD and ML are advanced computational approaches that help to understand how initial decisions create rigidity toward transition and high abatement cost. Thus, the application of advanced techniques for the measurement of carbon lock-in and to explain its sources is a potential area of exploration.

### Implications of Carbon Lock-in for Decarbonization

Carbon lock-in, being self-perpetuating inertia that keeps the carbon dependency intact, has profound implications for decarbonization goals set under Paris agreement. It is particularly vital to understand implications of carbon lock-in for diagnosing key hurdles. Carbon pricing is identified as the most important tool in literature for the decarbonization, but [Tvinnereim and Mehling \(2018\)](#) disagreed with this argument. Policymakers should provide a policy mix that keeps focus on carbon pricing along with regulations, subsidies, and institutional reforms, as path dependent institutions protect carbon intensive industries through various means like subsidies and regulatory framework ([Rentier et al., 2019](#); [Chou & Liou, 2023](#)). The governance reforms must support decarbonization process to break these institutional restraints. Besides, policies must be designed in such a way that targets for 2030 must not lock in pathways for long term targets of 2050 ([Sotiriou & Zachariadis, 2019](#)). The review of literature indicates that an effective policy is not the only requirement, but removing ineffective ones is equally important for decarbonization. Policy sequence and timing is also important to break the carbon lock-in curse. [Nacke et al. \(2022\)](#) identified three phases of policy sequencing.

The first phase is to break the lock-in, the second phase manages the backlash, and third phase enables recovery. Any delay in action can further deepen the lock-in ([Roth et al., 2022](#)) that is why policymakers need to devise a timely and dynamic policy. Carbon lock-ins have implications as billions of dollars are stuck in stranded assets and long-lived capital ([Erickson et al., 2015](#); [Vogl et al., 2021](#)). The shift towards renewables is imperative to minimize the potential impact of carbon lock-in but strains careful management to avoid economic disruption, therefore, overseas financial transfers can also exacerbate lock-in in this situation ([Chen et al., 2021](#)). Financial development must be redirected towards renewables and bilateral financial agreements must be reviewed under longer-term decarbonization commitments. Moreover, decarbonization must have a distributional

effect on income equality (Stewart, 2022) because carbon lock-in may create systemic financial risk and inequality traps. The context and external environment determine the role of technology. For example, natural gas can reduce emissions as compared to coal (Gürsan & de Gooyert, 2021), infrastructural expansion can unlock carbon in some areas & concurrently can reinforce it in others (Song et al., 2026).

Therefore, a policy formulation regarding technological and infrastructural development must be compatible with net zero goals. Infrastructure such as power plants, buildings, and transport last for decades (Liu et al., 2024; Seto et al., 2016). Implications of carbon lock-in for decarbonization at the societal level are most important element that can break carbon lock-in by shifting norms, cultures, and expectations. Literature revealed that household energy consumption forms behavioral lock-in (Mi et al., 2021) and the plastics industry shapes consumer behavior and delimit regulations to break lock-ins (Bauer & Fontenit, 2021). Social change is necessary condition for decarbonization. Education and social awareness can be useful to bring change in consumer behaviors, energy usage and for perfection in norms. The carbon lock-in has profound and multi-faceted implications for decarbonization. These implications suggest that decarbonization is not only a technical issue, and a comprehensive strategy is required to shift technological, institutional, industrial, economic and social domains to alleviate carbon emissions. The literature provides significant evidence of lock-out strategies but the requirement is to translate these strategies into practical solutions for dealing with climate crisis.

### Future Research Prospects for Carbon Lock-in

Significant research gaps exist despite a growing body of knowledge on carbon lock-in, and this review paper provides future research prospects to fill these gaps. The concept of carbon lock-in has evolved from technological and institutional systems (Unruh, 2000, 2002) and took the shape of a multidimensional phenomenon about technological, institutional, social behavioral, infrastructural & industrial dimensions (Unruh, 2000, 2002; Seto et al., 2016; Elahi, 2025; Olbrich & Bauknecht, 2024). There is a need to extend the analysis beyond measurement to the interaction of different types of carbon lock-ins and investigate their reinforcement to one another. The dimensional and methodological integration can provide more robust results. A methodological mix of quantitative and qualitative analysis provides more credible results and better strategic guidance. Agriculture, waste sector and finance are underreported areas with respect to carbon lock-in, despite significant contributions towards carbon emissions. Research on these areas will offer inclusive understanding of whole economy and lock-ins. Another understudied area of research is the micro-level dynamics of carbon lock-in.

Micro-level dynamics are particularly important for breaking the social carbon lock-in. Insights from the micro-level studies will answer the questions of how social norms lock in consumption and what mechanisms can break the lock-in. The literature lacks debate and investigation on the “lock-out” mechanism. Furthermore, as the literature puts strong focus on developed countries like China, US, UK, Germany, Netherlands, and Nordic Countries, there is a research gap on this issue in the Global South. Thus, an imbalance between literature from different income groups provides clear evidence. An in-depth analysis of the carbon lock-in dynamics for developing countries could be

the future course of action. These countries are the most vulnerable to climate change, and carbon lock-in can further elevate the risks. More specific studies on lower-income countries will provide evidence-based policy formulation mechanisms. Likewise, systematic comparison of lock-in and lock-out pathways under different institutional settings can be a rich area of exploration. Because limited attention has been given to governance and political structures that can successfully unlock the carbon rigidity.

Feasible political solutions for phasing out coal, oil and gas are required after careful discourse analysis. In spite of the numerous measurement methods from committed emissions to indices and econometric approaches, there exist serious concerns over standardization of measurement methods. A standard measurement method of carbon lock-in will make comparison easy, allow replicability, make policy guidance authentic, and offer space for meta-analysis. Besides, inclusion of forward-looking indicators to assess future lock-in from planned investments and policies will open new avenues of research with respect to forecasting. Accurate forecasting will help to manage carbon lock-in in advance, and lock-out will be easy. Research studies with respect to forecasting of carbon lock-in are particularly important for developing countries because they are more focused on economic development. Carbon lock-in is a reality now, but the unlocking mechanism is required and researchers have to find the best combination of strategies and conditions under which these strategies are more effective. These research areas are crucial to meet the short-term and long-term commitments of the Paris Agreement and to counter climate risks in future, both by developed and developing economies.

### CONCLUSION

This paper comprehensively synthesized the findings of 100 studies on carbon lock-in from Web of Science and Scopus covering diverse geographical regions, multiple methodologies, and numerous conceptual applications. The synthesis of literature reveals that in addition to being a technological issue, carbon lock-in is deeply embedded with institutional, industrial, resource and social progress over time. This area has moved from a simple description of theoretical foundations to empirical estimations and its multidimensional nature keeps the lock-out a formidable challenge. Literature provides empirical evidence of exacerbation of carbon lock-in through long-lived infrastructures, social norms, fossil fuel abundance and industrial settings which shows that carbon lock-in operates across different sectors. The review paper contributes to existing body of research on carbon lock-in in several ways. It provides a comprehensive synthesis of 100 Scopus and Web of Science peer-reviewed articles published within year 2000 to 2025. The geographical distribution reveals the distribution of research across countries and time. Extensive focus on China has been identified with huge research gap toward developing countries. A higher emphasis on carbon lock-in has emerged within past ten years.

This study highlights methodological integration while considering technological, institutional, social, resource and industrial dimensions. A thorough carbon lock-in literature investigation offers a future research agenda that addresses research gaps and decarbonization goals. The limitations of this review are the exclusion of non-English studies; the absence of books, book chapters, conference

proceedings; absence of policy reports and industrial analysis. These limitations may have excluded important insights from these sources. Under these limitations, study proposes a research agenda for policy and practice in the context of widespread application of carbon lock-in. The study proposes the shift of research from measurement of lock-in to development of unlocking mechanics, from single country to international and comparative analysis and interdisciplinary collaboration for transformation of entire set of systems to counter climate risks. Carbon lock-in is a reality and the entire world must deal with this collectively. In addition to decarbonization the entire life structure of the world has to be revised as carbon lock-in is the complex outcome of political, economic and social structures.

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