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Review

Locked in transition? Towards a conceptualization of path-dependence lock-ins in the renewable energy landscape

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ABSTRACT

In opposition to studies concerning fossil fuel-based energy systems, the transition literature often overlooks how path-dependence lock-ins affect the renewable energy landscape. Investigating this phenomenon is crucial because lock-ins can hamper the ability to keep pace with the evolving energy landscape, potentially hindering the shift from polluting energy systems to more sustainable alternatives. By laying the foundations for the conceptualization of renewable energy lock-ins, this study provides a framework for analyzing their influence on the energy transition process. It offers a literature review that introduces the various risks associated with these lock-ins, as opposed to their potential merits, illustrating them via empirical cases from different countries. The study reveals that lock-ins pose several risks to the renewable energy sector, including neglecting alternative technologies, impeding the promotion of decentralized facilities, limiting innovation, impairing energy justice, endangering the environment, and distorting the economic setting. It further discusses several incentives that may encourage various players to manipulate such lock-ins, including energy production, financial gain, power relationships, and environmental and social incentives. The study concludes by calling for a deeper conceptualization of renewable energy lock-ins while proposing a path for future research in this regard. By examining their impact on the renewable energy landscape, the research underscores the dual nature of lock-ins: they provide stability for the diffusion of renewable energy sources yet potentially reduce the capacity to adapt, change, or deviate from the established trajectory or path.

1. Introduction

While large energy systems based on fossil fuels can provide substantial amounts of energy with relative efficiency, they often harm the environment, emitting significant quantities of greenhouse gases and other pollutants [1]. Nevertheless, these energy systems dominated the global energy market for decades [2]. A common explanation for this dominance relates to the "carbon lock-in," i.e., the self-perpetuating inertia created by these systems, inhibiting efforts to introduce alternative energy technologies [3,4]. Some claim that the carbon lock-in results from a combination of different mechanisms, including path-dependence arising from historical investments, technological and infrastructural inertia that further hinders the transition to low-carbon alternatives, the economies of scale enjoyed by carbon-intensive technologies as well as institutional and policy barriers, which for various reasons may favor carbon-intensive systems [5].

Yet, the global energy transition process, characterized by the significant diffusion of renewable energy (RE) sources, has recently experienced relative success: RE sources have become widespread in many countries around the world, replacing large fossil fuel-based energy systems with cleaner means of energy production [6]. According to several indications, however, the RE landscape may also be influenced by path-dependence lock-ins [7,8]—a concept that is understood here as a process whereby past events constrain later developments, often leading to outcomes that cannot be easily reversed and/or altered [9]. Considering that RE sources have become a crucial component in the evolving energy sector [10], the lock-ins affecting them are often driven by similar underlying mechanisms to those at the core of the carbon lock-in: a combination of historical, technological, economic, policy, and institutional mechanisms [11,12].

On the one hand, such path-dependence lock-ins may provide certainty for the RE field, reducing transaction costs, easing the ability to raise capital, or increasing efficiency [13]. These merits are highly significant: they may facilitate greater penetration of RE systems at the

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expense of polluting fossil-fuel-based systems by reducing their relative costs and improving their performance [14]. However, on the other hand, path-dependence lock-ins may also reduce the flexibility of RE, leading to sub-optimal outcomes that cannot be easily altered [15]. While the energy literature often refers to the concept of flexibility as the ability to adjust supply and demand to achieve energy balance [16–18], in this study we refer to flexibility in a broader manner, one associated with the influence of lock-ins: the capacity of a system or process to adapt, change, or deviate from its established trajectory or path. Conversely, path dependency reduces flexibility by creating a lock-in "effect" whereby past choices restrict available options, making it difficult to transition to alternative paths [19]. In the framework of RE, such reduced flexibility may manifest in the inability to switch to different, even superior alternatives in terms of the chosen technology, the regulation scheme, the social setting, or the economic framework, given existing trajectories (e.g., [17,18]). The possible influence of lock-ins on RE sources may further increase the incentives to support fossil-fuel-based energy systems [22].

Although the literature has thoroughly discussed the role of lock-ins in various fields [23], it has mostly avoided addressing them extensively in the framework of RE, presuming that they do not affect this malleable field [24,25]. Hence, in opposition to energy systems based on fossil fuels [3,4], the transition literature has not delved into the influence of path-dependence lock-ins on the RE landscape, addressing this issue only anecdotally. The several studies focusing specifically on the role of lock-ins in RE mainly adopt a technological prism [7,8,26], neglecting other important aspects relating to social, economic, environmental, and regulatory factors.

This research lacuna limits our understanding of whether the RE landscape can adapt to the energy sector's growing need for new opportunities and a greater degree of freedom given the possible impact of lock-ins on the flexibility of RE [27]. As the world aims to reach 100 % RE as part of global efforts to address climate change [28], it is of the utmost importance that we explore the flexibility of the RE landscape and the factors that may impede it. The energy sector is in a constant state of flux, encompassing changes in both supply and demand. This dynamic leads to the emergence of new systems and technologies, coupled with shifts in behaviors and needs, all intertwined in a complex process [29–32]. To navigate and respond to these changes effectively and in a balanced manner, flexibility, in the sense of its comprehensive definition in this study–the ability to adapt, transform, or veer from paths or trajectories established in the past [19]–is of paramount importance. Consequently, decreased flexibility within the RE landscape, stemming from entrenched practices of lock-ins, can lead to the neglect of superior alternatives and reduce the capacity to keep pace with the ongoing transformations in the energy sector in a harmonious manner. This, in turn, may impede efforts to replace polluting energy systems with more sustainable means of energy production, hindering the struggle against climate change [22].

The current study seeks to address this lacuna by exploring the influence of path-dependence lock-ins on the RE landscape. In particular, it aims to shed light on the risks RE lock-ins may entail, in contrast to their possible benefits [14,33]. This is achieved by providing the basis for understanding the notion of RE lock-ins, their possible implications, and the incentives for manipulating them. The study, therefore, lays the foundations for conceptualizing RE lock-ins, which should improve our understanding of how they shape the energy transition process. Building upon these foundations, it calls upon scholars to deepen the conceptualization and offer a more holistic comprehension of the multifaceted influence of RE lock-ins.

This study relies upon an extensive literature review that enables us to introduce the various risks lock-ins may pose to the RE landscape, including possible implications and manipulations. The added value of this review, based on Van Wee and Banister's (2016) perspective, is that it highlights an overlooked research agenda, specifically concerning RE lock-ins [34]. Despite the anecdotal theoretical references to RE lock-ins, as reviewed in this study, the existing academic literature has offered limited empirical illustrations of this phenomenon. Consequently, we aim to fill this gap by illustrating the risks associated with RE lock-ins using a variety of new empirical cases from different countries, partly based on "grey literature." By combining a review of existing literature with new empirical examples, we offer a more holistic view of the topic while demonstrating how the theoretical concept of RE lock-ins is applied in practical settings. Notably, scholars have acknowledged the usefulness of this combined approach, in which a literature review is complemented by new empirical examples, in comprehensively covering an overlooked research agenda [35–38].

This study is relatively broad, providing the framework for a general conceptualization that presents an array of cases from multiple countries with different regulatory structures and characteristics. Indeed, more than 200 documents, including academic studies and "grey literature," were reviewed in the writing of this study. The academic studies were collected by searching popular academic databases–Web of Science, SCOPUS, Google Scholar, and TRID [39]. The search was based on different combinations of relevant keywords, including "renewable energy," "lock-ins," "path-dependency," "socio-technical systems," and "sustainable transition." By reviewing a wide range of studies, we succeeded in identifying common themes, patterns, and trends across a diverse set of studies and cases, which is especially important in the context of RE lock-ins. This enabled us to identify analytically the different risks associated with RE lock-ins as well as their implications and manipulations. Simultaneously, by providing an in-depth review of select individual documents, we were able to offer a deeper and more nuanced analysis of fundamental notions that constitute the theoretical basis of this study, including the notion of lock-ins as part of socio-technical transitions. Thus, incorporating an in-depth review together with the analysis of a significant number of documents provides a balanced approach that comprehensively covers the topic of RE lock-ins while allowing for a detailed exploration of the theoretical basis of the study [34].

Beyond academic articles, the empirical examples presented throughout the study were extracted from "grey literature," including governmental policies and regulations, online newspaper articles, third-party position papers, conference papers, preprints, and reports. These documents were located by searching the aforementioned academic databases as well as using more general web search engines, most notably Google. The empirical examples were chosen based on a narrative perspective [40], aiming to illustrate the different risks associated with RE lock-ins, as identified throughout the review. Hence, the initial criterion for selecting the documents behind the examples pertained to their alignment with the theoretical findings on lock-ins. A second criterion considered the variety of examples, specifically the representation of lock-ins from diverse countries to enhance result generalization. Finally, the third criterion was source reliability: priority was accorded to academic journals, official state documents, or those from accredited research institutions whenever available. In the absence of such documents, online newspaper sources or preprints were utilized, while ensuring the credibility of the authors or sources [41].

This study contributes to the transition literature by shedding light on the dual nature of lock-ins in the RE field, thus laying the foundations for their conceptualization. On the one hand, as already acknowledged [14], lock-ins can facilitate the diffusion of environmental innovation, such as RE systems, by allowing stakeholders to focus on the existing socio-technical system that evolved around them. However, on the other hand, as this study highlights, RE lock-ins entail significant risks, which can impede the establishment of a new socio-technical system that better promotes the diffusion of clean and sustainable energy sources. This dual perspective has important practical implications for decision-makers. While promoting RE within the current socio-technical system, decision-makers should also be mindful of the emergence of lock-ins that can reduce flexibility and jeopardize the transition to a low-carbon society. Additionally, this study adds to the literature on path-dependence lock-ins, providing empirical examples of how different actors may actively manipulate lock-ins to serve their own interests [23,42]. This underscores the importance of considering the role of lock-ins in the RE field. Raising awareness of attempts to exploit lock-ins and the quest to find a balance between their potential benefits and associated risks are crucial.

Fig. 1 below presents the structure of this study. As detailed, the next section introduces the notion of path-dependent lock-ins in the context of socio-technical transitions. The third section discusses the energy transition process, focusing on the diffusion of RE infrastructure. The interplay between these two sections enables us to present, in the fourth section, the main risks that RE lock-ins pose, while highlighting their underlying mechanisms and illustrating them using empirical examples. Thereafter, the fifth section discusses the incentives that motivate various players to manipulate lock-ins in the emerging RE landscape. Finally, this facilitates a reflection on the possible conceptualization of RE lock-ins considering the energy transition literature and allows us to propose a research agenda centered on RE lock-ins.

2. Path-dependence lock-ins and socio-technical transitions

Path dependency is the idea that the historical development of a system or process can strongly influence its current state and future outcomes. It suggests that past choices and events can create a "path" or trajectory that constrains and shapes present and future possibilities [43]. When a system or process becomes path-dependent, the accumulated choices, investments, and developments can create a momentum that favors the existing path, making it difficult to deviate or switch to alternative paths. This can result in lock-ins: the system or process becomes resistant to change and perpetuates its current state or trajectory [44].

Early scholarly literature about the concept of lock-ins focused on their mechanism vis-à-vis increasing returns of technology adoption and the positive feedback associated with path dependency–the initial increase in adoption leads to increasing experience with the technology, which drives technological improvements and use, subsequently leading to further adoption [13]. This mechanism has also been described through the lens of 'network externalities': a phenomenon wherein the value or utility a user derives from a good or service depends on the number of users of compatible products. Network effects may be positive

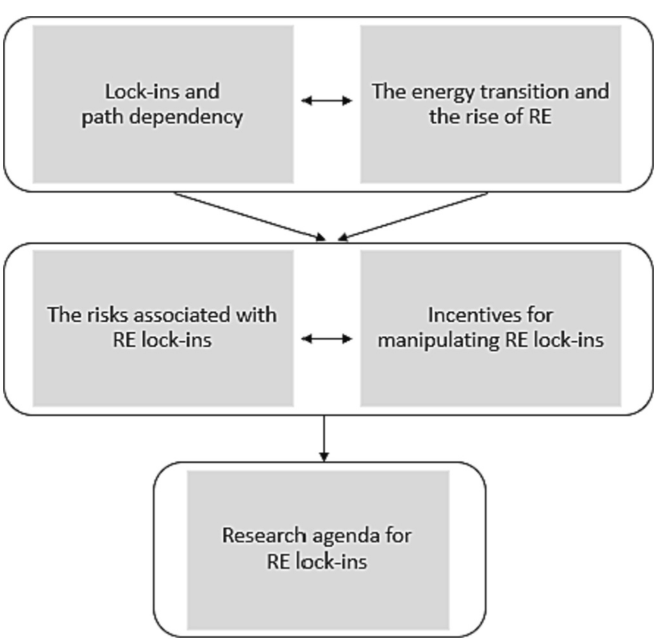

Fig. 1. The study's structure.

or negative, resulting in a given user deriving more or less value respectively from a product as more users join or leave the same network [45]. Hence, increasing returns, fueled by 'network externalities', can cause economies to become locked into an inferior development pathway that is difficult to escape [15,46]. Accordingly, technologies initially chosen for clear engineering reasons become locked in due to 'network externalities', making the adoption of more advanced and more appropriate technologies more difficult; sunk costs, learning effects, and coordination costs also contribute to such locked-in trajectories [47].

The concept of lock-ins has evolved from a static view of technological or systemic inertia to a dynamic understanding that considers the complex interplay of various factors over time. This shift in perspective has led to more effective strategies in addressing lock-ins and fostering transitions to more sustainable and adaptable systems [48]. Initially, lock-ins were often seen as static, long-lasting situations [49]. Over time, researchers and policymakers have come to recognize that lock-ins can be temporary and dynamic. They can arise, persist, and eventually break down or transform as new information, technologies, policies, or market forces emerge [11,12]. Moreover, the contemporary understanding of lock-ins recognizes that they are not isolated events but rather embedded within complex systems with multiple interacting factors. These factors include technological, economic, social, cultural, and political elements, all of which can influence and be influenced by lock-ins [19].

Indeed, the literature has examined different groups of path-dependence lock-ins. The first group is technological lock-ins, referring to the tendency to adhere to a certain technology, service, or mechanism, usually due to habituation processes [49]. The second group is institutional lock-ins, often related to the level of political support and other structural or institutional pressures [19]. The third group is social lock-ins: following expected norms related to social and cultural issues or the desire to justify projects to diverse audiences [50]. The fourth group is economic lock-ins, such as closing costs, salvage value, return on investment, and other economic and financial mechanisms that may influence future decisions [51]. The fifth group is legal lock-ins: legal, regulatory, or judicial limitations established based on the state of affairs in the past but that influence the current situation [52]. Finally, the last group is psychological lock-ins: difficulties in withdrawing and admitting past mistakes, as well as the need for self-justification [53].

Researchers have argued that path-dependent lock-ins of different kinds shape the escalation of commitment [23,54]. Escalation of commitment can be defined as "the tendency to 'carry on' with questionable endeavors, regardless of whether doing so is likely to result in success" [55]. Considering their contribution to the escalation of commitment, path-dependence lock-ins are often discussed in light of how they reduce flexibility by "causing the economy to lock itself into an outcome which is not necessarily superior to alternative ones and not easily altered" [15]. Within the context of path-dependence lock-ins, flexibility pertains to the ability of a system or process to adjust, evolve, or diverge from its predetermined course. It indicates the ability to overcome or mitigate the constraints imposed by historical choices and events that led to a particular path [19]. Hence, the reduced flexibility caused by path dependency is evidenced by the fact that choices made in the past result in a lock-in "effect," limiting the available options and making it difficult to switch to alternative paths [43].

The fixation on a single path, however, even if it is not necessarily the optimal one, may increase certainty for various players, thus yielding several benefits [14]. Such certainty may reduce transaction costs, ease the ability to raise capital, or increase efficiency, accordingly helping to establish a stable socio-technical system [33]. Trist and Emery (1960) first addressed the concept of socio-technical systems, describing it as the complex interaction between humans, machines, and the environmental aspects of the work system [56]. Geels (2004) discussed this notion more abstractly, referring to it as the linkages between elements necessary to fulfill societal functions (e.g., transport, communication, nutrition, energy). Hence, socio-technical systems consist of different elements that interact with each other: actors (e.g., individuals, firms, and other organizations), institutional structures (e.g., societal norms, technological standards, regulations, user practices, culture, collective expectations, etc.), and technologies and resources (e.g., knowledge, human and financial capital, natural resources) [57].

Nonetheless, by reducing flexibility, the mechanism of path-dependence lock-ins may also prevent the transition of socio-technical systems: the structural change of such systems in the economic, cultural, technological, institutional, natural, and environmental arenas [58,59]. In the course of such transitions, new technologies, products, services, organizations, regulations, norms, and user practices emerge while existing ones decline [60]. Various lock-ins may thus hinder the transition of socio-technical systems by preventing changes in such systems and reducing their flexibility, leading to pathways that are difficult to reverse [61,62]. This is especially true with regard to sustainable transitions, such as the energy transition process, which require increased flexibility to achieve a radical transformation towards a sustainable society in response to a number of persistent environment-driven problems that contemporary modern societies are facing [63,64].

Thus, while path-dependence lock-ins may increase the focus on a single socio-technical system and its stability, they may also prevent the transition of such systems by reducing their flexibility [13]. Accordingly, the next section introduces the energy transition process, characterized by the global diffusion of RE, which will be discussed later considering how it is shaped by path-dependent lock-ins.

3. The energy transition process: the rise of renewable energy

Large energy systems based on fossil fuels (e.g., coal, oil, natural gas, etc.) have dominated the global energy market for decades [65]. This can be partly explained by the “carbon lock-in”: existing fossil fuel-based systems and infrastructure created barriers to the deployment and growth of RE [3]. Factors such as long-term investments, network effects, technological interdependencies, and supportive policies for fossil fuels contributed to this lock-in. It resulted in higher costs, limited market penetration, slow policy changes, and technological inertia for RE [4].

To overcome the carbon lock-in and facilitate the transition to a low-carbon energy future, supportive policies, financial incentives, and technological advancements are needed [66]. These efforts have indeed yielded some fruits: RE sources currently account for more than a quarter of the world’s total electricity production [10]. However, the continued growth of RE is underway alongside a residual carbon lock-in, with its various effects [67]. The significant diffusion of RE sources at the expense of fossil fuel-based energy systems is often described as the energy transition [68], a process that has attracted increasing scholarly attention over recent decades [60,69–73].

The energy transition process is mainly characterized by the global diffusion of RE sources–such as solar, wind, hydroelectric, biomass, and other technologies– which can be described as non-perishable energy resources, or more simply as any source of energy that does not utilize fossil fuels such as coal, oil, and natural gas [74–76]. While RE sources vary, many of them possess common advantages [75,77,78]. Since they tend to be characterized by a reliance on non-perishable resources, future production is less constrained by resource limitations, unlike conventional fossil fuel based means of energy production [74,75,79]. Another significant advantage of RE sources, as an alternative to conventional electricity systems, is their very low-to-zero GHG emission rate [80–82], as well as the reduced emissions of other harmful pollutants [83–85]. Accordingly, RE is considered a prominent eco-innovation and an important tool in global efforts to cope with climate change [86,87].

The immersive diffusion of RE in recent years is often described as decentralized [88–90]. In this context, evidence from all over the globe indicates that the RE sector is characterized by a significant process of reconfiguring responsibilities [24,91]. As part of this process, the state is reshaping its own role, often reducing direct involvement in the establishment and operation of various infrastructures [92,93]. This is reflected in the increased involvement of a diverse range of players, most notably local communities and private players, in the establishment and operation of RE projects, at the expense of the state [90,94]. In addition to the reconfiguration of responsibilities, the decentralized diffusion of RE is also manifest in spatial terms. Unlike traditional fossil fuel-based means of energy production, RE infrastructures are characterized by the freedom of their installed capacities, resource diversification, and operation of facilities connected to grids as well as off-grid facilities [95–98]. These characteristics often encourage the wide spatial distribution of RE infrastructure in various geographical locations [99–101].

The diffusion of RE sources is likewise characterized by significant versatility: it can be established and operated by different players [94], in a range of regions [102] or energy market structures [103], and with varying scopes, technologies, and degrees of connectivity to the grid [98]. Moreover, compared to conventional energy systems, the RE landscape is characterized by relatively low entry barriers: indeed, the establishment and operation of several types of RE infrastructure require less financial investment [104] and dedicated knowledge [105]. Furthermore, the switching barriers of RE infrastructure are often considered lower than fossil fuel-based energy systems: in many instances, it is considered easier for diverse players to dismantle and establish RE facilities [106] or combine RE infrastructures with other uses (agriculture, tourism, manufacturing, etc.) [107,108].

Based on the presentation of the main characteristics of the global diffusion of RE, the next section discusses the risks lock-ins may pose in the context of the energy transition process.

4. The risks that renewable energy lock-ins pose

RE lock-ins combine characteristics related to the general concept of lock-ins, which may apply in various fields, with distinct features specifically derived from the nature of RE. Below we introduce six overarching risks stemming from the emergence of lock-ins in the RE field, each followed by an empirical example.

4.1. *Neglecting alternative technologies*

In many countries, the starting point for the energy mix is fossil fuel-based energy facilities [109] because these preceded RE facilities [110]. Accordingly, the process of transitioning to an RE-based energy sector tends to be gradual; indeed, it often requires reliance upon established RE technologies that can serve as trusted substitutes for mature fossil-fuel based energy systems [22]. The continuous use of established RE technologies to enable a reliable energy supply frequently leads to the emergence of various stakeholders who are highly accustomed to such technologies [111]. The need to rely on familiar RE technologies and the associated habituation process often translate into a lock-in: the adherence to certain RE technologies used in the past, even when they are not the optimal choice, which may hinder the penetration of alternative technologies [102]. Indeed, almost 90 % of global electricity production from RE is based on three main technologies: hydropower, wind energy, and solar energy [10]. The sector adheres to these relatively mature RE technologies even though the existing RE infrastructure is inferior to fossil fuel-based energy systems in terms of efficiency [112], storage capacity [113], and supply reliability [114]. This inferiority may hinder the global transition to RE, whereas alternative RE technologies may be able to improve efficiency, storage capabilities, versatility, and the space occupied [115]. Indeed, when a high demand for energy requires the expansion of production, decision-makers often choose to focus on established RE technologies (e.g., Germany) despite their aforementioned shortcomings [116]. In other cases, they may even focus on expanding the use of polluting fossil fuel-based energy systems to avoid these shortcomings (e.g., China), given their reluctance to use new RE technologies [117].

One example of such a lock-in concerns tidal power in the UK. As of 2022, hydropower, wind energy, and solar energy accounted for around 84 % of RE installed capacity in the UK. The remainder (16 %) is almost entirely based on biomass [118]. At the same time, attempts to promote innovative RE technologies in the UK, such as tidal power, have encountered significant difficulties. Tidal power has several advantages over other RE technologies, such as inexpensive maintenance costs and high-efficiency rates, reaching up to 80 % [119]. However, while tidal power can provide up to 20 % of the UK's electricity consumption [120], in practice it accounts for only a fraction of a percent [118]. One explanation for this relates to local decision-makers' avoidance of this technology in favor of more commonly used RE technologies, such as wind power [121]. Decision-makers tend to support the promotion of common RE technologies, understanding that their establishment and operation mechanisms have worked well in the past [118]. By contrast, innovative RE technologies, such as tidal power, often require new supporting mechanisms, and thus decision-makers consider them riskier [106]. This is the core of the lock-in: despite the many advantages of tidal power, it is not promoted because decision-makers adhere to more mature RE technologies [10]. This perspective is reflected in the words of former British Prime Minster David Cameron: "We have not seen any proposals coming forward that would make us consider this technology at the time. We have other, more established technologies, we focus on these days to meet our climate goals, such as wind, solar, and hydropower" [122]. Experts from the local RE industry claim that this mechanism also results in a feedback trend: tidal power is currently not widely promoted, while its prospective deployment in the UK is also unknown. Hence, given the significant risk and the limited return on investments, private developers have few incentives to promote the tidal power, further reducing the market's readiness for this technology, and so forth [107]. Indeed, as of 2022 there was no significant rise in the deployment of tidal power in the local energy market [118].

4.2. Impeding the promotion of decentralized facilities

In recent years, many countries have replaced fossil fuel-based energy systems with RE systems as part of their efforts to tackle climate change [10]. To reflect the commitment to promoting clean RE at the expense of polluting fossil fuel-based energy systems, many decision-makers choose to set ambitious national RE targets, to be met as quickly as possible [123]. The reasons for this include a genuine desire to tackle climate change [124], domestic commitments and political considerations [125], as well as international commitments in the framework of various agreements [126]. Accordingly, decision-makers in different countries tend to exert significant pressure on regulators to do their utmost to meet these targets as quickly as possible [127]. This pressure is often combined with the belief that promoting large-scale facilities is the fastest way to meet national RE targets because the installed capacity of each facility is more significant and the supervision of their establishment is more effective than supervising numerous decentralized projects [128–130]. Hence, this decision-makers' pressure often leads to a lock-in: encouraging regulators to promote large-scale RE projects at the expense of decentralized projects [131], even though this is not necessarily the optimal solution in environmental, energy, and technological terms [132–134]. This is the core of the lock-in: the past commitment of decision-makers to meet RE targets is translated into a significant pressure to promote large-scale RE projects. The path dependency associated with previous commitments to meet RE targets is hard to escape because it may violate agreements at the local or international level. Such lock-ins may hinder the promotion of decentralized RE facilities even when the latter offer significant benefits compared to large-scale alternatives, providing new opportunities and degrees of freedom for installed capacities, resource diversification, and operation of facilities connected to grids as well as those that are off-grid [98]. While it cannot always repel decision-makers' pressure, early and thorough planning by regulators might help to mitigate the effects of this lock-in, encouraging the promotion of RE facilities on different scales [135].

In Israel the influence of such a lock-in is evident. In 2009, the Israeli government announced a target of 10 % electricity production based on RE by 2020 [136]. Despite not meeting previous targets, the government announced new RE targets in 2020, promising to reach a share of 25 % electricity production based on RE by 2025 and 30 % by 2030 [137]. These targets were highly ambitious, encouraging the relevant regulators to promote large-scale RE projects, mostly in the form of solar farms, to satisfy the government and accord with its decisions [138]. The pressure concerning the establishment of large-scale RE projects is evidenced by a speech given by former Israeli Prime Minister Ehud Olmert, who addressed this issue in an official government meeting: "The State of Israel, with 300 days of sunshine a year, can lead the global effort to produce alternative energy such as solar energy. In order to do so we need to build large solar facilities, the largest in the world actually" [139]. This is the core of the lock-in with this regard: governmental pressure to meet previous commitments to RE targets led regulators to promote large-scale RE projects despite doubts concerning their economic and technological viability [140]. Indeed, during these years, medium and large-scale RE facilities provided more than 80 % of Israel's total RE installed capacity [141]. A senior regulator in the Israeli Ministry of Energy referred to the promotion of large-scale RE facilities, stating: "We promote large-scale solar power stations to assist Israel in meeting its RE targets while fully expressing the government commitment to addressing global concerns about climate change. However, these large-scale power stations are not necessarily the optimal choice in terms of grid use, land planning, and financial resources" [138]. Hence, such lock-ins, shaped by the government's desire to achieve its RE targets, lead regulators to promote large-scale RE facilities even though these are not necessarily the optimal choice in their perspective.

4.3. Limiting innovation

Seeking to encourage the promotion of RE facilities, many countries have established feed-in tariff mechanisms: a fixed payment for a defined amount of produced energy, often incorporating various subsidies [142]. The feed-in tariff is frequently based on a cost-plus strategy: regulators estimate the cost of constructing and operating a generic RE facility and add a reasonable profit that constitutes a subsidy [143]. In many cases, the feed-in tariff is designed to return the initial investment over a long period, often up to 20 years or more [144–149]. Therefore, this mechanism may result in a lock-in: the feed-in tariff is determined in advance for a lengthy period, meaning that various RE developers have little interest in or incentive to make changes to their RE facilities [150], even when such changes may be optimal from a broad market perspective [151]. The core of this lock-in, therefore, lies in the fact that the feed-in mechanism determined in the past often cannot be changed retroactively [143], so its effects often remain for a lengthy period and are hard to avoid. In this context, R&D (research and development) investments in general, and in the RE field specifically, are often based on the existence of suitable incentives [152,153]. However, the fixation caused by feed-in tariffs may reduce the incentives for different actors to develop and promote more innovative RE technologies that may be superior to existing technologies environmentally, economically, technologically, or in terms of efficiency, since they do not enjoy the feed-in tariff [115]. Accordingly, various actors potentially able to promote RE-related innovation may reduce their efforts in this regard both in terms of R&D and the actual establishment of RE facilities, preferring to focus on existing technologies [154]. Despite the inherent disadvantage of the feed-in mechanism, especially in the long term, many countries still prefer to use it, because it is a significant tool in encouraging the promotion of RE over fossil fuels. To overcome the aforementioned lock-in, some countries have established predetermined periods for changes in the feed-in tariff, thus ensuring greater flexibility [155]. In other cases, countries choose to mitigate these impacts by providing innovation grants, in particular for R&D, to encourage the promotion of RE technologies that do not benefit from the feed-in mechanism [156].

The effects of such a lock-in are evident in Germany [157]. The German government set a target of 50 % of electricity consumption from RE by 2030, and 80 % by 2050, within which wind energy plays an important role [158]. To achieve its ambitious RE targets, in 2014 the government set a high feed-in tariff for the establishment of wind facilities: onshore wind energy enjoyed 9.41 EUR cents per kWh for the first 5 years, then 4.87 EUR cents per kWh; offshore wind energy enjoyed 15 EUR cents per kWh for the first 12 years, then 3.5 EUR cents per kWh [159]. This policy scheme was allegedly successful, enabling Germany to become one of Europe's largest wind energy markets while more than doubling its wind capacity installation in three years [160]. However, it also resulted in a lock-in: due to the high feed-in tariffs, the RE industry in Germany has focused almost completely on wind energy for a long period, neglecting alternative RE technologies as well as other segments of the electricity sector, such as the grid. This lock-in mechanism also reduced the incentives for developers to promote more innovative RE technologies, affecting the competitiveness of the German RE industry, according to estimates [157]. Indeed, for years Germany lagged behind some of its neighboring countries in adopting RE technologies other than wind, including solar and hydropower. This was also evidenced by reduced investments in the transmission grid, which was therefore beset by significant malfunctions in various areas [157]. Hence, experts claim that this lock-in, caused by the high feed-in tariff for wind energy, had significant and wide-ranging ramifications for the German energy industry. It hindered the energy transition process in the country, while limiting the diversification of RE, and reduced the grid's capacity to adopt distributed energy sources like RE [157]. The German minister of energy, agriculture, and environment admitted that although this feed-in tariff mechanism has contributed to promoting wind energy, it distorted the incentives system in the German energy sector, leading to a significant delay in the transition to a low-carbon society [161].

4.4. *Impairing energy justice*

Evidence from different countries indicates that various aspects of the regulatory requirements for establishing and operating RE facilities may be highly complex, such as the necessary environmental permits, connection to the electricity grid, and construction planning [162–165]. Although complex regulations of this kind may delay or hinder the promotion of RE, regulators often do not eliminate them, and in some cases even adding to their complexity [166]. This is the result of path dependency that leads regulators to rely on previously established regulations, justifying actions in their framework [167]. Hence, regulatory complexity often results in a lock-in, as reflected in the continuous impact of previously established RE regulations, even when these regulations are not optimal. The core of this lock-in, therefore, lies in the fact that even when they are aware of the problems associated with complex regulation, regulators are often captive to their own regulatory perception: they tend to rely on existing regulations, adjusting or modifying them rather than removing them, which would in all likelihood increase regulatory complexity [168–171]. In many cases, the complete elimination of existing regulations requires admitting past mistakes or a significant transformation of the regulatory perspective. However, many regulators are incapable of this, making it difficult to escape the path dependency of past regulations [167]. While players with extensive regulatory knowledge and the ability to deal with complicated energy markets, such as large corporations, may be able to tackle this regulatory complexity, it can discriminate against other players, such as communities, who lack the necessary skills and capabilities [94,172,173,257], deterring them from active participation in the RE landscape. As such, lock-ins of this kind may impede efforts to enhance energy justice—the goal of achieving equal economic and social participation in the energy system [174–176].

China provides an example of such a lock-in. China's regulations concerning RE are mainly based on the 2005 *Renewable Energy Law of the People's Republic of China*, a complex multi-level regulation with which all players seeking to operate in the RE field must demonstrate familiarity [177]. This complexity manifests in various aspects, including overlapping electricity regulatory authorities, over-regulation of energy market entrance, and over-regulation of energy pricing [170]. For example, market entrance regulation for the energy sector, and the RE field in particular, requires significant investigation of a player's market practices to evaluate whether the player can meet the energy service standards and to protect the public interest. Since it requires significant and complex information, this investigation can take years and often discriminates against players without previous experience in the field [170]. Aware of the problematic nature of the complicated regulation, the Chinese government decided to revise the law [178]. However, the proposed solution was not based on easing or removing such complex regulations; rather it added more regulations, amending the 2005 law and preserving the regulatory complexity [177]. This is the core of the lock-in: path dependency, characterized by the reliance on previous regulations, is hard to escape due to past habits and regulatory fixation. For example, instead of removing the market entrance regulations, the background investigation of new players in the RE field has been reassigned to another governmental authority while adding additional examinations, thus practically enhancing the regulatory barriers for market entry [170]. This confers an advantage upon large corporations, in particular government corporations, which possess the necessary knowledge and skills [179]. Indeed, the International Energy Agency claimed that over the years China's complex regulation reduced the ability of inexperienced players, such as community players, to increase their participation in the local RE field [180]. Hence, this lock-in, resulting from the influence of previous regulations, has impaired energy justice in China's RE market.

4.5. *Endangering the environment*

Given their environmental and energy-related merits, various countries have deployed a considerable amount of RE facilities [10]. Many countries focus on specific RE technologies depending on their natural conditions–significant solar radiation, a suitable wind regime, or an abundance of rivers and water sources [75]–and consequently are characterized by a non-diversified RE mix [182]. Examples include solar energy in sunny Saudi Arabia [183], wind energy in windy Ireland [184], or hydropower in Brazil with its numerous rivers [185]. Yet, such a focus on specific RE technologies may translate into a lock-in: the reliance on a certain RE technology may make the cost of replacing it with other technologies too high [186], in financial terms or energy terms, i.e., a country's ability to provide reliable energy services for its entire population [187]. This lock-in may have devastating environmental consequences. While RE sources exert a positive environmental impact, providing energy with very low-to-zero greenhouse gas emissions [83,85], some may also have a negative environmental impact, especially in large intensities [188]. This includes wind farms that endanger animals and wildlife [189], hydropower facilities that interfere with water sources [190], or solar panels that harm the landscape [191] – environmental hazards that are often difficult to reverse. Hence, the core of this lock-in lies in path dependency, influenced by natural conditions, that often leads to focus on a single RE technology. This, in turn, increases the dependence on that technology while making it difficult to change the energy mix despite possible environmental hazards. Countries can mitigate the effect of such lock-ins through early planning regarding the diversification of their RE mix–this is expected to decrease their dependence on a single energy source, even at the cost of reduced energy efficiency [192].

One example of such a lock-in is hydropower in Brazil. Due to its significant water resources, Brazil has the third highest global potential for hydropower, following Russia and China. Indeed, in recent decades Brazil established many hydropower facilities: at their peak, they were responsible for most of the country's electricity supply [193]. However, this enhanced use of hydropower led to increased dependence on this energy source [194]: as of 2022, it accounted for more than two thirds of the country's electricity generation [185]. Local and international experts have emphasized how the intensive use of hydropower in Brazil offers many benefits, providing energy to the large population of the country in a continuous and reliable manner [195]. However, it also has devastating environmental consequences, including damaging water sources, which constitute both biological and social systems [196]. Several environmental and social organizations have criticized these adverse impacts, claiming that the irreversible damage is not worth the benefits associated with the use of hydropower [197,198]. The Brazilian government is aware of these environmental risks and even considered replacing hydropower with other technologies that could reduce the environmental hazards while further diversifying the country's energy portfolio. Nevertheless, the government eventually decided to continue using hydropower facilities for the foreseeable future because the cost of replacing them with other technologies is too high: both in terms of financial investments as well as energy security and the provision of reliable energy to the entire population [199,200]. Therefore, the establishment of numerous hydropower facilities in the past led to a lock-in with negative environmental ramifications: the government was unable to reduce its high dependency on a single source of energy despite environmental incentives to do so [201].

4.6. Distorting the economic setting

RE systems often do not operate under free market conditions. Indeed, they are subject to regulatory interventions vis-à-vis prices, quantities, and trade mechanisms [202,203]. Regulations may also determine which players can operate in the RE field by providing licenses, setting quotas, or offering dedicated incentives, such as subsidies [204]. In particular, considering the dominance of conventional means of energy production, various regulations provide specific players with infant industry protections to promote the establishment of RE infrastructure [205,206]. Such protections exist in various industries [207] but are especially common in the RE field [208]. However, they may result in a lock-in: they strengthen the position of certain players at the expense of others even when the infant industry protections are no longer in force. This lock-in may provide such players with market power, damaging the competitive structure of energy markets, and regulators clock [209]. Consequently, some players may be able to influence market conditions in a non-competitive manner, including setting non-competitive prices for energy services, impairing the quality of service, blocking the free transfer of information, and raising the entry barriers for new players [210]. Thus, this lock-in stems from a past decision to grant infant industry protections to promote RE. The path dependency associated with these protections leads to a situation in which certain players enjoy market power, which is difficult to reduce retroactively. Different countries respond to this lock-in's effects in various ways, including benefits to other players who enter the market, or alternatively establishing mechanisms that reduce the market power after the protections are no longer in force [211].

We can discern the influence of such a lock-in in Chile. Amidst efforts to tackle climate change, the Chilean government has promoted policies encouraging the establishment of RE facilities, specifically focusing on solar and wind energy [212]. Among these policies the government provided several prominent players with infant industry protections, including subsidies and tax benefits as well as a safety net in case of financial losses [213]. These protection mechanisms helped such players promote RE facilities [212]. Indeed, while in 2014 the share of wind and solar energy in Chile was negligible, by 2021 it provided more than 18,000 GWh to the local electricity market [214]. However, over time, these industry protections have ensured that the players enjoying them are highly dominant in the RE market, reducing new players' ability to compete with them in the absence of similar protections. This dominance continued even after the infant industry protections were no longer in force, meaning that the government found it almost impossible to change the situation [215]. Thus, past events leading to the provision of infant industry protections resulted in the emergence of an uncompetitive market structure that is difficult to reverse. Local competition experts later claimed that due to this dominance several RE players were able to set non-competitive prices for the energy they produce, specifically at peak times. They concluded that future infant industry protections, specifically in the energy market, should be granted more cautiously, given their possible long-term effect on the competitiveness of the market and its structure [216].

Table 1 below summarizes the main risks lock-ins may pose to the RE field, presenting the risks alongside the underlying mechanism and the examples discussed above, in addition to the potential players who may benefit or suffer from the associated lock-ins. Notably, however, other cases may differ from the presented examples, i.e., the lock-in mechanism behind these risks may vary, as may their effects on different players. Nevertheless, the nature of these risks and their core impact will in all probability be based on the presented framework.

Based on the risks associated with lock-ins in the RE field, as presented so far, in the next section we present the incentives that may encourage players to manipulate them for their own benefit.

5. Manipulating renewable energy lock-ins

Path-dependence lock-ins cause the economy—including its institutions, its mechanisms, and the players involved in its activity—to lock itself into an outcome that is not easily altered [15]. The literature concerning lock-ins has noted that different players may "strategically manipulate" lock-ins for their own benefit, i.e., they may encourage, use, or exploit lock-ins in different ways to serve their own interests [23]. However, it is still unclear how such manipulation actually manifests and what incentives motivate it, specifically in the context of RE. Accordingly, below we outline several notable incentives that may encourage players to manipulate lock-ins vis-à-vis RE infrastructure. Subsequently, we provide empirical examples of these manipulations based on the examples presented in the previous section.

5.1. Energy production incentives

Numerous RE technologies play a substantial role in the energy mix of various countries [217], with several nations committing to achieving a 100 % RE target in the near future [218–221]. As fossil fuel-based facilities give way to RE facilities, a series of opportunities emerge for stakeholders to change, guide, and influence the energy market with its newfound characteristics [68]. This evolving landscape allows players to position themselves strategically and play a pivotal role by controlling means of energy production [222]. Such stakeholders can solidify their dominance in the production of clean and sustainable energy either by selling energy to other players or utilizing it for their own consumption [84]. This can be achieved, inter alia, by manipulating lock-ins concerning the adherence to mature RE technologies. Indeed, various players who are operating with established RE technologies, such as solar, wind, or hydropower, have a vested interest in shaping the energy market by controlling the energy means of production. Hence, they often aim to deter competition from players promoting innovative RE technologies that could potentially disrupt their position [223]. Thus, they seek to reinforce the path-dependence that compels decision-makers to stick with the existing technologies [22].

For example, evidence indicates that various British wind energy companies funded publications highlighting the drawbacks of tidal power, especially its risks, thus influencing decision-makers in this regard. Such publications stressed that this technology, relatively new and unestablished, could potentially jeopardize the UK's energy security. As

Table 1
The risks of renewable energy lock-ins.

Risk	Lock-in mechanism	Example	Potential beneficiaries	Main sufferers
Neglecting alternative technologies.	Adherence to well-established RE technologies.	Avoiding tidal power in the UK.	Players engaged with current RE technologies.	Players engaged with new RE technologies.
Hindering the promotion of decentralized RE facilities.	Political pressure to meet RE targets.	Promoting large-scale RE facilities in Israel.	Players with significant resources, such as private corporations.	Players with restricted resources, such as individuals and communities.
Limiting innovation	Long-term economic frameworks.	Feed-in tariffs for wind energy in Germany.	Players enjoying the feed-in tariff.	Players left out of the feed-in tariff scheme.
Impairing energy justice	Fixation on past regulatory schemes.	Complex RE regulations in China.	Players with significant regulatory knowledge, such as private corporations.	Players with limited knowledge, such as individuals and communities.
Endangering the environment	High dependency on specific RE technologies.	Relying on hydropower in Brazil.	Players engaged with the highly deployed RE technology.	Players negatively affected by the highly deployed RE technology.
Distorting the economic setting	Infant industry protections.	Market power in Chile's RE sector.	Players who enjoy infant industry protections.	New players without infant industry protections.

a result, the key takeaway was that to facilitate a smoother energy transition process, greater emphasis should be placed on more established technologies, such as wind energy [224,225]. The findings of an independent research body revealed that these publications lacked solid evidence and were predominantly driven by propaganda [226]. This demonstrated how companies operating in the wind industry, which funded such publications, attempted to manipulate the lock-ins that led decision-makers to overlook new RE technologies. Their aim was to influence decision-makers to strongly favor established RE technologies over innovative ones, making it more challenging for them to deviate from this perspective.

5.2. *Financial incentives*

RE infrastructures represent a burgeoning sector offering significant energy and environmental advantages [102]. Consequently, there has been a substantial upsurge in financial investments in the RE domain recently: both public and private funding directed towards diverse aspects of the RE industry, encompassing the establishment of facilities, maintenance, grid infrastructure, consulting, supplementary services (e.g., storage), and beyond [227]. Various stakeholders aim to capitalize on this influx of capital using diverse strategies, including manipulating lock-ins, seeking to enjoy financial benefits by exploiting the large amount of capital flowing into the RE industry [153]. Such manipulation is evident vis-à-vis lock-ins stemming from infant industry protections. Such protections are designed to support certain players in industries that are in their early stages, such as the RE industry, enabling them to contend with more established players in older industries [211]. However, as time goes by, the path-dependence associated with these protections may generate an inherent competitive edge over other players, creating a lock-in that it is difficult to escape. Consequently, various stakeholders have a vested interest in strengthening this lock-in, thereby reinforcing the conditions that enable them to enjoy competitive advantages and the associated financial benefits [207].

For example, mature RE companies in Chile lobbied the government to continue the national infant industry protection scheme, even though the original legally-stipulated deadline for this scheme had passed and their activities in the RE industry were already well-established [215]. Local competition experts have addressed this issue, highlighting that these companies have engaged in prolonged efforts with government officials to preserve the infant protections. According to these experts, these companies did so to reap the direct financial benefits of the protections and, more significantly, to maintain their competitive edge. They emphasize that these companies worked diligently to sustain this advantage by persistently seeking the extension of these protections, even when it became evident that they were no longer serving their original purposes [216]. Hence, they effectively reinforced the lock-in associated with their competitive advantage, a consequence of path dependency, making it even more challenging to change the industry's dynamics [215].

5.3. *Power relationship incentives*

Control over means of energy production, such as RE, may lead to changes in the power relations between different players [69]. Considering that the transfer to sustainable RE technologies creates a new energy landscape, this allows for alterations in the dynamics compared to the previous situation. On the one hand, RE may constitute a game changer and shift the power source from large corporations or state monopolies (historically the dominant actors in many electricity markets) to local communities, who often become prosumers (i.e., both consumers and producers) [162,228,229]. On the other hand, the traditional players in the energy field, such as large private corporations, seek to preserve their power and enhance dependence on them [230,231]. Thus, various actors may manipulate lock-ins around RE infrastructure to strengthen their power vis-à-vis others. In this context, evidence indicates that large corporations may manipulate and strengthen lock-ins related to favoring large-scale RE facilities over decentralized RE, allowing them to perpetuate their dominance. They may do so by influencing regulators and decision-makers, presenting large-scale RE projects as more capable of rapidly meeting national RE targets than decentralized facilities [131]. Accordingly, large corporations emphasize the need for their significant skills and resources, which smaller players often lack [232].

For instance, various lobbyists on behalf of several large RE corporations have appeared in the Israeli parliament, clarifying that the only way to meet the country's RE targets is by promoting large-scale facilities. In particular, these corporations deliberately endeavored to secure preferential regulatory conditions for the establishment of large-scale RE facilities, such as wind farms or solar fields, instead of smaller facilities, fully aware that this would serve their interests over those of smaller players, such as local communities [233]. These efforts, among them intensive meetings with senior regulators [138], were successful, and regulatory preferences were granted to larger RE facilities for an extended period, evident in the conditions provided to these preferred facilities. Consequently, for a considerable period, large corporations dominated the RE sector in Israel [141]. Thus, the large RE corporations in Israel endeavored to reinforce the lock-ins that incentivize regulators to prioritize large-scale RE facilities over smaller ones, through manipulating their desire to please decision-makers by reaching RE targets as fast as possible.

5.4. *Environmental incentives*

RE infrastructures play a dual role in addressing environmental concerns. On the one hand, they offer significant benefits by reducing greenhouse gas emissions and harmful pollutants [80–82], contributing to environmental improvement. Conversely, RE may also have negative impacts, endangering wildlife [189], interfering with water sources [190], or disrupting landscapes [191]. Consequently, various stakeholders may manipulate lock-ins to leverage the environmental advantages of RE infrastructures or prevent their adverse effects. In so doing, actors can promote the adoption of specific technologies or minimize the use of others, all in the pursuit of environmental goals. Lock-in manipulation in this respect is evidenced by the encouragement of long-term economic frameworks such as a feed-in tariff. Various stakeholders may encourage the implementation of a feed-in tariff system for RE technologies that they perceive as environmentally advantageous [234]. This could incentivize the adoption and usage of these technologies. At the same time, it can also discourage the use of other RE technologies that are seen as exerting negative environmental impacts, especially if they do not enjoy the same benefits from the feed-in tariff [235]. Various methods can encourage the establishment of a feed-in tariff, such as promoting supporting publications, influencing decision-makers, engaging in meetings with regulators, and more [236].

For example, several environmental organizations in Germany opposed the promotion of hydropower facilities due to their negative environmental effects, mostly on rivers and other water sources in the country. At the same time, such organizations realized that the promotion of RE is essential in reducing national greenhouse gas emissions [237]. These environmental organizations, therefore, publicly supported the government feed-in tariff scheme to promote wind energy, perceiving it as environmentally superior to the alternative of hydropower. They did this via various means, including meetings with government officials as well as publishing articles on the subject. By supporting this scheme, they helped the government harness public opinion in favor of its implementation [238]. Accordingly, the feed-in tariff for wind energy was published, giving significant priority to this technology over hydropower technology and serving the environmental goals of those organizations [157]. Hence, these organizations have manipulated lock-ins to perpetuate the use of wind technology for a lengthy period, while reducing the possibility of technological change in the future, specifically with regard to hydropower.

5.5. Social incentives

Studies from different countries show that the public generally favors RE projects due to their positive environmental impact [239–241].[1] Within the RE industry, various stakeholders aspire to gain the benefits of this positive social perception. Besides seeking a positive reputation, they also aim to outshine competitors in terms of public esteem: research indicates that the social acceptance of RE projects, bolstered by a positive reputation, plays a significant role in encouraging the widespread adoption of RE infrastructure [243–246]. Consequently, many actors are keen to leverage the positive reputation associated with RE to drive further RE projects, creating a feedback loop of promotion and acceptance. Accordingly, some players may manipulate lock-ins around RE infrastructure to strengthen their hold over the field and enjoy the accompanying social reputation. This can manifest, for instance, in the manipulation of lock-ins relating to regulators' adherence to previous regulations. Experienced actors within the RE industry may strategically employ tactics to raise regulatory barriers to entry by influencing regulators in this regard [247]. By encouraging the reinforcement of the existing regulatory framework and maintaining its complexity, these players can effectively limit the number of new competitors entering the market [180]. As a result, they can enjoy a relatively higher reputation due to their significant involvement in the RE field while further increasing their projects' social acceptance [248].

For instance, evidence suggests that government-owned RE corporations in China have played a significant role in shaping the country's RE regulations by exerting influence on regulatory decisions [249]. As a result of their involvement, regulators have adhered to existing RE regulations, which have become even more convoluted over time [170]. The International Renewable Energy Agency has highlighted the involvement of government-owned RE corporations as a factor contributing to the growing complexity of Chinese RE regulations [249]. The increased complexity, in turn, has severely limited the ability of communities and individuals to participate in the local RE sector [180], effectively granting the government-owned corporations a favourable public reputation, particularly due to the lack of competition from smaller community players. Indeed, research demonstrates that the restricted involvement of communities in China's RE industry has resulted in a more positive "green" reputation for government corporations. This situation has facilitated their promotion of additional RE projects, fueled by the heightened social acceptance stemming from their positive reputation [248].

6. Renewable energy lock-ins as a research agenda

The current energy transition process is characterized by significant diffusion of RE all around the world [10]. Unlike energy systems based on fossil fuels, the literature often regards RE sources as malleable and unaffected by lock-ins [24,25]. This study, however, has shed light on the role that path-dependence lock-ins play in the RE field, specifically focusing on their risks, as opposed to their potential merits. These risks are associated with reduced flexibility–the (in)ability of a system or process to adapt, change, or deviate from its established trajectory or path– thus limiting the possibility of switching to different, superior RE alternatives. Hence, the study contributes to the transition literature (e.g., [7,11,238]) by highlighting the diverse risks embedded in RE lock-ins. As shown, these risks may include neglecting alternative RE technologies, hindering decentralized RE facilities, limiting innovation, impairing energy justice, endangering the environment, and distorting the economic setting. These risks question whether the RE field can adapt to energy markets' growing need for new opportunities and a greater degree of freedom, as the RE landscape may be constrained by various lock-ins [27].

Despite the aforementioned risks, path-dependence lock-ins may also entail certain merits: by providing certainty, lock-ins may reduce transaction costs, ease the ability to raise capital, or increase efficiency [13]. These merits may be crucial for RE: they can facilitate the increased penetration of RE systems at the expense of polluting fossil-fuel-based systems potentially reducing their relative costs and improving their performance [251]. Thus, this study lays the foundations for the conceptualization of lock-ins in the RE field by illuminating their duality. On the one hand, as already noted by the literature, they may support the diffusion of environmental innovation, enabling players to focus on the existing socio-technical system that has gradually emerged around them [14]. On the other hand, given the significant risks presented in this study, lock-ins may also prevent the establishment of a new socio-technical system around RE, which may further encourage the diffusion of clean and sustainable energy sources. Hence, this duality also has important practical implications for decision-makers. While decision-makers should do their utmost to promote RE as part of the current socio-technical system, they should also reflect upon the emergence of lock-ins, which may reduce the flexibility of the field and thus put the transition to a low-carbon society at risk.

This study also contributes to literature concerning path-dependence lock-ins [23,42] by providing empirical examples of how various players may actively manipulate lock-ins for their own benefit, specifically focusing on the RE field. This issue further emphasizes how important it is for decision-makers to reflect upon the role of lock-ins in the RE field: different actors may have a clear interest in harnessing them for their own benefit. Therefore, decision-makers should be aware of such attempts to manipulate lock-ins and balance their merits with the significant risks, which may be associated with limited flexibility. Indeed, the literature has discussed several strategies to ease the (negative) influence of lock-ins, specifically in the infrastructure sector: for instance,

[1] It should be clarified that this public support often refers to the general notion of promoting RE, unlike its promotion adjacent to specific populations, which frequently encounters opposition for NIMBY reasons [242].

setting periodical review points throughout the lifespan of projects, thus increasing the checks and balances [252], or more realistic front-end planning [253], the setting of limits [254], and, more radically, the complete avoidance of promoting infrastructure projects [255]. These methods should, therefore, be examined and adjusted to suit the unique characteristics of the RE field.

Despite its valuable contributions to the literature, this study has several limitations. Literature review studies of various types frequently draw criticism regarding their methodology, encompassing both structural and objective aspects [34]. Notably, in our case, the methodological fusion of a literature review with new empirical examples poses specific challenges, although numerous scholars have acknowledged that such studies constitute a beneficial means of highlighting overlooked research agendas [35–38]. This juxtaposition of two methods within a single article may generate incoherence and potentially compromise the totality of each approach. To address this inherent drawback, we sought to mitigate it by clearly outlining the study's structure and elucidating the rationale behind this combined methodology in the introduction.

Additionally, this study encounters a common methodological concern arising in research that introduces the social dimension into the realm of energy studies [256]: the endeavor to amalgamate multiple disciplines within a single investigation, which in our case aimed to bridge the gap between path-dependence lock-ins and research regarding the RE landscape [71]. Consequently, the analytical depiction of the risks associated with RE lock-ins and their manipulations primarily relies on anecdotal findings from the literature rather than in-depth studies due to the scarcity of focused and dedicated literature in this combined area. This necessitated a comprehensive review of a large volume of articles to delineate trends related to RE lock-ins.

Moreover, in the absence of comprehensive empirical academic studies on the subject, to introduce the empirical cases this study necessarily resorted to "grey literature" sources, further highlighting the limitations of the literature review process. This situation may diminish the credibility of the empirical cases, despite our considerable effort to select documents from reliable sources and authors. Furthermore, given that this study aims to provide a broad overview of the phenomenon of RE lock-ins, it was not able to delve deeply into each individual empirical case. Simultaneously, our limited capability to introduce numerous empirical cases, given the scope of the study, restricts a more extensive examination of instances from various regions around the globe.

Given these shortcomings, this study calls for future research concerning the important phenomenon of RE lock-ins, specifically focusing on its empirical exploration. Accordingly, various topics addressed in the study, particularly the diverse risks associated with RE lock-ins, could benefit from a more comprehensive exploration of additional regions and a wider range of approaches, including both quantitative and qualitative methods such as interviews, surveys, and other relevant research techniques. In this context, a deeper examination of the technological risks of RE lock-ins is necessary [7,8,26]. This study suggested that lock-ins may prevent the adoption of innovative RE technologies or result in avoiding the use of superior technologies. Future research should further explore the empirical influence of lock-ins in this framework, in different locations and times, concentrating on both local and global perspectives. In particular, such studies should examine whether and to what extent lock-ins tangibly lead to the adoption of specific RE technologies that are not necessarily the optimal alternatives.

Future research should also examine more comprehensively the risk RE lock-ins may represent in the context of energy justice. In particular, scholars should empirically explore whether the emergence of lock-ins and their possible manipulation reduce the power of community players vis-a-vis large private corporations, thus limiting their ability to participate in the RE field (e.g., [164,245]). Moreover, future research should examine the environmental influence of RE lock-ins, specifically in countries that are highly dependent on specific RE technologies. In particular, additional studies could compare the negative environmental "price" such countries pay for adhering to the same RE technology with the financial costs associated with changing this technology (e.g., [196]). Future research should also explore the economic influence of lock-ins on the RE field, as has been done in other fields (e.g., [246]), examining whether lock-ins contribute to the emergence of market power in different energy sectors around the globe, and specifically assessing the influence of infant industry protection in this regard.

Moreover, this study demonstrated the incentives motivating different players to "strategically manipulate" lock-ins for their own benefit, based on Hetemi et al.'s (2020) claim in this regard [23]. Accordingly, future studies should deepen the exploration of the incentives behind the manipulation of RE lock-ins. This may include qualitative exploration, including in-depth interviews, to examine various players' perspectives concerning the process of manipulating RE lock-ins. Such research may expose the rationale behind the formation of RE lock-ins, their manipulation, and how players perceive the aims achieved through these lock-ins.

Finally, this study primarily concentrated on examining the impact of path-dependence lock-ins on the RE landscape. However, it is important to note that in real-world scenarios, these environmentally friendly energy systems coexist with conventional fossil fuel-based energy systems as part of a more complex energy environment. Consequently, the carbon lock-in and path-dependence lock-ins related to RE are intertwined. Therefore, while this study laid the foundations for the conceptualization of path-dependence lock-ins in the RE landscape, it is imperative that future research further refine and deepen this conceptualization while considering the intricate nature of the energy landscape and the diverse factors affecting this issue, including the mutual relationship between RE and carbon-based energy systems and the complexity of the energy sector.

By focusing on the phenomenon of RE lock-ins in the context of the energy transition process, and specifically the risks they may pose, this study laid the foundation for their conceptualization, encouraging additional research in this regard.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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