# ENVIRONMENTAL RESEARCH
## LETTERS

**TOPICAL REVIEW**

# Systematic map of the literature on carbon lock-in induced by long-lived capital

Vivien Fisch-Romito[1,6] (iD), Céline Guivarch[1,2] (iD), Felix Creutzig[3,4] (iD), Jan C Minx[3,5] (iD) and Max W Callaghan[3,5] (iD)

1 Centre International de Recherche sur l'Environnement et le Developpement, 45 bis avenue de la Belle Gabrielle, Nogent-sur-Marne Cedex 94736, France
2 École des Ponts—ParisTech, 6-8 Avenue Blaise Pascal, Cité Descartes, Champs sur Marne, 77455 Marne la Vallée Cedex 2, France
3 Mercator Research Institute on Global Commons and Climate Change, Torgauer Straße 12-15, EUREF 19, 10829 Berlin, Germany
4 Sustainability Economics of Human Settlements, Technical University Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany
5 Priestley International Centre for Climate, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom
6 SMASH, 22 rue de Cherbourg, 75015 Paris, France

E-mail: vfisch@centre-cired.fr

## Abstract

Long-lived capital-stocks (LLCS) such as infrastructure and buildings have significant and long-lasting implications for greenhouse gas emissions. They contribute to carbon lock-in and may hinder a rapid decarbonization of energy systems. Here we provide a systematic map of the literature on carbon lock-in induced by LLCS. Based on a structured search of the Web of Science and Scopus, we identified 226 publications from 38 095 search results using a supervised machine learning approach. We show biases toward power generation and toward developed countries. We also identify 11 indicators used to quantify carbon lock-in. Quantifications of committed emissions (cumulative emissions that would occur over the remaining operational lifetime of an asset) or stranded assets (premature retirement/retrofitting or under-utilization of assets along a given pathway) are the most commonly used metrics, whereas institutional indicators are scarcely represented. The synthesis of quantifications shows that (i) global committed emissions have slightly increased over time, (ii) coal power plants are a major source of committed emissions and are exposed to risk of becoming stranded, (iii) delayed mitigation action increases stranded assets and (iv) sectoral distribution and amount of stranded assets differ between countries. A thematic analysis of policy implications highlights the need to assure stability and legitimacy of climate policies and to enable coordination between stakeholders. Carbon pricing is one of the most cited policy instrument, but the literature emphasizes that it should not be the only instrument used and should instead be complemented with other policy instruments, such as technical regulations and financial support for low carbon capital deployment. Further research is warranted on urban-scale, in developing countries and outside the electricity generation sector, notably on buildings, where stranded assets could be high.

## 1. Introduction

The objective of the Paris Agreement on climate change to 'hold the increase in the global average temperature to well below 2°C above pre-industrial levels' requires reaching net zero emissions globally during the second half of the 21*st* century. This implies a fast reduction of global emissions in the next decades (Rogelj *et al* 2018) and one pillar of

this transition is a rapid replacement of polluting capital by clean capital (Rozenberg *et al* 2020). Polluting capital is that whose use directly emits $CO_2$, such as fossil fuel power plants and internal combustion engine vehicles, but also capital that indirectly induces emissions, such as building shells, roads and urban forms because of their influence on energy demand and mitigation possibilities (Guivarch and Hallegatte 2011).

Most of the capital concerned by this transition can be qualified as 'long-lived capital stock' (LLCS), which has specific characteristics that may hinder rapid transitions (Lecocq and Shalizi 2014). First, by definition LLCS has long life spans, from around 15 years for personal vehicles to more than 50 years for buildings (Reyna and Chester 2015, Erickson *et al* 2015), and to centuries if not millennia in the case of road networks (De Benedictis *et al* 2018). A second key characteristic of LLCS is the lumpiness of capacity installation (Lecocq and Shalizi 2014). While lock-in builds on the long life spans of infrastructure and capital stocks, lumpiness refers to the concentration in a short period of time of investments in specific capital stocks or infrastructure. Examples are railroads in the 19*th* century, nuclear power plants between 1960 and 1990, and (Chinese) high-speed railways since 2008. This lumpiness leaves a short window of opportunity to influence the capital stock characteristics and whether it locks in high carbon patterns or not.

Moreover, the dynamics of LLCS are driven by path-dependent evolution induced by four intertwined and mutually reinforcing mechanisms: scale economies, learning effects, network economies and adaptive expectations (Arthur 1994, Unruh 2000). Scale economies refer to reduced unit production costs over time due to the spread of fixed costs over increasing production volume (Kalkuhl *et al* 2012, Klitkou *et al* 2015). Learning effects describe how knowledge accumulation from a technology results in decreasing costs over time. This has been observed for power generation plants in the past (McDonald and Schrattenholzer, 2001), with higher learning rates for more granular technologies, such as photovoltaics (Creutzig *et al* 2017, Nemet 2019, Wilson *et al* 2020), and lower if not zero (or even negative) learning rates for large-scale technologies, such as nuclear (Grubler 2010). Network economies result from the advantages of using a technology with wider adoption because of coordination effects between industries or through regulations and norms. For example, a road portion increases in value as the network expands because of new possible destinations (Unruh 2000). Adaptive expectations are due to the adoption of a technology reducing uncertainty, and hence increasing confidence in using this technology. This mechanism shapes preferences and cultural norms such as habits for travel behaviors (Lanzini and Khan 2017).

LLCS therefore induces inertia that prevents or delays transitions towards low-carbon systems, a phenomenon called carbon lock-in (Unruh 2000). The capital built today will influence the paths of future emissions for several decades. The transition to low-carbon capital can therefore only be made by taking into account the existing stock and its economic and technological characteristics. LLCS is also embedded in broader institutional context that can keep promoting the high-carbon capital in place or create the conditions for the emergence of an alternative low-carbon technology (Seto *et al* 2016).

It is therefore essential to understand to what extent this existing stock of long-lived capital and its expected evolution is compatible, or not, with long-term climate objectives, and to identify levers available to make this stock 'climate compatible'. A certain level of lock-in associated with existing carbon-intensive capital is inevitable but its depth can be problematic and hinder a low carbon transition (Bjornaavold and Van Passel, 2017). This raises the questions of how to quantify carbon lock-in and how its 'strength' differs between sectors or geographical areas. Answering these questions is a crucial condition for policies and decisions which avoid creating or exacerbating carbon lock-in. This article contributes to this by reviewing the literature about carbon lock-in related to long-lived capital stock. Our goal is to describe the current state of knowledge, and to show what evidence there is of the (in)compatibility of the existing LLCS and its expected evolution with the long term climate objectives. Specifically, we aim to (i) highlight what sectors and geographic areas have been studied, and where there are research gaps, (ii) identify how carbon lock-in has been quantified in the literature and what findings emerge from it, and (iii) analyze the policy implications of carbon lock-in avoidance or escape.

In a previous traditional literature review, Seto *et al* (2016) synthesized the causes and types of carbon lock-in. Authors conceptualized three major types: '(a) lock-in associated with the technologies and infrastructure that indirectly or directly emit $CO_2$ and shape the energy supply; (b) lock-in associated with governance, institutions, and decision making that affect energy-related production and consumption, thereby shaping energy supply and demand; and (c) lock-in related to behaviors, habits, and norms associated with the demand for energy-related goods and services'. This review also identified conditions which reinforce carbon lock-in and some strategies for escaping it. However, to our knowledge, no study to date has comprehensively synthesized case studies and associated results on carbon lock-in. The rapid expansion of the scientific literature on the topic (Cui *et al* 2019) calls for scalable methods to deal with large numbers of articles (Tsafnat *et al* 2014, Minx *et al* 2017, Beller *et al* 2018, Westgate *et al* 2018, Nakagawa *et al* 2019, Callaghan *et al* 2020).

Our article hence complements the review by Seto *et al* (2016) by providing a systematic map of the literature about carbon lock-in. We collected, described and catalogued the available literature based on a systematic review methodology (James *et al* 2016). The screening process was streamlined using a machine learning approach (O'Mara-Eves *et al* 2015, Lamb *et al* 2019). We map out the distribution of existing studies across sectors, geographic areas and spatial scales and identify mature areas of research as well as

research gaps. We further describe the different methodologies and indicators used to quantify carbon lock-in and provide a synthesis of those estimates. In particular, we analyze how evaluations of global stranded assets depend on the temperature objective of the scenarios and on whether action in scenarios is early or delayed. We study how global committed emissions evaluations have evolved over time, and also provide a comparison of the results for our indicators between sectors and geographical areas. Finally, we offer a synthesis of existing qualitative statements in the publications about policies to escape or avoid carbon lock-in. The rest of this article is structured as follows : section 2 details our methodology, section 3 presents and discusses our results and section 4 concludes.

## 2. Methodology

We apply systematic mapping and subsequent synthesis to understand what the evidence is of the (in)compatibility of the existing LLCS and its expected evolution with the long term climate objectives. Systematic mapping (Haddaway *et al* 2016, James *et al* 2016), and evidence gap mapping (McKinnon *et al* 2015, Snilstveit *et al* 2016), have their roots in the social sciences (Oakley *et al* 2005, Bates *et al* 2007). Systematic maps provide an open-framed inquiry related to the state-of-evidence in a particular field by systematically collating, describing and cataloging the relevant evidence (James *et al* 2016). Like other evidence synthesis methods, systematic mapping approaches provide formal procedures that aim to minimize different sources of bias during the review process and promote a comprehensive, rigorous, transparent and objective overview of the available evidence. We describe in detail the process of constructing and analyzing our systematic map of the literature on carbon lock-in across five discrete methodological stages (see figure 1) and subsequent synthesis below. We close this section by describing our approach to the thematic analysis of policy implications identified in the various papers.
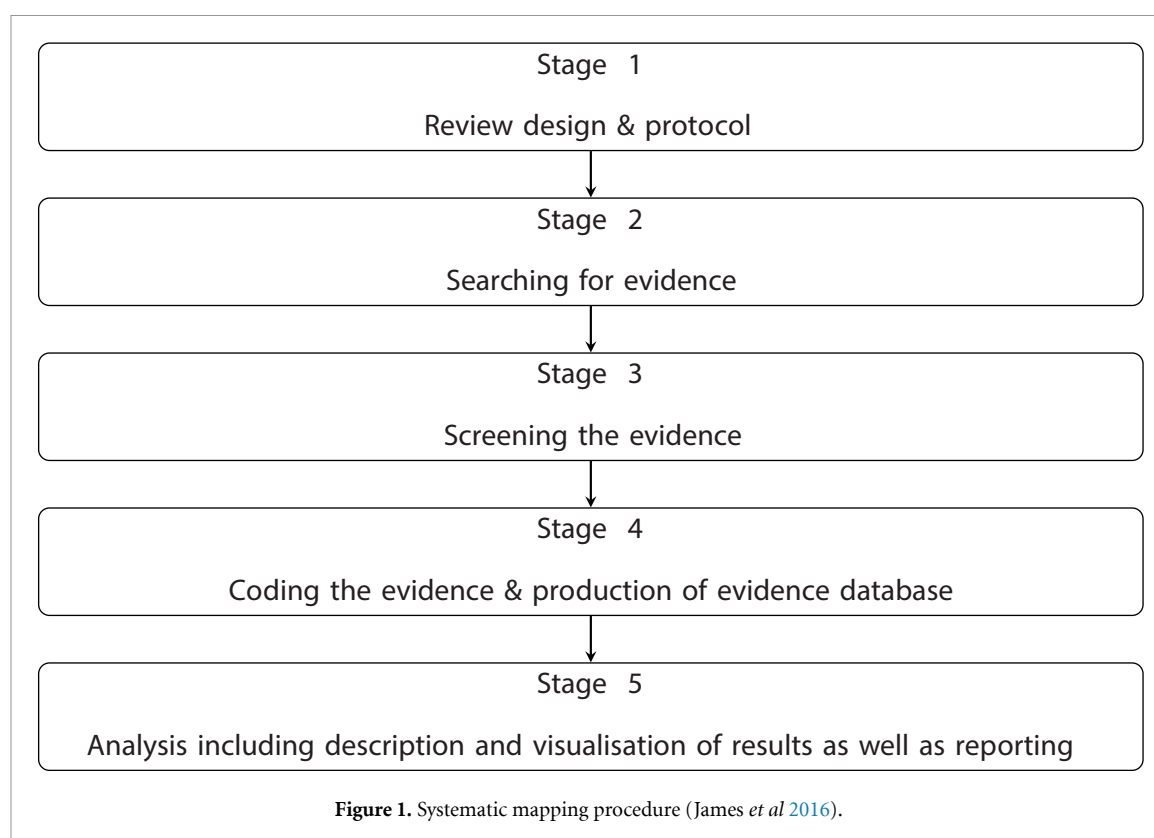
### 2.1. Steps 1 and 2 - Review design, scope and search query

To operationalise our review question, we scope our review in the following way: we consider long-lived capital across three categories identified by Seto *et al* (2016), namely (i) carbon-emitting infrastructure, such as power plants and vehicles, (ii) carbon emissions-supporting infrastructure, such as fossil fuel distribution network, and (iii) energy-demanding infrastructure, such as building shells, roads and urban forms. Our focus is on studies that analyse the capital built to extract, transport and transform the fossil fuel resources, but not fossil fuels themselves - even though these can contribute to lock-in as well. We also limit the scope of our inquiry

to articles that explicitly study carbon lock-in, and not only lock-in of a specific technology with no consideration of the greenhouse gases emissions implication of the technology use. From the three types of carbon lock-in conceptualized by Seto *et al* (2016) - namely (a) technological and infrastructural, (b) institutional and (c) behavioral - we limited our analysis only on the first two. Behavioural lock-in is a much less mature scientific concept and would require a lot more groundwork before starting any synthesis that would mainly rest on highly disciplinary evidence from sociology, behavioural economics or psychology (Beretti *et al* 2013, Stoknes 2014). This is beyond what can be provided here. So we leave it to a dedicated future effort that would need to involve additional scientific expertise.

We constructed a transparent keyword-based query and search both the Web of Science (WOS) and Scopus. Our search string consists of synonyms related to climate change, LLCS and lock-in. The keywords were initially chosen on the basis of the authors experience. We then developed and tested a series of alternative search strings against a sample of 30 key articles available on WOS compiled *a priori* by the authors (see the test list in Supplementary Material 1 (stacks.iop.org/ERL/16/053004/mmedia)). We selected the search string presented in table 1, which could retrieve 29 of the 30 articles (notably the one article was only not retrieved because the associated abstract was not available on WOS). In this query we included the generic keywords 'scenario', 'pathway' and 'integrated assessment' in the LLCS and lock-in keywords category to also include articles using integrated assessment model and/or climate change mitigation scenarios. Some articles from this literature have addressed carbon lock-in induced by LLCS among other topics without necessarily mentioning related keywords explicitly in the abstract (see for instance Creutzig *et al* (2016) or Luderer *et al* (2018)). To limit the number of results obtained, we also included keywords combined with the Boolean NOT to exclude articles about forest and agriculture because they do not fit the definition of LLCS we used. Overall, our query yielded an initial total of 34 002 unique publications on WOS and Scopus in June 2019. We chose this rather extensive search string over more focused alternatives for matters of comprehensiveness and given the availability of a machine learning pipeline for streamlined evidence screening and selection (see below).

Although the search string is extensive, we recognize several shortcomings of our search strategy. First, we focused on English publications only, but recognise the existence of relevant articles on carbon lock-in in other languages. Second, we focused on the two bibliographic databases WoS and Scopus, but these do not cover the entire academic literature and miss grey literature entirely. To partially compensate for the second and third points, additional documents

**Figure 1.** Systematic mapping procedure (James *et al* 2016).

**Table 1.** Description of search query.

| Climate keywords | LLCS keywords | Lock-in keywords |
|---|---|---|
| ((carbon NEAR/3 (emission* OR budget)) OR ($CO_2$ NEAR/3 (emission* OR budget)) OR decarboni*ation OR (degree* NEAR/3 ("1.5" OR "2")) OR (climat* NEAR/3 (mitig* OR policy OR policies OR goal)) OR (energy NEAR/2 (consum* OR use))) | (infrastructure* OR transport* OR fossil OR industry OR electricity OR shipping OR building* OR gas* OR coal* OR power OR "built environment" OR "building stock*" OR urban* OR cities OR city OR "integrated assessment") | (lock* OR "stranded" OR retirement OR divest* OR "inertia" OR "path dependen*" OR "pathway*" OR "scenario*" OR "earlier" OR "early" OR (commit* NEAR/3 (emission* OR $CO_2$))) |

Keywords for exclusion : (*forest* OR agric* OR agro*)

were identified by 'snowballing' (Sayers 2007) - extracting references from relevant publications on carbon lock-in including grey literature. Overall, whilst not being fully exhaustive, we feel that our approach provides an extensive view of the available literature.

**2.2. Step 3 - screening and selecting the evidence**
A growing challenge for rigorous evidence synthesis methodologies is that many search strings return tens of thousands of results - particularly in an open-framed context like systematic mapping. Here, the selected search string returned a total of 34,002 publications in June 2019 after deleting duplicates. Available guidelines for systematic evidence mapping (Snilstveit *et al* 2016, Collaboration for Environmental Evidence. 2018, Saran and White 2018) require the comprehensive screening of all search results - ideally by two independent screeners. It is our observation that due to the rapid expansion of

scientific literature, authors tend to artificially restrict their search queries in order to keep the number of articles for screening manageable, even though this may substantially limit the analysis.

An alternative way to approach this is to relax the stringency of screening in exchange for building a comprehensive search query that yields a number of search results greater than that which can be screened by hand. Machine learning can be used to assist the screening and selecting articles by training an algorithm with the screening decisions made by humans (O'Mara-Eves *et al* 2015, Westgate *et al* 2018, Lamb *et al* 2019, Nakagawa *et al* 2019). Only the subset of remaining articles predicted to be most likely to be relevant are then screened manually. We set out the screening process we followed in detail below, and summarise in figure 2.

First, to ensure screening consistency between reviewers and a common understanding of inclusion/exclusion criteria, four authors screened the

same set of 100 articles independently at the beginning of the process. The screening results were compared and reviewers jointly discussed consistency in the light of inclusion/exclusion criteria (table 2).

After the consistency check, the reviewers screened a further 508 records independently, resulting in an initial random sample of 608 documents. We added 41 articles identified *a priori* as pertinent for our topic in order to provide more 'relevant' labels in our training dataset. These articles were extracted from the test list we built and from the references list of Erickson (2015) and Seto *et al* (2016). We justify the choice of these two articles by the fact they are highly cited and fit our topic perfectly through their analysis of different types of carbon lock-in in different sectors.

We then started an iterative process where at each iteration, we 1) trained a machine learning model to predict the relevance of a document given its title and abstract; 2) predicted the relevance of the unseen documents; and 3) assigned the next set of documents to be screened by the authors by selecting the documents predicted to be most relevant. We went through three iterations of machine learning prioritized screening and each had decreasing proportions of relevant documents in the set of screened articles. In the first iteration of 494 documents, 35% of records were relevant. In the last iteration of 300 documents, only 5% documents were relevant, suggesting that the returns to additional screening would be small.

We then added 4,093 further documents by repeating the queries in February 2020, and by searching for documents citing the article on lock-in by Unruh (2000). We screened the 97 documents predicted most likely to be relevant from these additional documents, finding a further 28 relevant documents.

We performed full text screening on the 335 documents included during the screening process. Only articles with full text available and in English were kept. 184 of these articles were kept, to which we added 6 further documents identified manually and 36 documents identified through the aforementioned snowballing procedure. A total of 226 documents were finally included for our map and review.

### 2.3. Step 4: coding the evidence and production of evidence database

We developed a codebook (included as Supplementary material 3 to this article) for systematic extraction of information. In our codebook we reported results for each study in rows. We define a study as an instance where geographical and/or sectoral carbon lock-in is reported (either qualitatively or quantitatively). Overall, we found a total of 431 studies across the 226 included publications. For each study we extracted the meta-data (Authors, Title, Date, DOI) of the corresponding publication. We further recorded qualitative data on the study context such as the

scale of analysis, the geographic areas and the sectors studied. For each quantification of carbon lock-in, we also extracted the numerical indicators related to carbon lock-in and their corresponding values. Overall, we found 286 quantifications of carbon lock-in from 92 publications. A common table with limited choices was constructed in order to ensure consistent information extraction between the authors.

### 2.4. Thematic analysis of qualitative statements

We used thematic synthesis to systematically analyse policy implications and options for avoiding carbon lock-in mentioned in our final sample of studies. Widely used in psychology, thematic synthesis is a method for identifying, analysing and highlighting themes within qualitative studies (Braun and Clarke 2006). It also enables a tractable and easily updatable synthesis of extracted statements (Thomas and Harden 2008, Hilaire *et al* 2019). Thematic synthesis allows us to identify a list of possible policy interventions for avoiding carbon lock-in and characterize the appropriateness of these interventions and the factors influencing their implementation.

Overall, we manually extracted 136 qualitative statements (QS) on policy implications from abstract, conclusion or discussion sections of our final set of articles, assuming that most of the statements on policy implications would be in these sections. To be included, QS had to explicitly refer to policy action or instruments to escape or avoid carbon lock-in. We classified QS into broad groups of policy instruments, following Goulder and Parry (2008), namely: incentive-based instruments, regulatory instruments, technology policies and others. QS from the 'others' category were then reassessed to highlight the most frequently mentioned specific features associated with these policies to avoid or escape carbon lock-in.

## 3. Results

### 3.1. Literature mapping

We first analyzed the literature distribution across sectors, geographic areas studied, and scales of analysis. We find that carbon lock-in has been mainly analyzed in the electricity generation sector (figure 3(a)) with 98 related publications representing 43% of our sample. Publications remaining at an aggregated sectoral level or analyzing carbon lock-in in a generic way also account for a significant portion of our sample with 66 publications representing 29 % of our sample. Conversely, the industry and fossil fuel production & distribution sectors have been little studied with, respectively, 13 and 14 related articles representing a combined 11% of our sample. This focus on the power sector can be explained by its large contribution to annual global $CO_2$ emissions, representing between 30 and 40% of total emissions from 2005 to 2018 (Crippa *et al* 2019). However,

**Table 2.** Inclusion/Exclusion criteria.

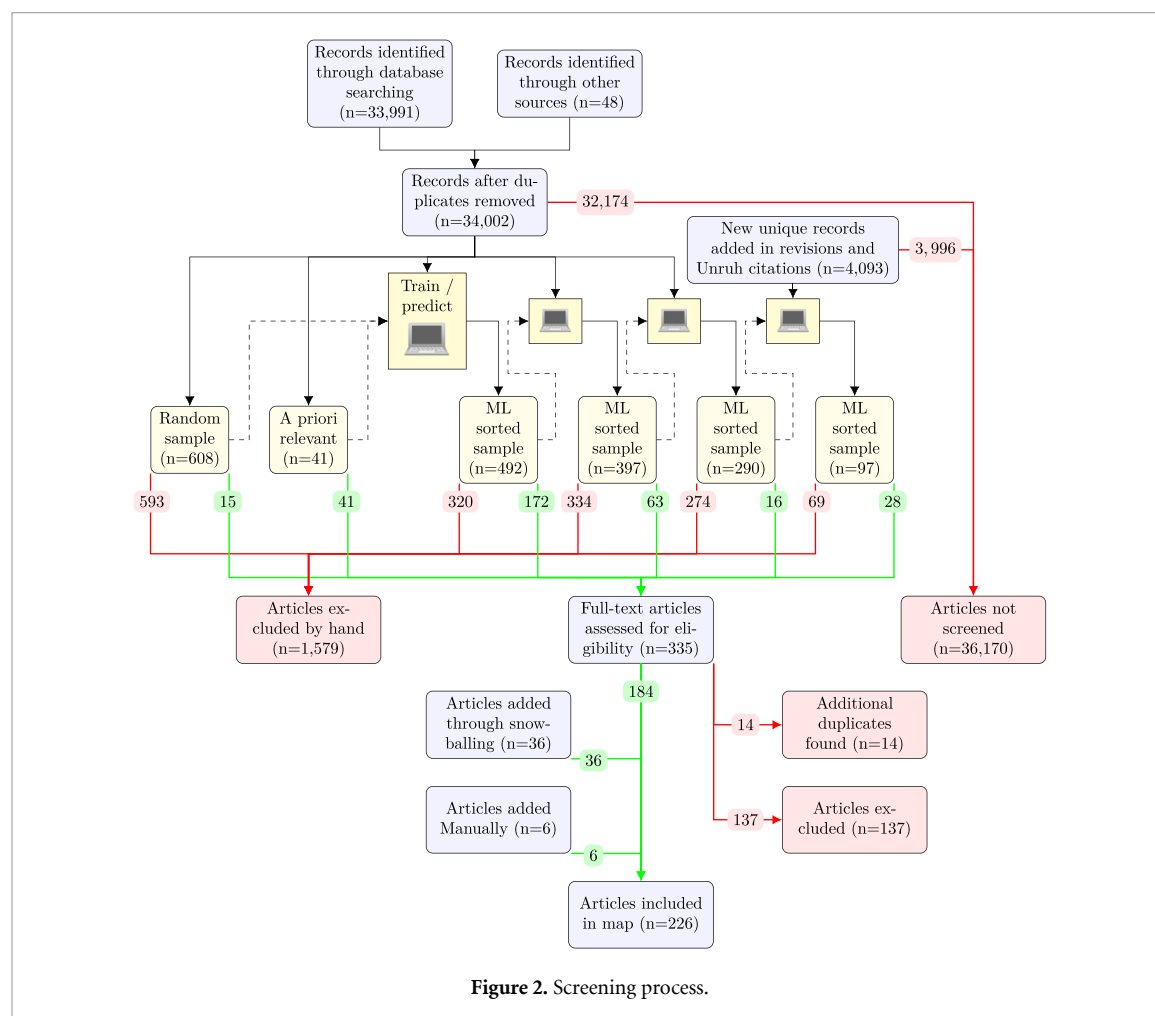| Include/Exclude | Reason |
|---|---|
| Include | Publication using scenarios in the energy demand or supply sectors must include keywords related to carbon lock-in, investments dynamic or stock renewal in the abstract |
| Exclude | Publications only focusing on lock-in but not related to climate change mitigation or GHG emissions induced by long-lived capital |
| Exclude | Publications only about carbon lock-in induced by fossil fuels themselves or natural resources |
| Exclude | Publications only analysing behavioural carbon lock-in |



**Figure 2.** Screening process.

while in the electricity sector the observed operational lifetimes of capital vary between 30 and 60 years (Rode *et al* 2017), capital in other sectors such as buildings, fossil fuels extraction facilities, or urban form can remain in place longer and could present a larger potential source of long-term carbon lock-in (Reyna and Chester 2015, Bos and Gupta 2018). Moreover, the shares of global emissions in sectors other than power generation will tend to increase in the coming decades due to the faster decarbonisation of the power sector (Méjean *et al* 2019) and the harder-to-mitigate emissions in sectors such as aviation or industry (Davis *et al* 2018).

Carbon lock-in has been studied at different scales, from subnational to global, but unevenly in the literature (figure 3(b)). Global/Generic and national scales represent the majority of existing publications with, respectively, 46% and 33% of our sample. There are on the other hand only 16 publications in our sample analyzing carbon lock-in on a multi-country scale, 8 of which are related to the European Union. These low numbers are partially compensated by the fact that several quantitative studies at the global level also include results for different world regions, such as Johnson *et al* (2015). 32 publications, or 14% of our sample, specifically analyzed the subnational scale. As for the multi-country scale, some analyses at the national scale also include specific results at lower scale, such as Jiang *et al* (2017) at the Chinese provinces level. Urban settlements account for nearly 70% of today's global carbon emissions (Acuto and Parnell 2016) and subnational mitigation policies are specific and differ from larger scale policies (Creutzig *et al* 2015). Carbon lock-in

is also a 'fractal trap' in the sense that its occurrences at different scales tend to reinforce each other (Bernstein and Hoffmann, 2019). This calls for a greater emphasis on the regional and city scales for future research.

To analyse the geographical distribution of the literature, we used two different indicators: 1) the number of publications related to a country or a world region (independent of the scale of analysis; e.g. an article focusing on a particular city in a country was counted as related to that country); and 2) the number of different sectors analysed per country/world region. The chosen sectors are the same as those presented on figure 3.

The literature has investigated 45 countries, but with uneven focus (figure 4(a)). China and the United States are the most studied countries, with 29 and 27 publications, respectively, covering 5 sectors (figure 4(b)). The UK has been widely studied as well with 19 publications covering 4 different sectors. In contrast, 13 countries have been analyzed by only 1 publication each. More than 9 publications are related to Australia, Germany and India, but for only 3 sectors each. Even if publications are more numerous for those countries compared to others, future studies on the missing sectors would be relevant. 26 publications provide carbon lock-in analysis for world regions. A large part of this sub sample (17 articles) is about the European Union, which makes sense because it is the only world region studied that forms a political union with climate policies formulated at this level.

Our results reveal a literature bias towards developed countries. That can be seen in the aggregated number of publications associated with five world-regions (IPCC categories): Developed Countries, Asia & Developing Pacific, Africa & Middle East, Latin America & Caribbean and Eastern Europe & West-Central Asia (regional definitions are presented in the Supplementary Material 2). 92 publications are associated with Developed Countries, 38 with Asia & developing Pacific, 10 with Africa & Middle East, 10 in Latin America & Caribbean and 8 in Eastern Europe and West-Central Asia. Even though developing countries (excluding China and India) are not major contributors to global $CO_2$ emissions at the moment, they may contribute to a high proportion of future emissions growth, which calls for more research in these countries. Among the Developed Countries publications, some countries are over-represented compared to their contribution to global emissions, particularly the United Kingdom of Great Britain and Northern Ireland, but also to a lesser extent Germany, Sweden and Australia (figure 5). Russian Federation contributes significantly to global $CO_2$ emissions but has been proportionally less studied, with only 5 publications. Although China has been the most studied country, the share of associated publications is still lower than its share of emissions in 2018 (figure 5).

**Table 3.** Indicators used in the literature by time frame of analysis. The number of publications is indicated in each cell.

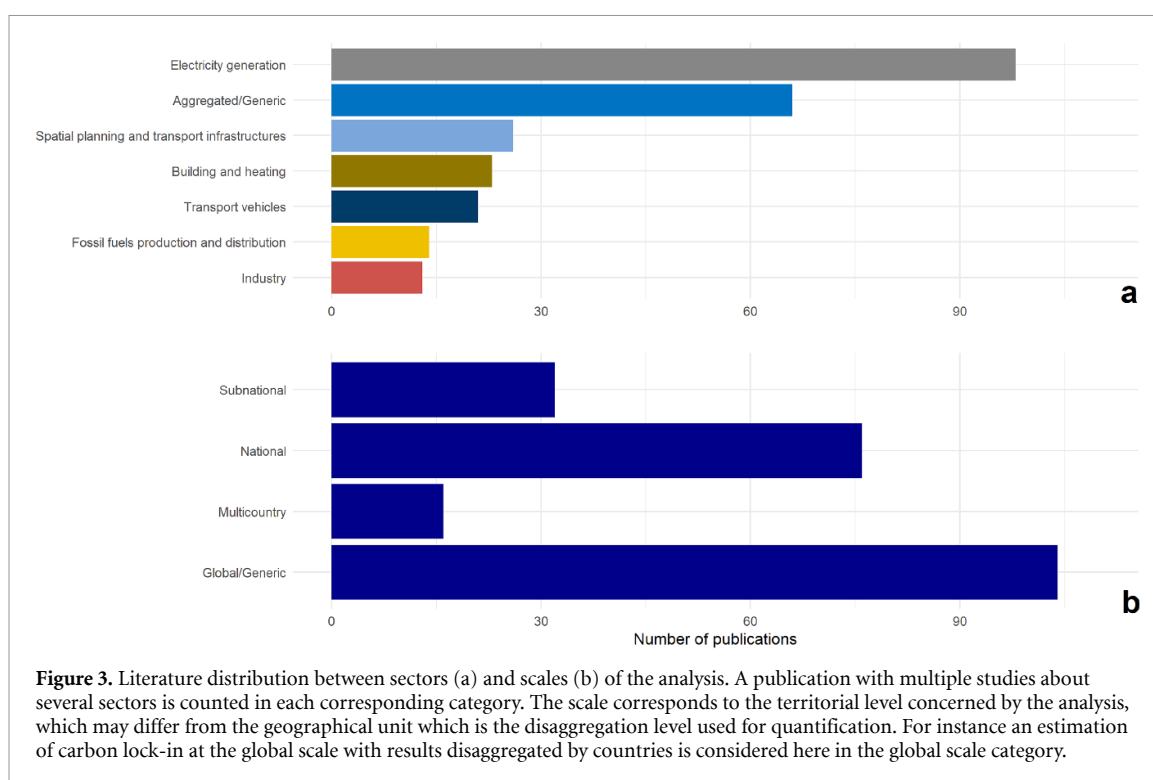| Indicator | Backward | Static | Forward |
|---|---|---|---|
| Installed capacity | | 2 | 4 |
| Age of existing stock | | 4 | |
| Committed emissions | 5 | 13 | 8 |
| Capital costs intensity | | 1 | 1 |
| Stranded assets | | 5 | 31 |
| Mitigation costs | | 1 | 10 |
| Emissions/Energy gap | | | 12 |
| Residual emissions | | | 2 |
| Elasticity related to LLCS variables | 3 | | 1 |
| Technology scale | 1 | 2 | 2 |
| Employment | | 2 | |

### 3.2. Review of carbon lock-in quantifications

#### 3.2.1. Carbon lock-in indicators

In our analysis of the literature, we find 92 publications that contain 286 quantitative estimations of carbon lock-in. We sort them according to geographical scope (subnational, national, multicountry, and global), and sector (electricity, building, spatial planning, transport vehicles, fossil fuel production, industry).

The electricity sector has received the most quantifications, with 170 estimations in 60 publications, which represents 65 % of the subsample of quantitative studies. This result is valid as well for all geographic levels, except for cities (figure 6 and Supplementary Material 1 figure 1). On the other hand, publications containing quantifications for transport vehicles and spatial planning represent each less than 10% of the quantitative studies. Few quantifications (3) for cities have been done compared to other geographical units. More city case studies would be needed to quantify the impact of different policies on $CO_2$ emissions in the long term and give insights for local planning choices.

We identified 11 indicators used in the literature (table 3). These have been applied for different time frames of analysis that can be classified as backward-looking, static for a given year, or forward-looking using scenarios. Backward-looking analyses study periods in the past over a certain time frame. Static analyses provide a snapshot at a given year, often just a few years before the date of publication of the study, corresponding to the latest year for which data is available. Forward-looking analyses construct scenarios of future evolutions and analyze those trajectories. Few articles (7) have carried out quantitative retrospective analyses on carbon lock-in compared to static (30) or prospective (63) analyses. In the next paragraph, we describe each of the different indicators used and summarize the common trends in results where publications numbers are sufficient.

**Figure 3.** Literature distribution between sectors (a) and scales (b) of the analysis. A publication with multiple studies about several sectors is counted in each corresponding category. The scale corresponds to the territorial level concerned by the analysis, which may differ from the geographical unit which is the disaggregation level used for quantification. For instance an estimation of carbon lock-in at the global scale with results disaggregated by countries is considered here in the global scale category.
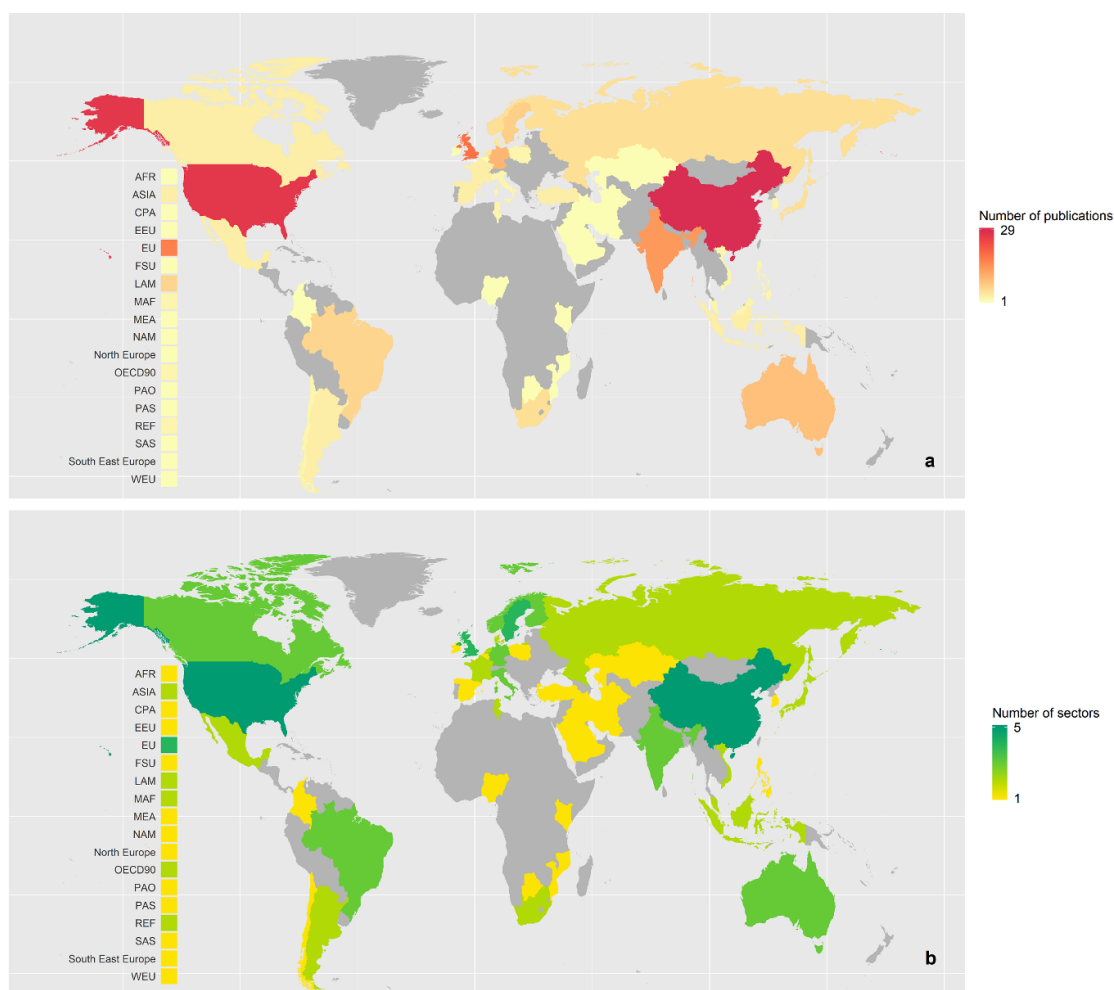
Studies have focused on the evolution of *installed capacity*, corresponding for example to the electricity output for a power plant or the traffic volume for a road. Installed capacity, as projected over time, is used as a measure of carbon lock-in in the electricity generation and fossil fuel production & distribution sectors. Articles have highlighted the risk of a rapid increase in high-carbon installed capacity by 2030 if climate policies are further delayed (Bertram *et al* 2015, Turhan *et al* 2016, Kefford *et al* 2018, McGlade *et al* 2018). However, these studies could potentially overestimate the carbon lock-in induced by LLCS evolution by not considering low carbon retrofitting such as carbon capture and storage integration for power plants. This is shown by Li *et al* (2011) which quantified in a static manner the share of power generation capacity existing at a given year in China that could be retrofitted with carbon capture and storage.

Other studies have quantified carbon lock-in in relation to the lifetime of the capital considered. Some authors have referred to the *age* of the existing infrastructure stock, analyzing either its distribution or its average value. The younger the stock, the lower the probability to replace this capital in the short term. This indicator has been used mainly in the electricity generation sector (figure 6). The global age distribution tends to be bimodal between OECD and non OECD countries. For instance, in China a large part of industrial and electricity sector capital is younger than 10 years (Lane *et al* 2016, Zheng *et al* 2018) whereas in the EU and the US an important part of electricity generation capital is more than 30 years old. (Lane *et al* 2016, Rode *et al* 2017).
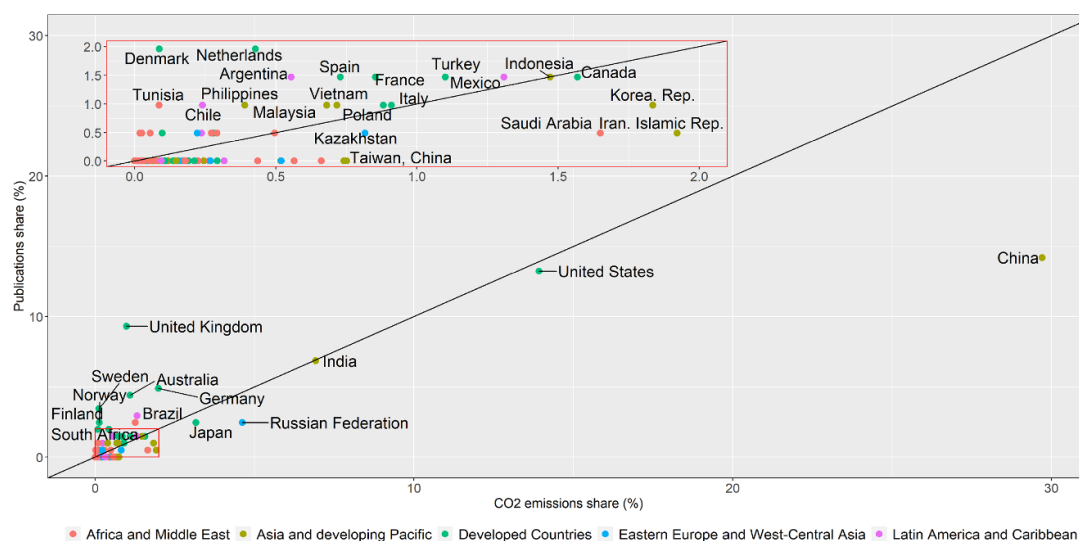
The concept of *committed emissions* has also been used to quantify the cumulative emissions that would occur over the remaining entire operation lifetime of an asset (Davis *et al* 2010). This indicator has been mainly applied in static and forward-looking frameworks (table 3). Past committed emissions over a given a period have also been analysed, but to a lesser extent (Davis and Socolow 2014, Jiang *et al* 2017, Pfeiffer *et al* 2018, Tong *et al* 2019). In a static framework, the committed emissions calculated can be compared with carbon-budgets associated with a temperature target to quantify the potential (in)consistency of the existing stock with the temperature goal. Whereas most of the indicators have been used for one or two time frames, committed emissions have been used for backward-looking, static and forward-looking analyses.

The operational life of infrastructure does not only depend on its age. Indeed, any infrastructure project is based on an investment plan with an expected long-term profitability. A change in the regulatory and economic context (for example the implementation of a carbon tax) can thus modify the operational costs, rendering the continued use of an infrastructure uneconomical. This is why other indicators also include economic aspects to quantify carbon lock-in. Two publications have quantified the *capital costs intensity* as the level of capital investment required for extraction or production of given unit (Shackley and Thompson 2012, Erickson 2015). The assumption behind this is that the more capital-intensive an investment, the more it may be isolated from price fluctuations and hence the more operators will be likely to keep using this capital.
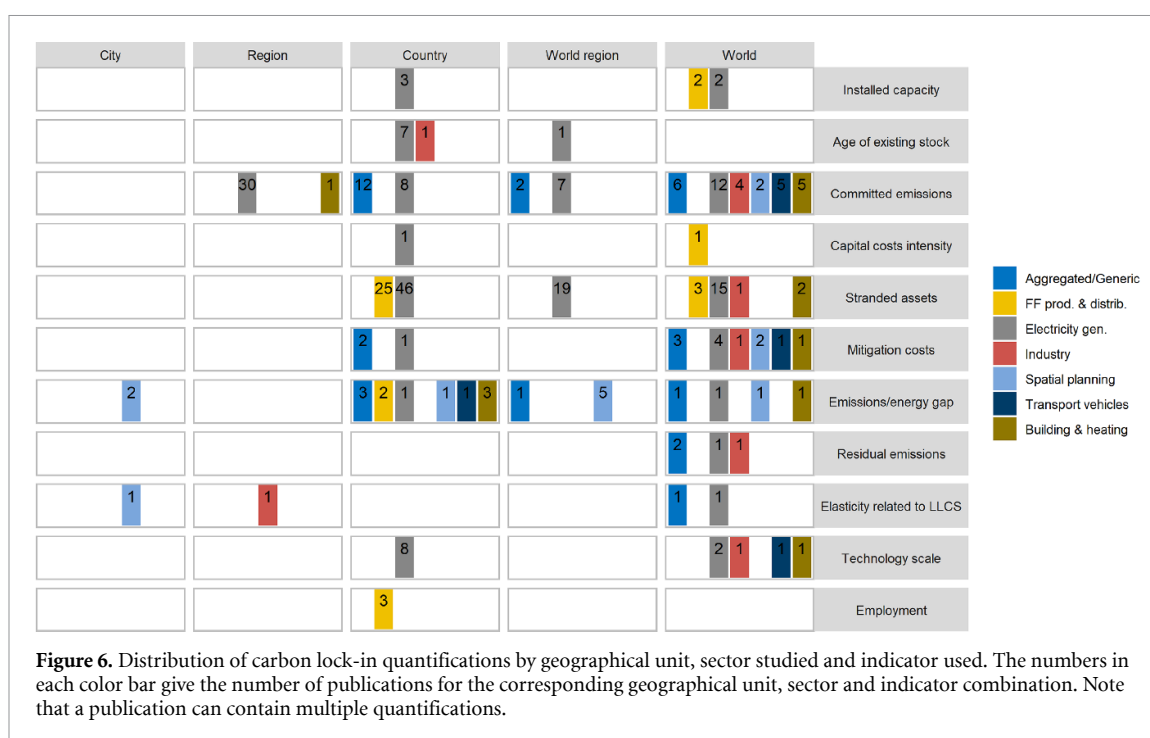
**Figure 4.** Geographical distribution of the literature by numbers of publications (a) and numbers of sectors analyzed (b). The maps present the results for countries analyzed, with all scales of analysis combined. For instance publications focusing on a particular city in a country are counted as related to that country. The bar plots show the geographical distribution among world regions of publications with global or multi-country scales of analysis. The codes for world regions are given in the Supplementary Material 1 table 1.



**Figure 5.** Shares of publications against shares of 2018 $CO_2$ emissions for each country. The black line corresponds to the points where the share of publications equals the share of $CO_2$ emissions. Data used for $CO_2$ emissions come from Crippa *et al* (2019).

**Figure 6.** Distribution of carbon lock-in quantifications by geographical unit, sector studied and indicator used. The numbers in each color bar give the number of publications for the corresponding geographical unit, sector and indicator combination. Note that a publication can contain multiple quantifications.

In the same manner, carbon lock-in literature has made extensive use of the *stranded assets* indicator. It is defined as the premature retirement/retrofitting or under-utilization of existing assets in relation to a potential reference capital (Saygin *et al* 2019). This indicator measures the implications - the assets lost-if the carbon lock-in is to be escaped from. Stranded assets can be either the stranded investments or the stranded profits depending on the reference lifetime chosen. Indeed, the reference lifetime considered can be the 'physical' one over which the capital can be used or the 'economic' one over which capital investment costs are recovered. Making this distinction is important because it can have significant impact on the results obtained as the difference between these two lifetimes can be of several decades (Kefford *et al* 2018). The majority of existing estimations are about the electricity generation and fossil fuel production & distribution sectors (figure 6). Two distinct methodologies have been used. For the first one, some authors have used the age distribution of the existing stock for a given year based on unit-level assessments to project its evolution, assuming all capital stock is used until the end of its potential lifetime. This evolution is then compared (i) either in a static manner to the capital stock targeted for a future year (Pfeiffer *et al* 2016, Farfan and Breyer 2017a,b) (ii) or with a forward looking approach to the capital stock evolution extracted from a low-carbon scenario (CTI 2014a,b, Lane *et al* 2016, Kefford *et al* 2018, Cui *et al* 2019, Saygin *et al* 2019). The second approach is to quantify the stranded assets using models with an endogenous evolution of capital stock (Mercure *et al* 2014, Iyer *et al* 2015, Johnson *et al* 2015, Luderer *et al* 2016, van Soest *et al* 2017, Coulomb *et al* 2019).

In this case, capital can be retired early because new economic conditions make its use unprofitable. Results obtained are expressed either in terms of electricity capacity/production retired or in monetary terms to quantify the loss of expected revenue. Given the numerous quantifications for these two indicators - committed emissions and stranded assets - the synthesis of the results is presented in the section 3.2.2 below.

*Mitigation costs* is also an indicator which has been used to quantify the transition costs induced by the inertia of long-lived capital. It represents the potential macroeconomic costs associated with the transition to a low-carbon system for different levels of short-term climate policy ambition. Mitigation costs have been quantified as the variation of an economic indicator between a 'reference' scenario (either with no mitigation policies or with current policies only) and a mitigation scenario or a scenario considered as 'optimal' to reach a long term temperature target. It is an indicator widely used in the integrated assessment literature to compare the macroeconomic costs of different scenarios. We extracted only the studies using specifically this indicator to quantify carbon lock-in. The economic variables chosen to represent the mitigation costs have been GDP losses (Ha-Duong *et al* 1997, Richels *et al* 2009, Waisman *et al* 2012, Lucas *et al* 2013, Riahi *et al* 2015, Luderer *et al* 2016) or consumption losses (Lecocq *et al* 1998, Kalkuhl *et al* 2012, Bertram *et al* 2015). The literature has mainly used mitigation costs to quantify carbon lock-in at the global scale. A common result with this indicator is that when mitigation policies are non-existent or when their stringency is low in the short term, overall mitigation costs increase, reflecting short-term inertia

and path-dependency. We considered as mitigation costs as well the unlocked costs calculated by Erickson *et al* (2015) as the carbon price needed to retire an existing investment in 2015 at half its economic lifetime and replace it with a corresponding low-carbon alternative.

Other studies have evaluated the contribution of infrastructure stock evolution to $CO_2$ emissions by dynamically taking into account both technical and economic factors. To do so, some authors have calculated the *emissions/energy gap* at a given future year between different scenarios of infrastructure stock evolution. Another approach has been to compare *residual emissions* – the amount of $CO_2$ emissions whose abatement remains uneconomical or technically infeasible in the long term (Kriegler *et al* 2015, Luderer *et al* 2018) – between scenarios. Models used in these publications have projected an increase of global residual emissions when the strengthening of mitigation efforts is delayed. While former indicators have been applied only for forward-looking studies, *elasticities related to capital stock variables* allows authors to retrospectively isolate the contribution of capital stock evolution to increases in $CO_2$ emissions. Correlations have been estimated between $CO_2$ emissions from coal capital & economic growth, $CO_2$ emissions & material stock or $CO_2$ emissions & industrial agglomeration index (Steckel *et al* 2015, Lin *et al* 2017, Zhang *et al* 2018). Avner *et al* (2014) also used this type of approach in a forward looking framework, looking at fossil fuel price elasticity of $CO_2$ emissions for different scenarios of public transport supply.

A last group of indicators, used more marginally, relates to institutional and political factors that influence the transition rate of LLCS. This concerns first of all *employment*, with analyses of the distribution of jobs between low and high carbon sectors or the regional concentration of jobs in carbon-intensive sectors (Bjornaavold and Van Passel, 2017, Spencer *et al* 2018). The issue of employment is not just a question of social acceptability in case of rapid transition. One of the conditions for the emergence of a capital-intensive low-carbon technology in the face of a dominant technology is the rapid reduction of cost through learning effects. These learning effects depend on the production process of the technology and therefore on the skills of the workers (Bjornaavold and Van Passel, 2017). The second institutional indicator is the *technology scale* expressed as the market share of given technologies (Erickson *et al* 2015, Spencer *et al* 2018, Skoczkowski *et al* 2018). The hypothesis here is that widespread adoption of a technology induces significant carbon lock-in through confidence in the technology (adaptive expectations) and coordination between sectors (network effects).

The indicator statistics reveal that the majority of existing estimations have used committed emissions or stranded assets as metrics (figure 6 and table 3).
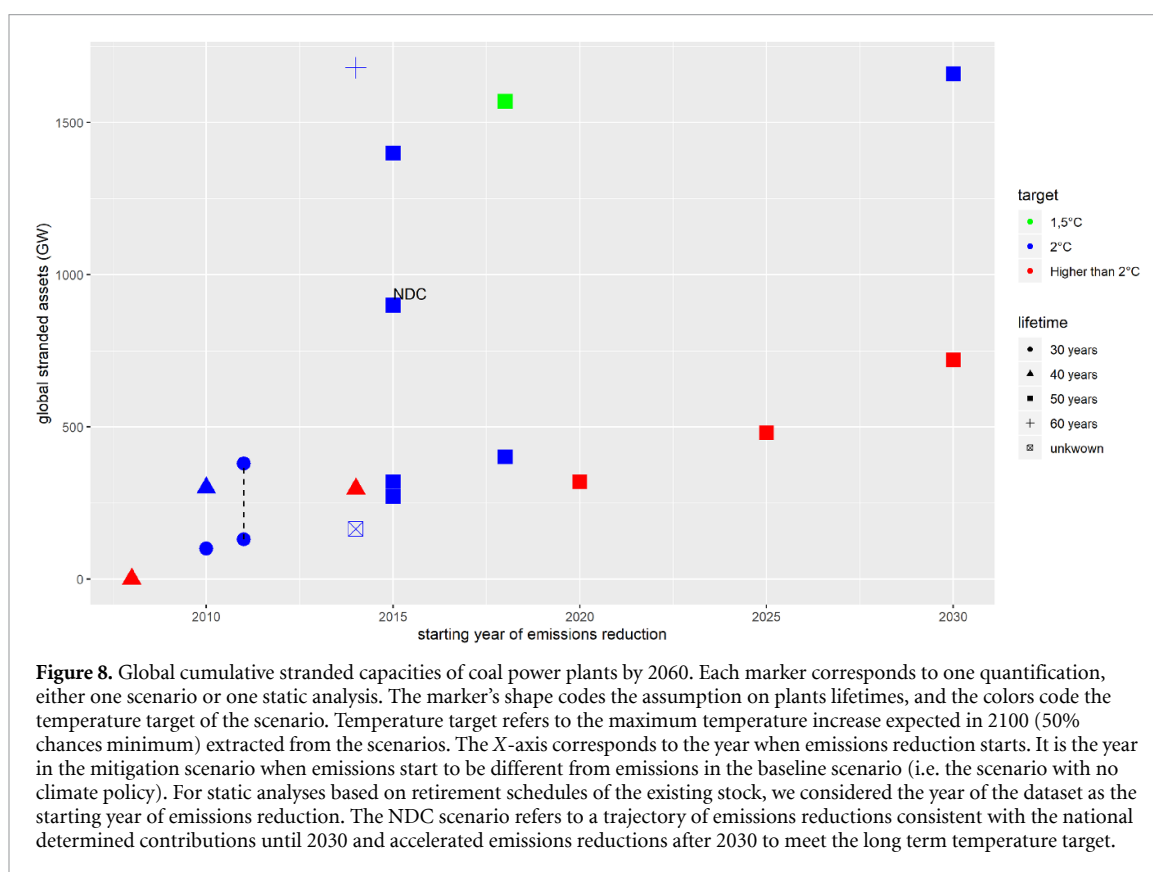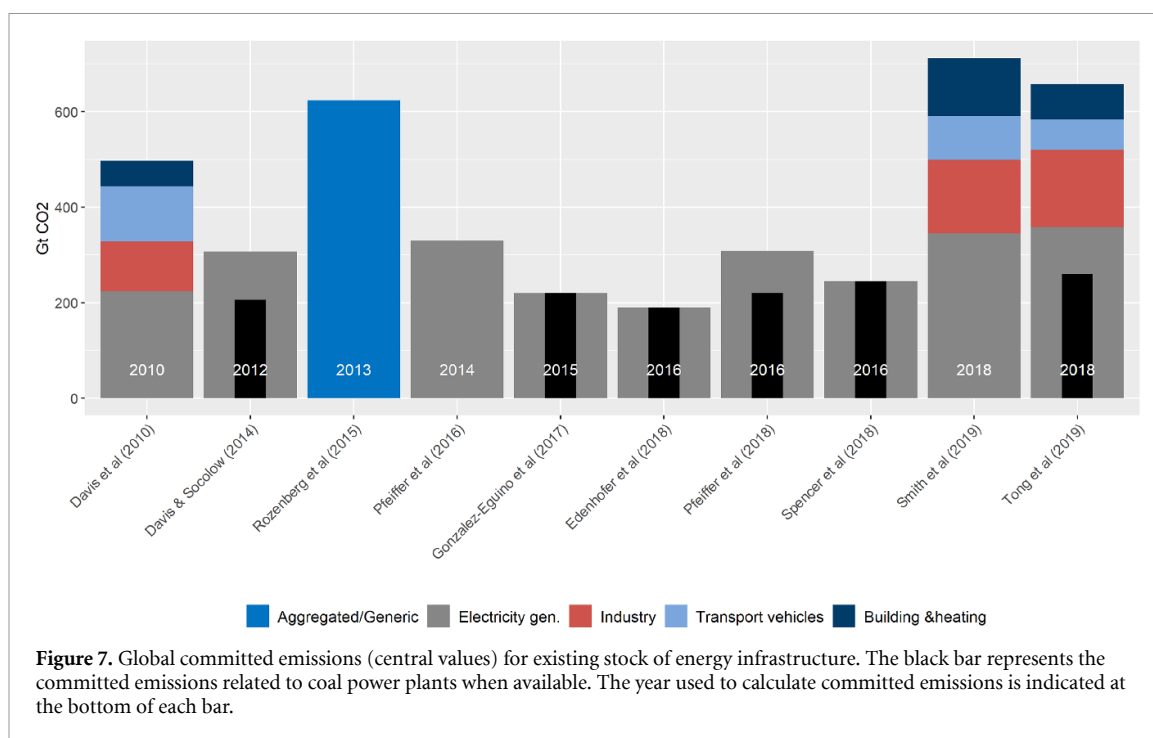
These indicators have been used at a diversity of geographical levels compared to other indicators and in multiple sectors. However, more retrospective analysis could be carried out for stranded assets, in particular in order to analyse which policy instruments triggered these premature closures and what the associated economic impacts were. The majority of indicators used refers to technical and economic dimensions of carbon lock-in. Conversely, few analyses have been carried out to quantify institutional carbon lock-in.

### 3.2.2. Synthesis of results concerning committed emissions and stranded assets

10 studies in the literature have estimated cumulative committed emissions for a given year and at the global scale (figure 7). These articles differ by the sectors included in the analysis. From the four studies that include all sectors, a slight increase over time of committed emissions seems to emerge. However, this result is to be taken with care since it comes from a very small number of studies, and part of the result may come from different methodologies, data sources or assumptions, in particular on capital lifetimes and utilization rates. No clear trend over time emerges for the electricity sector, but again this may be due to different methodologies and assumptions across studies. One study (Tong *et al* 2019) recently analyzed, with the same methodology, data sources and assumptions, the evolution in committed emissions over time and found an increase in total committed emissions from just above 400 $GtCO_2$ in 1998 to 658 in 2018, with the majority of the increase in the power generation sector and in China.
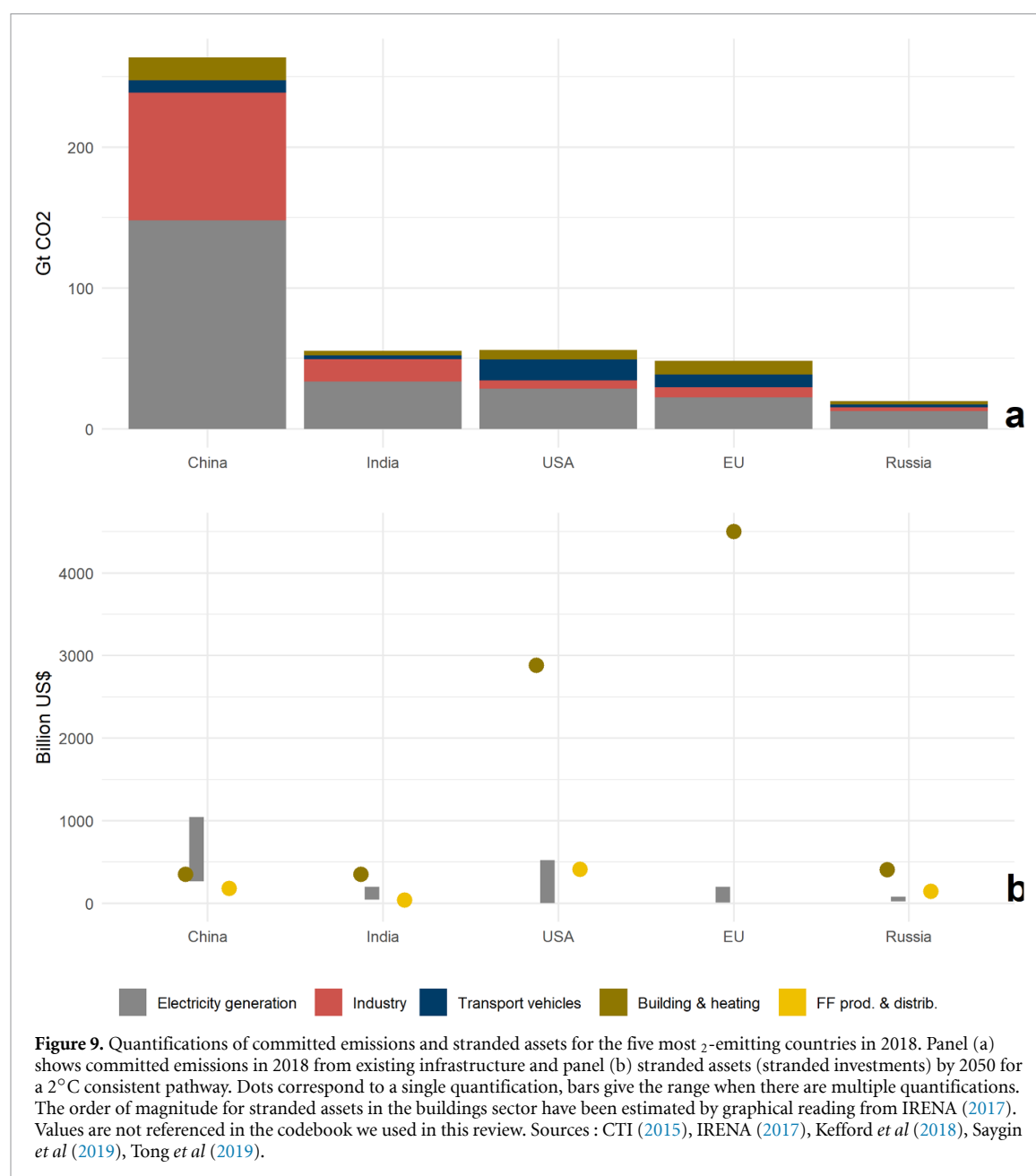
The existing infrastructure contributing the most to global committed emissions are power plants, accounting for between 48% and 54% of the total (Smith *et al* 2019, Tong *et al* 2019). This high contribution of the electricity sector is also found at the national level for the 5 countries with the highest $CO_2$ emissions. For all 5 countries, the share of the electricity sector in total committed emissions is above 45% (figure 9). Industry is the second largest source of committed emissions, particularly in emerging countries such as China and India with shares close to 30%.

Existing evaluations of stranded assets have also highlighted the carbon lock-in induced by the power generation sector. Coal-power plants constitute the electricity generation capital with the highest risk of stranded assets. For scenarios consistent with a 2°C target, cumulative global early retired capacities by 2060 would represent less than 50 GW for oil, a maximum of around 600 GW for gas and up to 1700 GW for coal (Iyer *et al* 2015, Kefford *et al* 2018). This large difference justifies the greater emphasis of the stranded assets literature on coal power plants. Estimations are sensitive to modelling hypothesis (figure 8). The later the climate policy

**Figure 7.** Global committed emissions (central values) for existing stock of energy infrastructure. The black bar represents the committed emissions related to coal power plants when available. The year used to calculate committed emissions is indicated at the bottom of each bar.



**Figure 8.** Global cumulative stranded capacities of coal power plants by 2060. Each marker corresponds to one quantification, either one scenario or one static analysis. The marker's shape codes the assumption on plants lifetimes, and the colors code the temperature target of the scenario. Temperature target refers to the maximum temperature increase expected in 2100 (50% chances minimum) extracted from the scenarios. The *X*-axis corresponds to the year when emissions reduction starts. It is the year in the mitigation scenario when emissions start to be different from emissions in the baseline scenario (i.e. the scenario with no climate policy). For static analyses based on retirement schedules of the existing stock, we considered the year of the dataset as the starting year of emissions reduction. The NDC scenario refers to a trajectory of emissions reductions consistent with the national determined contributions until 2030 and accelerated emissions reductions after 2030 to meet the long term temperature target.

is implemented, the higher the expected stranded assets are. Even if the climate policy is implemented before 2020, the short-term level of stringency is a determining parameter. Compared to the scenarios assuming a strong emissions reduction as early as 2015 and consistent with a 2°C target, global cumulative stranded coal power assets are expected to be higher by a factor 2-3 for National Determined Contributions (NDC) pathways (these NDC pathways correspond to scenarios where mitigation policies until 2030 correspond to the NDCs from Paris Agreement on Climate Change and where emissions reductions accelerate after 2030 to meet the long term temperature target). This estimation of the

**Figure 9.** Quantifications of committed emissions and stranded assets for the five most $_2$-emitting countries in 2018. Panel (a) shows committed emissions in 2018 from existing infrastructure and panel (b) stranded assets (stranded investments) by 2050 for a 2°C consistent pathway. Dots correspond to a single quantification, bars give the range when there are multiple quantifications. The order of magnitude for stranded assets in the buildings sector have been estimated by graphical reading from IRENA (2017). Values are not referenced in the codebook we used in this review. Sources : CTI (2015), IRENA (2017), Kefford *et al* (2018), Saygin *et al* (2019), Tong *et al* (2019).

additional stranded assets induced by NDCs comes from a single publication (Iyer *et al* 2015) and therefore could be refined by further research. Results are very sensitive to the assumed operational lifetime for stranded assets calculation especially for lifetimes higher than 50 years. Only one study (Cui *et al* 2019) quantified stranded assets for 1.5°C scenario obtaining results significantly higher than other studies with similar coal power plants lifetime and year of climate policy implementation.

However, some publications have suggested that stranded long-lived assets may be even more important outside of the power sector. While stranded power sector assets by 2050 could reach up to $1.8 trillion in scenarios consistent with a 2°C target, Saygin *et al* (2019) found a range of $5-11 trillion in the buildings sectors. Muldoon-Smith and Greenhalgh (2019)

even estimated a potential value at risk for global real estate assets up to $21 trillion. CTI (2015) also quantified $2.2 trillion of unnecessary capex in fossil fuel production and distribution from 2015 to 2025.

The sectoral distribution and amount of stranded assets differ across countries (figure 9). Capital for fossil fuel production and distribution represents a larger share of potentially stranded assets in fossil fuel producing countries such as the United States and Russian Federation. Electricity generation would be a larger share of total stranded assets in emerging countries because this capital is relatively new compared to its operational lifetime. Conversely, buildings could represent a larger part of stranded capital in more developed countries such as the United States, EU or even Russian Federation because of high market value and low turnover rate.

**Table 4.** Findings from the thematic analysis on qualitative statements about policy implications to escape carbon lock-in. The 136 qualitative statements extracted from our sample are available in the Supplementary Material 3.

| Topic | Counts | Sources |
|---|---|---|
| Supporting low-carbon technology deployment | #22 | Greene and Plotkin (2001), Sandén and Azar (2005), Delrio and Unruh (2007), Ahman and Nilsson (2008), Bento (2010), Lehmann *et al* (2012), Kalkuhl *et al* (2012), Avner *et al* (2014), Mercure *et al* (2014), Lecocq and Shalizi (2014), Aglietta *et al* (2015), Bertram *et al* (2015), Steckel *et al* (2015), Fouquet (2016), Wesseling *et al* (2016), Hansen *et al* (2017), Schmidt *et al* (2017), Bos and Gupta (2018), Leibowicz (2018), Tvinnereim and Mehling (2018), Edenhofer *et al* (2018), Szabo *et al* (2019) |
| Carbon pricing should be introduced | #21 | Greaker and Heggedal (2010), Lehmann *et al* (2012), Hood (2014), Lecocq and Shalizi (2014), Mercure *et al* (2014), Shahnazari *et al* (2014), Bertram *et al* (2015), Erickson (2015), Fay *et al* (2015), Hermwille *et al* (2015), Mattauch *et al* (2015), Steckel *et al* (2015), Aghion *et al* (2016), Pfeiffer *et al* (2016), IRENA (2017), Jiang *et al* (2017), Edenhofer *et al* (2018), Zheng *et al* (2018), Wilson and Staffell (2018), Rosenbloom *et al* (2019), Wang *et al* (2020) |
| Climate policies orientation needs to be stable over time | #20 | Delrio and Unruh (2007), Bento (2010), Greaker and Heggedal (2010), Nolden (2012), Chignell and Gross (2013), Nam *et al* (2013), Hood (2014), Shahnazari *et al* (2014), Wang *et al* (2014), Lazarus *et al* (2015), Pfeiffer *et al* (2016), Hansen *et al* (2017), IRENA (2017), Bergen and Mu\ noz (2018), Spencer *et al* (2018), La Vi\ na *et al* (2018), Skoczkowski *et al* (2018), Wilson and Staffell (2018), Kalkuhl *et al* (2020), Rosenbloom *et al* (2019) |
| Carbon pricing if introduced needs to be complemented with other instruments | #17 | Sandén and Azar (2005), Delrio and Unruh (2007), Maréchal (2007), Avner *et al* (2014), Lecocq and Shalizi (2014), Mercure *et al* (2014), Bertram *et al* (2015), Fay *et al* (2015), Jotzo and Mazouz (2015), Steckel *et al* (2015), Mattauch *et al* (2015), Pfeiffer *et al* (2016), Tvinnereim and Mehling (2018), Kalkuhl *et al* (2020), Meyer and Schwarze (2019), Rosenbloom *et al* (2019), Lamperti *et al* (2020) |
| Implementing technology mandates | #13 | Gül and Turton (2011), Shackley and Thompson (2012), Chignell and Gross (2013), Mercure *et al* (2014), Bertram *et al* (2015), Erickson (2015), Jotzo and Mazouz (2015), Steckel *et al* (2015), Shearer *et al* (2017), Pfeiffer *et al* (2018), Rozenberg *et al* (2020), Tvinnereim and Mehling (2018), Li and Strachan (2019) |
| Coordination between sectors and actors | #12 | Frantzeskaki and Loorbach (2010), Carley (2011), Gül and Turton (2011), Lehmann *et al* (2012), Malekpour *et al* (2015), Mäkinen *et al* (2015), Sachs *et al* (2016), Wesseling *et al* (2016), Karakaya *et al* (2018), Gadre and Anandarajah (2019), Gross and Hanna (2019), Tozer (2019) |
| Highlighting co-benefits and avoided costs | #11 | Delrio and Unruh (2007), Briggs *et al* (2015), Steckel *et al* (2015), Kriegler *et al* (2015), Clausen *et al* (2017), Martínez Arranz, (2017), Edenhofer *et al* (2018), Skoczkowski *et al* (2018), de Macedo and Jacobi (2019), Meyer and Schwarze (2019), Rosenbloom *et al* (2019) |
| Creating participation processes | #10 | Praetorius (2009), Lehmann *et al* (2012), Briggs *et al* (2015), Vandevyvere and Nevens (2015), Sachs *et al* (2016), Schmid *et al* (2016), Wesseling *et al* (2016), Schmidt *et al* (2017), Spencer *et al* (2018), Skoczkowski *et al* (2018) |
| Implementing performance standards | #10 | Bento (2010), Li *et al* (2010), Shackley and Thompson (2012), Verbruggen (2012), Zaid *et al* (2014), Fay *et al* (2015), Pfeiffer *et al* (2016), Edenhofer *et al* (2018), Pfeiffer *et al* (2018), Rozenberg *et al* (2020) |
| Setting a compensation scheme | #5 | Odenberger and Johnsson (2007), Kefford *et al* (2018), Edenhofer *et al* (2018), Jotzo and Mazouz (2015), Rentier *et al* (2019) |
| Supporting low-carbon R&D | #4 | Gül and Turton (2011), Mattauch *et al* (2015), Aghion *et al* (2016), Tvinnereim and Mehling (2018) |
| Not picking any technology as 'winners' | #4 | Marechal and Lazaric, (2010), Shackley and Thompson (2012), Bjornaavold and Van Passel, (2017), Hansen *et al* (2017) |
| Implementing tax on high-emitting capital | #3 | Barrington-Leigh and Millard-Ball, (2017), Rozenberg *et al* (2020), Kalkuhl *et al* (2020) |

The contrasting results between the two indicators for the buildings sector can be explained by the methodology used to calculate committed emissions. Estimation in global studies tend to underestimate carbon lock-in outside the electricity sector as they do not take into account additional inertia induced by building shells, conditions, asset locations or transport infrastructure (Guivarch and Hallegatte 2011). More research is needed about stranded assets outside of the power sector given their potential magnitude.

### 3.3. Synthesis of policies to break out carbon lock-in

Here we summarize identified policy implications suggested to escape or avoid carbon lock-in (table 4). The qualitative statements (QS) we found emphasize that three governance dimensions need to be

integrated regardless of the instruments used: stability, coordination and legitimacy. *Long-term stability* of climate policy orientations is referred to in 20 QS. When the policy implementation appears certain and credible, stakeholders are confident and invest early in low-carbon LLCS (Bento 2010, Nam *et al* 2013, Shahnazari *et al* 2014, Wang *et al* 2014, Vogt-Schilb *et al* 2015) to adapt to the future regulatory context and to avoid sunk investments in high-carbon LLCS. The predictable evolution of climate policies leads to investments more consistent with the long term target, limiting carbon lock-in extension or stranded assets due to unanticipated shock in climate policy (Lazarus *et al* 2015, Bergen and Mu noz 2018, Kalkuhl *et al* 2020).

The transition of LLCS towards low-carbon systems cannot be done without assuring its *legitimacy*. This idea appears in the qualitative statements we extracted through different channels such as the transparency and emphasis on co-benefits and avoided costs (11 QS) or the creation of participatory processes (11 QS). Carbon lock-in is at the intersection of political, economic and institutional constraints among a multitude of actors. There is hence the need to ensure the largest possible consensus and support around the rapid transition of existing capital and the associated policy instruments.

Policy packages should also create the space for the *coordination* between actors and sectors (12 QS), counterbalancing existing coordination effects between 'dirty' sectors. These three aspects - stability, legitimacy and coordination - are not independent and influence each other: creating legitimacy between different actors of LLCS transition policies reinforce the long term stability, and policies that appear stable and credible to stakeholders lead to more coordination.

A variety of different policy instruments are mentioned in our sample (table 4). *Incentive-based instruments* include emissions taxes, tradable allowance systems, subsidies to emissions abatement or taxes on goods associated with emissions. 21 documents refer to the implementation of carbon price instruments through taxes or allowances with the objective to provide incentives making high-carbon LLCS less attractive. However, some qualitative statements highlight limitations of carbon pricing with regard to the constraints on the LLCS such as the difficulty to assure commitment and stability over time (Pfeiffer *et al* 2016, Kalkuhl *et al* 2020), the legitimacy of this instrument (Pfeiffer *et al* 2016, Rosenbloom *et al* 2019) or the fact that it does not prevent sunk costs and stranded assets (Tvinnereim and Mehling 2018, Meyer and Schwarze 2019). 17 QS highlight the need to integrate carbon pricing in a broader policy package. Other incentives instruments are mentioned with 3 QS related to taxes on high-emitting capital.

The second category of instruments considered is *regulatory instruments* with technology mandates and performance standards. Technology mandates refer to a specific requirement regarding the production process such as making the use of a given technology or equipment mandatory. Performance standards impose conditions regarding the output but do not impose any technology. We obtained 13 and 10 QS related to technology mandates and performance standards, respectively. For performance standards, the buildings and heating sector is more represented, with 50 % of the statements compared to other instruments. One explanation is the very slow turnover of building stocks. This means that some choices about energy performance attributes such as the building orientation or its compactness for instance are irrevocable. This calls for immediately choosing the highest energy performance which can be assured with performance standards (Verbruggen 2012, Fay *et al* 2015). Limiting further sunk costs because of long capital lifetimes also justify the usage of technology mandates especially in the electricy sector with several mentions of moratoria for new coal power plants (Mercure *et al* 2014, Bertram *et al* 2015, Steckel *et al* 2015, Pfeiffer *et al* 2018, Rozenberg *et al* 2020).

*Technology policies* include R&D support and support to technology deployment. Few QS (4) are related to support for R&D contrary to support for technology deployment with 22 QS. One approach is to decrease investment risks in new low-carbon capital (Mercure *et al* 2014, Aglietta *et al* 2015, Edenhofer *et al* 2018). Another approach is to subsidize low-carbon capital to create niche emergence and compensate for the lower costs of fossil fuel capital induced by past cumulative learning effects (Mercure *et al* 2014, Fouquet 2016, Bos and Gupta 2018, Szabo *et al* 2019).

## 4. Conclusion

Long-lived capital-stocks, such as infrastructure and buildings, induce path-dependent evolution and therefore constitute a constraint for the rapid reduction of greenhouse gas emissions. Here, we systematically map the literature about carbon lock-in. To do so, we use machine learning to identify 226 relevant publications for a set of 38 095 articles from the Web of Science and Scopus databases. We extracted qualitative and quantitative information for each publication. The synthesis of this information reveals common analytical approaches, as well as geographical or sectoral specificities.

We find that research on carbon lock-in has mainly focused on power generation. We also identify a bias toward developed countries, which represent the majority of our sample. Comparing the share of global emissions in 2018 and the share of publications for each country, we also highlight understudied countries such as Russian Federation or China (even though the latter has been the most studied country in the literature, it represents a smaller share

of publications than its share in global emissions) and overstudied countries such as the United Kingdom of Great Britain and Northern Ireland, Australia, Sweden or Germany.

We also scrutinized publications that quantify carbon lock-in. We identify 11 types of indicators used : installed capacity, age of existing stock, committed emissions, stranded assets, capital costs intensity, mitigation costs, emissions/energy gap, residual emissions, elasticity related to long-lived capital stock, technology scale and employment. The majority of quantitative studies have evaluated carbon lock-in with forward-looking indicators. Committed emissions and stranded assets are the two most widely used indicators. The literature indicates that global committed emissions of existing energy infrastructure increased slightly since 2010. However, this result is to be taken with care since it comes from a very small number of studies. Stranded assets have mainly been quantified for the power generation sector. Coal-power plants are the most important and most investigated stranded assets in the electricity sector. In scenarios consistent with a 2°C target, coal-power plants represent on average about 70% of cumulative early retired capacity. Studies also demonstrate, unsurprisingly, that the later climate policies are implemented, the higher the expected stranded assets are. In scenarios consistent with a 2°C target, stranded coal power assets are evaluated to be higher by a factor 2-3 for pathways that assume relatively low-ambition policies following National Determined Contributions until 2030 compared to pathways assuming ambitious climate policies starting in 2015. However, recent literature suggests that stranded long-lived assets may be even more important outside of the power sector - notably for the buildings sector in developed countries due to its high market value and low turnover rate.

We finally synthesized qualitative statements related to policies to escape carbon lock-in. They highlight the need to assure (i) the stability of climate policy orientations, (ii) the coordination between actors and sectors and (iii) the legitimacy of targets and instruments used. Although the carbon price is one of the two most mentioned policy instrument, it is also regularly pointed out that it cannot prevent carbon lock-in if used alone. Carbon pricing therefore needs to be complemented with other instruments, such as fiscal support for low-carbon capital deployment and the provision of low-carbon infrastructure.

Our work has some limitations related to the systematic review methodology. First of all, some abstracts may use keywords or synonyms other than those used in our search query. Although we also analysed the references of each article to limit this omission, the terminology used for the same subject can vary significantly between organizations and research domains, in particular for transdisciplinary research topic such as sustainable development (Glavic and

Lukman 2007). In addition, although the authors defined commonly criteria for publications inclusion/exclusion, the manual filtering of articles can be subject to a certain amount of subjectivity as to whether or not these criteria are met. One way of limiting this potential bias would have been to jointly check all the excluded articles, but this would have led to a much greater amount of work time allocated to the filtering stage. We also conclude from the results of our machine-learning assisted screening that the returns to additional screening would be low, but not zero. It is therefore unlikely that we identified 100% of relevant studies returned by our queries.

Despite these limitations, we identify different knowledge gaps. First, more analyses in non-electricity sectors are required. The two reasons are that (i) the rates of capital renewal can be slower than in the electricity sector but also that (ii) the contribution of sectors other than electricity is likely to increase in the coming decades, as the electricity sector is the 'easiest' sector to decarbonise. Secondly, studies at urban scale are lacking, although cities are called upon to play an increasing role in the implementation of mitigation policies in the future. Thirdly, although developed countries are large contributors to global emissions with the majority of the physical stock already built, future development pathways will need to be analyzed in developing countries in order to disentangle the factors contributing to carbon lock-in (Lee and Koski 2014). In addition, although some of the countries not studied may not contribute significantly to global emissions, they may have specific characteristics of interest for the analysis of carbon lock-in and mitigation policies. This is notably the case for islands, including small island developing states (SIDS), which are geographically confined, are limited in outward sprawl, and display a smaller number of power plants and gasoline stations. These characteristics make them ideal candidates for escaping carbon lock-in (Soomauroo *et al* 2020). Finally, carbon lock-in depends not only on techno-economic factors but also on institutional factors, and the increasing use of indicators integrating this latter dimension seems necessary to assess more precisely lock-in risks.

Multiple possible low-carbon transition pathways involving rapid transitions of capital exist. However, decisions concerning the transitions cannot avoid the question of feasibility and the underlying political and economic constraints. Identifying existing or future socio-technical and institutional barriers is crucial to informing policy makers on the realistic implementation of public policies (Lamb and Minx 2020). The measures of carbon lock-in strength induced by LLCS delineate the 'dynamic political feasibility space' (Jewell and Cherp 2020). Multidimensional monitoring can allow the iterative readjustment decarbonization targets in different sectors or regions and the implemententation of policy packages consistent with

the dimensions highlighted in this review. Some of the indicators that quantify carbon lock-in could support efforts to track progress towards the Paris Agreement targets and to inform the next 'global stocktakes' (Peters *et al* 2017).

## ORCID iDs

Vivien Fisch-Romito ⓘ https://orcid.org/0000-0002-2419-196X
Céline Guivarch ⓘ https://orcid.org/0000-0002-9405-256X
Felix Creutzig ⓘ https://orcid.org/0000-0002-5710-3348
Jan C Minx ⓘ https://orcid.org/0000-0002-2862-0178
Max W Callaghan ⓘ https://orcid.org/0000-0001-8292-8758

## References

Acuto M and Parnell S 2016 Leave no city behind *Science* **352** 873

Aghion P, Dechezleprêtre A, Hemous D, Martin R and Van Reenen J 2016 Carbon taxes, path dependency and directed technical change: Evidence from the auto industry *J. Political Economy* **124** 1–51

Aglietta M, Hourcade J-C, Jaeger C and Fabert B P 2015 Financing transition in an adverse context: climate finance beyond carbon finance *Int. Environ. Agreements: Politics, Law Economics* **15** 403–20

Ahman M and Nilsson L J 2008 Path dependency and the future of advanced vehicles and biofuels *Util. Policy* **16** 80–9

Arthur W B 1994 *Increasing Returns and Path Dependence in the Economy* (Ann Arbor, MI: University of Michigan Press)

Avner P, Rentschler J and Hallegatte S 2014 *Carbon Price Efficiency: Lock-in and Path Dependence in Urban Forms and Transport Infrastructure* (The World Bank)

Barrington-Leigh C and Millard-Ball A 2017 More connected urban roads reduce US GHG emissions *Environ. Res. Lett.* **12** 044008

Bates S, Clapton J and Coren E 2007 Systematic maps to support the evidence base in social care *Evidence and policy: A J. Res. Debate Practice* **3** 539–51

Beller E *et al* 2018 Making progress with the automation of systematic reviews: Principles of the Int. Collaboration for the Automation of Systematic Reviews (ICASR) *Systematic Rev.* **7** 77

Bento N 2010 Is carbon lock-in blocking investments in the hydrogen economy? A survey of actors' strategies *Energy Policy* **38** 7189–99

Beretti A, Figuières C and Grolleau G 2013 Behavioral innovations: The missing capital in sustainable development? *Ecol. Economics* **89** 187–95

Bergen M and Muñoz F D 2018 Quantifying the effects of uncertain climate and environmental policies on investments and carbon emissions: A case study of Chile *Energy Economics* **75** 261–73

Bernstein S and Hoffmann M 2019 Climate politics, metaphors and the fractal carbon trap *Nat. Clim. Change* **9** 919–25

Bertram C, Luderer G, Pietzcker R C, Schmid E, Kriegler E and Edenhofer O 2015 Complementing carbon prices with technology policies to keep climate targets within reach *Nat. Clim. Change* **5** 235–9

Bjornaavold A and Van Passel S 2017 The lock-in effect and the greening of automotive cooling systems in the European Union *J. Environ. Manage.* **203** 1199–207

Bos K and Gupta J 2018 Climate change: the risks of stranded fossil fuel assets and resources to the developing world *Third World Quarterly* **39** 436–53

Braun V and Clarke V 2006 Using thematic analysis in psychology *Qualitative Res. Psychol.* **3** 77–101

Briggs M, Webb J and Wilson C 2015 Automotive odal Lock-in: The role of path dependence and large socio-economic regimes in market failure *Econ. Anal. Policy* **45** 58–68

Callaghan M W, Minx J C and Forster P M 2020 A topography of climate change research *Nat. Clim. Change* **10** 118–23

Carley S 2011 Historical analysis of U.S. electricity markets: Reassessing carbon lock-in *Energy Policy* **39** 720–32

Chignell S and Gross R J K 2013 Not locked-in? The overlooked impact of new gas-fired generation investment on long-term decarbonisation in the UK *Energy Policy* **52** 699–705

Clausen J, Göll E and Tappeser V 2017 Sticky Transformation–How path dependencies in socio-technical regimes are impeding the transformation to a Green Economy *J. Innovation Manage.* **5** 111–38

Collaboration for Environmental Evidence 2018 *Guidelines and Standards for Evidence synthesis in Environmental Management* Pullin A S, Frampton G K, Livoreil B and Petrokofsky G Eds Version 5.0

Coulomb R, Lecuyer O and Vogt-Schilb A 2019 Optimal transition from coal to gas and renewable power under capacity constraints and adjustment costs *Environ. Resour. Econ.* **73** 557–90

Creutzig F, Baiocchi G, Bierkandt R, Pichler P-P and Seto K C 2015 Global typology of urban energy use and potentials for an urbanization mitigation wedge *Proc. Natl Acad. Sci.* vol 112 pp 6283–8

Creutzig F *et al* 2016 Urban infrastructure choices structure climate solutions *Nature Climate Change* **6** 1054–6

Creutzig F, Agoston P, Goldschmidt J C, Luderer G, Nemet G and Pietzcker R C 2017 The underestimated potential of solar energy to mitigate climate change *Nat. Energy* **2** 17140

Crippa M *et al* 2019 Fossil $CO_2$ and GHG emissions of all world countries (Luxemburg: Publication Office of the European Union)

CTI 2014a Carbon supply cost curves: Evaluating financial risk to coal capital expenditures *Online, Energy Transition Advisors*

CTI 2014b Carbon supply cost curves: Evaluating financial risk to oil capital expenditures *Online, Energy Transition Advisors*

CTI 2015 The $2 trillion stranded assets danger zone: How fossil fuel firms risk destroying investor returns *London: Carbon Tracker Initiative, November*

Cui R Y *et al* 2019 Quantifying operational lifetimes for coal power plants under the Paris goals *Nat. Commun.* **10** 4759

Davis S J and Socolow R H 2014 Commitment accounting of $CO_2$ emissions *Environ. Res. Lett.* **9** 084018

Davis S J, Caldeira K and Matthews H D 2010 Future $CO_2$ emissions and climate change from existing energy infrastructure *Science* **329** 1330–3

Davis S J *et al* 2018 Net-zero emissions energy systems *Science* **360** 6396

De Benedictis L *et al* 2018 The long-term effects of the historical Roman road network: trade costs of Italian provinces *Tech.*

*rept.* Centre for North South Economic Research, University of Cagliari and Sassari

de Macedo L S V and Jacobi P R 2019 Subnational politics of the urban age: evidence from Brazil on integrating global climate goals in the municipal agenda *Palgrave Commun.* **5** 18

Delrio P and Unruh G 2007 Overcoming the lock-out of renewable energy technologies in Spain: The cases of wind and solar electricity *Renewable Sustainable Energy Reviews* **11** 1498–513

Edenhofer O, Steckel J C, Jakob M and Bertram C 2018 Reports of coal's terminal decline may be exaggerated *Environ. Res. Lett.* **13** 024019

Erickson P 2015 *Carbon Lock-in From Fossil Fuel Supply Infrastructure* (Stockholm: Stockholm Environment Institute)

Erickson P, Kartha S, Lazarus M and Tempest K 2015 Assessing carbon lock-in *Environ. Res. Lett.* **10** 084023

Farfan J and Breyer C 2017a Aging of European power plant infrastructure as an opportunity to evolve towards sustainability *Int. J. Hydrog. Energy* **42** 18081–91

Farfan J and Breyer C 2017b Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator *J. Cleaner Prod.* **141** 370–84

Fay M, Hallegatte S, Vogt-Schilb A, Rozenberg J, Narloch U and Kerr T 2015 *Decarbonizing Development: Three Steps to a Zero-Carbon Future* (Washington DC: The World Bank)

Fouquet R 2016 Lessons from energy history for climate policy: Technological change, demand and economic development *Energy Res. Social Sci.* **22** 79–93

Frantzeskaki N and Loorbach D 2010 Towards governing infrasystem transitions: Reinforcing lock-in or facilitating change? *Technol. Forecast. Soc. Change* **77** 1292–301

Gadre R and Anandarajah G 2019 Assessing the evolution of India's power sector to 2050 under different $CO_2$ emissions rights allocation schemes *Energy Sustainable Develop.* **50** 126–38

Glavič P and Lukman R 2007 Review of sustainability terms and their definitions *J. Cleaner Production* **15** 1875–85

Goulder L H and Parry I W H 2008 Instrument choice in environmental policy *Rev. Environ. Economics Policy* **2** 152–74

Greaker M and Heggedal T-R 2010 Lock-In and the transition to hydrogen cars: should governments intervene? *The B.E. J. Economic Anal. Policy* **10** 40

Greene D L and Plotkin S E 2001 Energy futures for the US transport sector *Energy Policy* **29** 1255–70

Gross R and Hanna R 2019 Path dependency in provision of domestic heating *Nature Energy* vol 4 (Nature Publishing Group) pp 358–64 Number: 5

Grubler A 2010 The costs of the French nuclear scale-up: A case of negative learning by doing *Energy Policy* **38** 5174–88

Guivarch C and Hallegatte S 2011 Existing infrastructure and the 2 °C target *Clim. Change* **109** 801–5

Gül T and Turton H 2011 Long-term scenarios of the global energy and transport system *Transition to Hydrogen* eds Wokaun A and Wilhelm E (Cambridge: Cambridge University Press) pp 177–211

Ha-Duong M, Grubb M J and Hourcade J-C 1997 Influence of socioeconomic inertia and uncertainty on optimal $CO_2$-emission abatement *Nature* **390** 270–3

Haddaway N R, Bernes C, Jonsson B-G and Hedlund K 2016 The benefits of systematic mapping to evidence-based environmental management *Ambio* **45** 613–20

Hansen T, Klitkou A, Borup M, Scordato L and Wessberg N 2017 Path creation in Nordic energy and road transport systems – The role of technological characteristics *Renewable Sustainable Energy Rev.* **70** 551–62

Hermwille L, Obergassel W and Arens C 2015 The transformative potential of emissions trading *Carbon Manage.* **6** 261–72

Hood C 2014 Policies and actions to 'unlock'high-emissions assets: The example of coal-fired power generation *Energy, Climate Change and Environment: 2014 Insights*

Hilaire J, Minx J C, Callaghan M W, Edmonds J, Luderer G, Nemet G F, Rogelj J and del Mar Zamora M 2019 Negative emissions and international climate goals—learning from and about mitigation scenarios *Climatic Change* (Berlin: Springer) pp 1–31

IRENA Stranded Assets 2017 Stranded assets and renewables: How the energy transition Affects the value of energy reserves, buildings and capital stock *Tech. rept.* Working Paper

Iyer G C *et al* 2015 The contribution of aris to limit global warming to 2 °C *Environ. Res. Lett.* **10** 125002

James K L, Randall N P and Haddaway N R 2016 A methodology for systematic mapping in environmental sciences *Environ. Evidence* **5** 7

Jewell J and Cherp A 2020 On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5 °C? vol 11 (Wiley Interdisciplinary Reviews: Climate Change)

Jiang S, Chen Z, Shan L, Chen X and Wang H 2017 Committed $CO_2$ emissions of China's coal-fired power generators from 1993 to 2013 *Energy Policy* **104** 295–302

Johnson N, Krey V, McCollum D L, Rao S, Riahi K and Rogelj J 2015 Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants *Technol. Forecast. Soc. Change* **90** 89–102

Jotzo F and Mazouz S 2015 Brown coal exit: A market mechanism for regulated closure of highly emissions intensive power stations *Economic Anal. Policy* **48** 71–81

Kalkuhl M, Edenhofer O and Lessmann K 2012 Learning or lock-in: Optimal technology policies to support mitigation *Resour. Energy Econ.* **34** 1–23

Kalkuhl M, Steckel J C and Edenhofer O 2020 All or nothing: Climate policy when assets can become stranded *J. Environ. Economics Manage.* **100** 102214

Karakaya E, Nuur C and Assbring L 2018 Potential transitions in the iron and steel industry in Sweden: Towards a hydrogen-based future? *J. Cleaner Production* **195** 651–63

Kefford B M, Ballinger B, Schmeda-Lopez D R, Greig C and Smart S 2018 The early retirement challenge for fossil fuel power plants in deep decarbonisation scenarios *Energy Policy* **119** 294–306

Klitkou A, Bolwig S, Hansen T and Wessberg N 2015 The role of lock-in mechanisms in transition processes: The case of energy for road transport *Environ. Innovation Societal Trans.* **16** 22–37

Kriegler E *et al* 2015 Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy *Technol. Forecast. Soc. Change* **90** 24–44

La Viña A G M, Tan J C, Guanzon T I M, Caleda M J and Ang L 2018 Navigating a trilemma: Energy security, equity and sustainability in the Philippines' low-carbon transition *Energy Res. Social Sci.* **35** 37–47

Lamb W F and Minx J C 2020 The political economy of national climate policy: Architectures of constraint and a typology of countries *Energy Res. Social Sci.* **64** 101429

Lamb W F, Creutzig F, Callaghan M W and Minx J C 2019 Learning about urban climate solutions from case studies *Nat. Clim. Change* **9** 279

Lamperti F, Dosi G, Napoletano M, Roventini A and Sapio A 2020 Climate change and green transitions in an agent-based integrated assessment model *Technol. Forecast. Soc. Change* **153** 119806

Lane J L, Smart S, Schmeda-Lopez D, Hoegh-Guldberg O, Garnett A, Greig C and McFarland E 2016 Understanding constraints to the transformation rate of global energy infrastructure: Constraints to the transformation rate of energy infrastructure *Wiley Interdisciplinary Reviews: Energy and Environment* **5** 33–48

Lanzini P and Khan S A 2017 Shedding light on the psychological and behavioral determinants of travel mode choice: A meta-analysis *Transp. Res.* F **48** 13–27

Lazarus M, Tempest K, Klevnäs P and Korsbakken J I 2015 Natural Gas: Guardrails for a Potential Climate Bridge New Climate

Economy contributing paper Stockholm Environment Institute, Stockholm, Sweden, and Seattle, WA, US

Lecocq F and Shalizi Z 2014 The economics of targeted mitigation in infrastructure *Climate Policy* **14** 187–208

Lecocq F, Hourcade J-C and Ha Duong M 1998 Decision making under uncertainty and inertia constraints: sectoral implications of the when flexibility *Energy Economics* **20** 539–55

Lee T and Koski C 2014 Mitigating global warming in global cities: comparing participation and climate change policies of C40 cities *J. Comparative Policy Anal.: Res. Practice* **16** 475–92

Lehmann P, Creutzig F, Ehlers M-H, Friedrichsen N, Heuson C, Hirth L and Pietzcker R 2012 Carbon lock-out: advancing renewable energy policy in Europe *Energies* **5** 323–54

Leibowicz B D 2018 Policy recommendations for a transition to sustainable mobility based on historical diffusion dynamics of transport systems *Energy Policy* **119** 357–66

Li F G N and Strachan N 2019 Take me to your leader: Using socio-technical energy transitions (STET) modelling to explore the role of actors in decarbonisation pathways *Energy Res. Social Sci.* **51** 67–81

Li J, Gibbins J, Cockerill T, Chalmers H, Lucquiaud M and Liang X 2011 An assessment of the potential for retrofitting existing coal-fired power plants in China *Energy Procedia* **4** 1805–11

Li J, Colombier M and Giraud P-N 2010 Grappling with Climate Challenge in the Built Environment in China *J. Energy Eng.* **136** 27–31

Lin C, Liu G and Müller D B 2017 Characterizing the role of built environment stocks in human development and emission growth *Res. Conservation Recycling* **123** 67–72

Lucas P L, Shukla P R, Chen W, van Ruijven B J, Dhar S, den Elzen M G J and van Vuuren D P 2013 Implications of the international reduction pledges on long-term energy system changes and costs in China and India *Energy Policy* **63** 1032–41

Luderer G, Bertram C, Calvin K, De Cian E and Kriegler E 2016 Implications of weak near-term climate policies on long-term mitigation pathways *Clim. Change* **136** 127–40

Luderer G *et al* 2018 Residual fossil CO2 emissions in 1.5–2 °C pathways *Nat. Clim. Change* **8** 626–33

Malekpour S, Brown R R and de Haan F J 2015 Strategic planning of urban infrastructure for environmental sustainability: Understanding the past to intervene for the future *Cities* **46** 67–75

Mäkinen K, Kivimaa P and Helminen V 2015 Path creation for urban mobility transitions: Linking aspects of urban form to transport policy analysis *Management Environ. Quality: An Int. J.* **26** 485–504

Marechal K and Lazaric N 2010 Overcoming inertia: insights from evolutionary economics into improved energy and climate policies *Climate Policy* **10** 103–19

Maréchal K 2007 The economics of climate change and the change of climate in economics *Energy Policy* **35** 5181–94

Martínez Arranz A 2017 Lessons from the past for sustainability transitions? A meta-analysis of socio-technical studies *Glob. Environ. Change* **44** 125–43

Mattauch L, Creutzig F and Edenhofer O 2015 Avoiding carbon lock-in: Policy options for advancing structural change *Economic Modelling* **50** 49–63

McDonald A and Schrattenholzer L 2001 Learning rates for energy technologies *Energy Policy* **29** 255–61

McGlade C, Pye S, Ekins P, Bradshaw M and Watson J 2018 The future role of natural gas in the UK: A bridge to nowhere? *Energy Policy* **113** 454–65

McKinnon M C, Cheng S H, Garside R, Masuda Y J and Miller D C 2015 Sustainability: Map the evidence *Nature* **528** 185–7

Méjean A, Guivarch C, Lefèvre J and Hamdi-Cherif M 2019 The transition in energy demand sectors to limit global warming to 1.5° *Energy Efficiency* **12** 441–62

Mercure J-F, Pollitt H, Chewpreecha U, Salas P, Foley A M, Holden P B and Edwards N R 2014 The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector *Energy Policy* **73** 686–700

Meyer P B and Schwarze R 2019 Financing climate-resilient infrastructure: Determining risk, reward and return on investment *Front. Eng. Manage.* **6** 117–27

Minx J C, Callaghan M, Lamb W F, Garard J and Edenhofer O 2017 Learning about climate change solutions in the IPCC and beyond *Environ. Sci. Policy* **77** 252–9

Muldoon-Smith K and Greenhalgh P 2019 Suspect foundations: Developing an understanding of climate-related stranded assets in the global real estate sector *Energy Res. Social Science* vol 54 (Amsterdam: Elsevier) pp 60–7

Nakagawa S, Samarasinghe G, Haddaway N R, Westgate M J, O'Dea R E, Noble D W A and Lagisz M 2019 Research Weaving: Visualizing the Future of Research Synthesi *Trends Ecology Evolution* **34** 224–38

Nam K-M, Waugh C J, Paltsev S, Reilly J M and Karplus V J 2013 Carbon co-benefits of tighter $SO_2$ and $NO_x$ regulations in China *Glob. Environ. Change* **23** 1648–61

Nemet G F 2019 *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation* (Routledge)

Nolden C 2012 The governance of innovation diffusion—a socio-technical analysis of energy policy *EPJ Web Conf.* **33** 01012

Oakley A, Gough D, Oliver S and Thomas J 2005 The politics of evidence and methodology: lessons from the EPPI-Centre *Evidence Policy: A J. Res. Debate Practice* **1** 5–32

Odenberger M and Johnsson F 2007 Achieving 60% $CO_2$ reductions within the UK energy system—Implications for the electricity generation sector *Energy Policy* **35** 2433–52

O'Mara-Eves A, Thomas J, McNaught J, Miwa M and Ananiadou S 2015 Using text mining for study identification in systematic reviews: A systematic review of current approaches *Systematic Rev.* **4** 1–22

Peters G P, Andrew R M, Canadell J G, Fuss S, Jackson R B, Korsbakken J I, Le Quéré C and Nakicenovic N 2017 Key indicators to track current progress and future ambition of the Paris agreement *Nat. Clim. Change* **7** 118–22

Pfeiffer A, Millar R, Hepburn C and Beinhocker E 2016 The '2 °C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy *Appl. Energy* **179** 1395–408

Pfeiffer A, Hepburn C, Vogt-Schilb A and Caldecott B 2018 Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement *Environ. Res. Lett.* **13** 054019

Praetorius B 2009 Optimising the Framework for Innovation in the Electricity System – Lessons from Five Case Studies in Germany *GAIA—Ecol. Perspectives Sci. Society* **18** 221–8

Rentier G, Lelieveldt H and Kramer G J 2019 Varieties of coal-fired power phase-out across Europe *Energy Policy* **132** 620–32

Reyna J L and Chester M V 2015 The growth of urban building stock: Unintended lock-in and embedded environmental effects *J. Ind. Ecol.* **19** 524–37

Riahi K *et al* 2015 Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals *Technol. Forecast. Soc. Change* **90** 8–23

Rode D C, Fischbeck P S and Páez A R 2017 The retirement cliff: Power plant lives and their policy implications *Energy Policy* **106** 222–32

Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, Handa C, Kheshgi H, Kobayashi S and Kriegler E 2018 Mitigation pathways compatible with 1.5 C in the context of sustainable development

Rosenbloom D, Meadowcroft J and Cashore B 2019 Stability and climate policy? Harnessing insights on path dependence,

policy feedback and transition pathways *Energy Res. Social Sci.* **50** 168–78

Rozenberg J, Vogt-Schilb A and Hallegatte S 2020 Instrument choice and stranded assets in the transition to clean capital *J. Environ. Economics Manage.* **100** 102183

Richels R G, Blanford G J and Rutherford T F 2009 Int. climate policy: a 'second best' solution for a 'second best' world? *Clim. Change* **97** 289–96

Sachs J D, Schmidt-Traub G and Williams J 2016 Pathways to zero emissions *Nat. Geosci.* **9** 799–801

Sandén B A and Azar C 2005 Near-term technology policies for long-term climate targets—economy wide versus technology specific approaches *Energy Policy* **33** 1557–76

Saran A and White H 2018 Evidence and gap maps: a comparison of different approaches *Campbell Systematic Reviews* **14** 1–38

Sayers A 2007 Tips and tricks in performing a systematic review *Br. J. General Practice* **57** 425

Saygin D, Rigter J, Caldecott B, Wagner N and Gielen D 2019 Power sector asset stranding effects of climate policies *Energy Sources, Part B: Economics, Planning and Policy* (London: Taylor and Francis) vol 14 pp 99–124

Schmid E, Knopf B and Pechan A 2016 Putting an energy system transformation into practice: The case of the German Energiewende *Energy Res. Social Sci.* **11** 263–75

Schmidt T S, Matsuo T and Michaelowa A 2017 Renewable energy policy as an enabler of fossil fuel subsidy reform? Applying a socio-technical perspective to the cases of South Africa and Tunisia *Glob. Environ. Change* **45** 99–110

Seto K C, Davis S J, Mitchell R B, Stokes E C, Unruh G and Ürge Vorsatz D 2016 Carbon lock-in: types, causes and policy implications *Annual Review Environment Resources* **41** 425–52

Shackley S and Thompson M 2012 Lost in the mix: will the technologies of carbon dioxide capture and storage provide us with a breathing space as we strive to make the transition from fossil fuels to renewables? *Clim. Change* **110** 101–21

Shahnazari M, McHugh A, Maybee B and Whale J 2014 Evaluation of power investment decisions under uncertain carbon policy: A case study for converting coal fired steam turbine to combined cycle gas turbine plants in Australia *Appl. Energy* **118** 271–9

Shearer C, Fofrich R and Davis S J 2017 Future $CO_2$ emissions and electricity generation from proposed coal-fired power plants in India *Earth's Future* **5** 408–16

Skoczkowski T, Bielecki S, Węglarz A, Włodarczak M and Gutowski P 2018 Impact assessment of climate policy on Poland's power sector *Mitigation Adaptation Strategies Global Change* **23** 1303–49

Smith C J, Forster P M, Allen M, Fuglestvedt J, Millar R J, Rogelj J and Zickfeld K 2019 Current fossil fuel infrastructure does not yet commit us to 1.5 °C warming *Nat. Commun.* **10** 101

Snilstveit B, Vojtkova M, Bhavsar A, Stevenson J and Gaarder M 2016 Evidence and Gap Maps: A tool for promoting evidence informed policy and strategic research agendas *J. Clinical Epidemiol.* **79** 120–9

Soomauroo Z, Blechinger P and Creutzig F 2020 Unique opportunities of island states to transition to a low-carbon mobility system *Sustainability* **12** 1435

Spencer T *et al* 2018 The 1.5 °C target and coal sector transition: at the limits of societal feasibility *Climate Policy* **18** 335–51

Steckel J C, Edenhofer O and Jakob M 2015 Drivers for the renaissance of coal *Proc. of the National Academy of Sciences* vol 112 p E3775–81

Stoknes P E 2014 Rethinking climate communications and the 'psychological climate paradox *Energy Res. Social Sci.* **1** 161–70

Szabó L, Kelemen Á, Mezősi A, Pató Z, Kácsor E, Resch G and Liebmann L 2019 South East Europe electricity roadmap – modelling energy transition in the electricity sectors *Climate Policy* **19** 495–510

Thomas J and Harden A 2008 Methods for the thematic synthesis of qualitative research in systematic reviews *BMC Medical Res. Methodol.* **8** 45

Tong D, Zhang Q, Zheng Y, Caldeira K, Shearer C, Hong C, Qin Y and Davis S J 2019 Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target *Nature* (Berlin: Nature) vol 572 pp 373–7

Tozer L 2019 The urban material politics of decarbonization in Stockholm, Londo and San Francisco *Geoforum* **102** 106–15

Tsafnat G, Glasziou P P, Choong M W, Dunn A G, Galgani F and Coiera E W 2014 Systematic review automation technologies *Systematic Rev.* **3** 74–74

Turhan E, Cerit Mazlum S, Şahin Ü, Şorman A H and Cem Gündoğan A 2016 Beyond special circumstances: climate change policy in Turkey 1992-2015: Climate change policy in Turkey *Wiley Interdisciplinary Reviews: Climate Change* **7** 448–60

Tvinnereim E and Mehling M 2018 Carbon pricing and deep decarbonisation *Energy Policy* **121** 185–9

Unruh G C 2000 Understanding carbon lock-in *Energy Policy* **28** 817–30

van Soest H L *et al* 2017 Early action on Paris Agreement allows for more time to change energy systems *Clim. Change* **144** 165–79

Vandevyvere H and Nevens F 2015 Lost in transition or geared for the S-Curve? An analysis of Flemish transition trajectories with a focus on energy use and buildings *Sustainability* **7** 2415–36

Verbruggen A 2012 Financial appraisal of efficiency investments: why the good may be the worst enemy of the best *Energy Efficiency* **5** 571–82

Vogt-Schilb A, Hallegatte S and de Gouvello C 2015 Marginal abatement cost curves and the quality of emission reductions: a case study on Brazil *Climate Policy* **15** 703–23

Waisman H, Guivarch C, Grazi F and Hourcade J C 2012 The Imaclim-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresigzt *Clim. Change* **114** 101–20

Wang C, Ye M, Cai W and Chen J 2014 The value of a clear, long-term climate policy agenda: A case study of China's power sector using a multi-region optimization model *Appl. Energy* **125** 276–88

Wang H, Chen W, Bertram C, Malik A, Kriegler E, Luderer G, Després J, Jiang K and Krey V 2020 Early transformation of the Chinese power sector to avoid additional coal lock-in *Env. Res. Lett.* **15** 024007

Wesseling J, Lechtenböhmer S, Ahman M, Nilsson L J, Worell E and Coenen L 2016 How to decarbonise energy-intensive processing industries?: Survey and conceptualisation of their specific innovation systems *ECEEE*

Westgate M J, Haddaway N R, Cheng S H, McIntosh E J, Marshall C and Lindenmayer D B 2018 Software support for environmental evidence synthesis *Nat. Ecol. Evolution* **2** 588–90

Wilson C, Grubler A, Bento N, Healey S, De Stercke S and Zimm C 2020 Granular technologies to accelerate decarbonization *Science* **368** 36–9

Wilson I A G and Staffell I 2018 Rapid fuel switching from coal to natural gas through effective carbon pricing *Nat. Energy* **3** 365–72

Zaid S M, Myeda N E, Mahyuddin N and Sulaiman R 2014 Lack of energy efficiency legislation in the Malaysian building sector contributes to Malaysia's growing GHG emissions *E3S Web of Conferences* vol 3 01029

Zhang L, Rong P, Qin Y and Ji Y 2018 Does industrial agglomeration mitigate fossil $CO_2$ Emissions? An empirical study with spatial panel regression model *Energy Procedia* **152** 731–7

Zheng B *et al* 2018 Infrastructure shapes differences in the carbon intensities of Chinese cities *Environmental Sci. Technol.* **52** 6032–41