Quantifying Carbon Lock-In

Masters Thesis
Faculty of Science, Graduate School of Climate Sciences,
University of Bern

Submitted by
Violet A. Buxton-Walsh

August 21st, 2023

Supervisor
Prof. Dr. Ralph Winkler
Department of Economics

Abstract

This masters thesis aggregates data on global emissions to produce country-level emissions trajectories through the end of the century. By specifically accounting for the relative contribution of "committed" and "considered" emissions from long-lived assets (existing or planned carbon-intensive infrastructure, respectively) to total emissions, I suggest a methodology for quantifying the degree of potential carbon lock-in faced by various economies across warming scenarios, and highlight how the construction of long-lived assets may jeopardize existing climate change mitigation targets. I find that in congruence with the existing literature, the greatest threats to overshooting mitigation goals come from existing and planned coal infrastructure, and that emerging economies are faced with the greatest risks of carbon lock-in. By modeling future emissions with an emphasis on carbon lock-in, this study contributes a methodology which enables policymakers to evaluate the risks that considered and committed infrastructure may pose to their emissions reductions goals, and generates more realistic baselines against which to compare the impact of policies intended to mitigate carbon lock-in.

Acknowledgements

Many thanks to Johannes Ackva, who changed the way I understand climate. The concept of emissions streams, identification of initial data sources, and the idea to examine their evolution over time with respect to carbon lock-in were the product of his work at Founders Pledge.

Additional thanks to Professor Ralph Winkler, for the exceptionally patient supervision of this work and his many helpful suggestions.

Further thanks to:
L.H., who I'd not have finished this without.
AL, for creating much needed accountability with remarkably little judgement.
H.C. for some exceptionally useful advice, which was always given with kindness.
H.T. for inspiring my scenario plots.
L.T., for her supportive commiseration.
L.L. for repeatedly repairing my VScode setup.
N.A. for fixing my git setup, and finally removing that repo from my home directory.
J.B. and S.H. for their help in abstracting my data manipulations.

And of course, thank you to everyone who did a pom with me, especially NB, BM, and HP.

Lastly, thanks to my parents for insisting that I actually graduate, and to D.K.– for taking the brunt of it.

List of Tables and Figures

In order of appearance:

Table of contents

1. Introduction

In recent years, an increasing number of countries have adopted strict climate goals, with many pledging to reach net-zero emissions by mid-century. The United States and the European Union aim to become carbon neutral by 2050, with China intending to meet the same benchmark only ten years later, in 2060. Countries still in economic transition have also committed to ambitious decarbonization timelines, with Brazil also aiming to reach net-zero by 2050, and India by 2070 (CAT 2023, WRI 2021).

Achieving these targets will require comprehensively phasing out fossil fuels across sectors. However, continued investment in long-lived, carbon-intensive infrastructure in the form of industrial and energy production assets poses a major threat to realizing these climate policy aims. For rapidly industrializing economies, growing populations, energy demand, and rising standards of living will require significant increases in energy output over the coming years. If this increased demand is met through the construction of new fossil assets with long lifetimes, this may jeopardize any already ambitious net zero targets laid out. Energy and industrial production are sectors of particular concern, because their operation depends on significant capital investments in physical infrastructure such as power, steel production, and petrochemical plants. Once built, these assets generally continue to operate for their entire natural lifetime of 40 to 60 years without seeing significant increases in efficiency, all the while producing emissions (Cui et al. 2019, Global Energy Monitor 2022). The so-called "long-lived assets" are responsible for the bulk of global emissions, as they dominate the electricity sector, which makes up nearly ¾ of global emissions. Irrespective of the threat they pose to emissions targets (as these can be somewhat arbitrary), emissions from long-lived fossil assets are both a significant source of emissions, and likely to be unusually persistent. Because of their pervasiveness, creating industrialization pathways which rely on alternatives to long-lived fossil assets may be rather cost effective mitigation efforts in the long run, particularly for wealthy nations whose other remaining emissions lie in comparatively difficult to decarbonize sectors with higher abatement costs. Establishing a basic understanding of the status and trajectory of these emissions from long-lived assets is therefore key to avoiding them, and better assessing the threat they pose to mitigation goals.

One significant barrier to reducing the emissions of long-lived assets is encapsulated theoretically by the idea of carbon lock-in. This concept claims that the co-evolution of fossil-fuel dependent technology and institutions results in strong path dependencies, which in turn generates barriers to decarbonization that dominate even in the face of contrary economic incentives. While compelling, carbon lock-in remains an abstract concept, and it is unclear how or if it can be operationalized in order to avert these path dependencies. This study operates under the hypothesis that if the concept of carbon lock-in could be quantified, this would likely make the theory more concrete and actionable. Much of the value in this would be to enable a direct comparison of the barriers to decarbonization resulting from long-lived asset emissions across various countries and regions, facilitating prioritization of the largest and most cost-effective emissions reductions over the long term, and evidence-based mitigation policymaking more generally. In the case of this study, quantification also highlights the significant future emissions resulting from long-lived assets which are currently in the planning phase, underscoring the potential for well targeted current action to profoundly affect future emissions. Of course, enumerating carbon lock-in also highlights the potential to avoid large amounts of future emissions through well targeted investments of climate finance.

To quantify carbon lock-in, this study collects and models data on emissions from long-lived assets in order to project future trajectories. These bottom-up emissions estimates are then compared to overall emissions under different shared socioeconomic pathways, and the ratio between emissions from long-lived assets and total projected emissions provides a metric that captures the degree of potential carbon lock-in faced by various economies. Preliminary results suggest that coal and heavy industry represent the primary threats contributing to lock-in, with Southeast Asia and other developing regions having the greatest risks of becoming locked-in to substantial future emissions. Quantifying carbon lock-in also provides a background against which to measure mitigation effects on cumulative global emissions, instead of only considering the local and marginal emissions reductions prioritized by abatement costs and other measures. As a result, the metric somewhat demonstrates the differences in priorities which may emerge when taking a longer term perspective on mitigation, and suggests local marginal abatement may not always be strictly preferable to preventing the further construction of long-lived assets. With this in mind, the aim of this thesis is to make action guiding the compelling theoretical basis for the entrenchment of long-lived assets: carbon lock-in, and set forth an empirical metric which can assist policymakers in identifying global decarbonization objectives.

2. Literature review

Rather than exhaustively surveying the literature on carbon lock-in, this section aims to provide the necessary background for the reader to interpret methodological choices made in this study. This entails giving an overview of carbon lock-in, and providing context on the counterfactual emissions pathways in which modern efforts to reduce emissions are operating. This is captured by the two following subsections, which provide background on the carbon lock-in and future emissions modeling literatures.

2.1 Carbon Lock-In

Carbon lock-in, originally posited in by Unruh (2000), is the idea that industrial economies have become "locked-in" to fossil-fuel-reliant energy sectors through the co-evolution of technologies and institutions which makeup the energy system. It argues that this creates persistent market failures, and inhibits the diffusion of carbon-saving technologies in spite of their environmental and economic advantages. Carbon lock-in also explains some of the reasons why economies may be slow to decarbonize, as it suggests that energy sector development consists of path-dependent processes driven by increasing returns to scale and 'learning by doing'. Eventually, this can result in low substitution elasticity for possible energy sources, and macro-level barriers to the diffusion of mitigation technologies.

Unruh conceptualizes the combined interactions of technological and social systems with governing institutions as a single entity called the techno-institutional complex (TIC), which can become locked-in through effects impacting any one of its components. The scope of this thesis is limited to exploring the technological component of lock-in as represented by emissions from long-lived assets, because this is far more easily tied to accessible data on emissions and asset construction than the political or institutional elements of the TIC. Critically, the cost-effectiveness of interventions is considered relative, and subject to determination by the TIC in a locked-in economy (Unruh 2000, Unruh 2002). Furthermore, Unruh & Carillo-Hermosilla (2006) argue that carbon lock-in may be globalizing and could eventually constrain climate change mitigation options, and that economic modeling approaches which abstract away technological and institutional evolution are insufficient for modeling future emissions and impacts. Since making these claims, the urgency of decarbonization has only increased, and the hypothesized lock-in effects have arguably already emerged in some economies. This study clearly captures these impacts in countries like China, where the lasting emissions of the coal fleets built out in the years since Unruh's first publication on carbon lock-in are clearly demonstrated by committed emissions (CREA, 2023).

Applied work examining carbon lock-in includes that of Davis et al. (2010), who pioneered an approach to measuring the remaining lifetime emissions of existing infrastructure, concluding that the sources of the most threatening emissions have yet to be built. The authors also expect that fossil intensive infrastructure will expand unless extraordinary efforts are undertaken to develop alternatives. Mattauch et al. (2015) examine the plausibility of such extraordinary measures taking place by exploring the robustness of policies aimed at avoiding lock-in, and emphasizing the interaction between learning-by-doing spillovers and substitution elasticities in clean and dirty sectors. Meanwhile, Erickson et al. (2015) assessed the speed, strength, and scale of carbon lock-in for major energy-consuming assets in the power, buildings, industry, and transport sectors at the global level, essentially quantifying carbon lock-in for each sector globally. This thesis builds on the efforts of Erickson (2015) in particular, as it undertakes the emissions scenario specific assessments of lock-in which they claim are necessary to minimize the future costs of 'stranded assets', and establish lock-in values at a country level. Later explorations of lock-in include Seto et al. (2016), who discuss lock-in as a special case of the path dependency common to complex systems, and establish that even a small risk of lock-in is a major liability for future emissions. The authors present a tripartite version of lock-in comprised of infrastructure, institutional, and behavioral elements, for which increasing returns to scale and social dynamics inhibit innovation. Ultimately, they frame lock-in as a tragedy of the commons, and consider the difficulty of measuring lock-in effects on institutions and behavior.

Empirical studies which support the theory of carbon lock-in include Caldecott et al. (2018), a report on the exponential growth of energy demand in Southeast Asia, and the estimates of committed emissions from Tong et al. (2019). The first combines the concepts of carbon lock-in and carbon budgets to create carbon lock-in curves which illustrate the carbon budget implications of existing and proposed assets in order to identify assets at higher risk of stranding, and assess the compatibility of potential construction plans for power generating assets with global and country-level carbon budgets. The second estimates emissions from long-lived assets as well, with findings that suggest that "committed" emissions from existing energy infrastructure significantly exceeds the carbon budget required to limit global warming to 1.5 °C. The committed emissions data included in this study is taken from these results (see section 3.1, Data).

Carbon lock-in is a relatively new concept in climate economics literature, and is therefore discussed somewhat infrequently. In several ways it deviates from generally accepted thinking about emissions abatement by suggesting that mitigation priorities may not be reducible to abatement costs as previously thought, but overall, it fills a gap in the assignment of mitigation priorities by accounting for longer term trends, and considering future effects of both action and inaction on cumulative emissions. This thesis builds on previous work by making the connection between the concept of carbon lock-in and long-lived assets explicit, and thereby making lock-in measurable.

2.2 Future Emissions Pathways

In this study, carbon lock-in will be quantified as the cumulative fraction of emissions from long-lived assets, requiring an understanding and evaluation of both emissions from long-lived assets and overall emissions. While emissions from long-lived assets can be extrapolated into the future based on existing and planned fossil-intensive infrastructure, overall emissions cannot be so easily derived. In order to establish some baseline against which carbon lock-in can be measured, this section discusses the body of literature which aims to assess the likelihood of particular climate change scenarios.

For modeling purposes, global emissions depend on a set of socioeconomic assumptions provided by the UN IPCC's Shared Socio-economic Pathways (SSPs) (CIESIN, 2023). SSPs independently specify trends in emissions per capita and population growth, and are often conceptualized as narratives which capture variable responses to climate change in terms of both adaptation and mitigation (O'Sullivan 2018). Typically, Integrated Assessment Models (IAM) combine SSPs with estimates of end of century radiative forcing in the form of Representative Concentration Pathways (RCPs) which proxy total emissions in order to translate from the assumptions inherent in SSP and RCP permutations into emissions in a given year. The resulting emissions trajectories are used as inputs for Global Climate Models (GCMs), which simulate the potential impacts of these emissions on global temperatures (Hausfather 2018). As I will address later, often the modeling results which are presented are those which correspond to the most extreme possible SSP and RCP values, which represent worst case scenarios that although useful for establishing an upper bound to damage estimates, may be unrealistic and provide less action-relevant guidance for climate policy than impact assessments for scenarios than other scenarios.

Given the status of economics as the study of scarcity, the field of climate economics is concerned with allocating limited resources towards emissions reduction efforts, and making critical decisions about which mitigation strategies to prioritize. This task depends greatly on assumptions about emissions futures, because prioritization decisions are usually made by comparing the likely benefits of particular policies, which may in turn depend on the counterfactual emissions scenario against which the impacts of a particular intervention are compared. If the impact of mitigation strategies is only considered on the worst possible worlds, and these worlds are not the most plausible future, mitigation policy decisions will fail to account for all available information about the state of the world and are likely to be suboptimal. In other words, measuring the impact of mitigation policies against inappropriate counterfactual emissions scenarios misrepresents their likely effect, and informed guesses as to scenario likelihoods may be a valuable tool for better targeting climate policies.

The prevalence of modeling exceedingly high emissions scenarios in climate research, while instructive in terms of delineating worst-case outcomes, can inadvertently lead to a skewed perception of likely futures, and misguided policy priorities. Some authors have argued that the high climate sensitivities used in CMIP6 are unsupported by the paleoclimate record, while prominent climate scientists have published comments criticizing the misleading overutilization of “business as usual” scenarios (RCP 8.5) in impact studies and by the United Nations Intergovernmental Panel on Climate Change (UN IPCC) (Zhu et al. 2020, Hausfather & Peters 2020). Moreover, the public discourse on climate change often focuses on the impacts which are unlikely to occur in any case, but could only conceivably happen under extremely high warming scenarios, normalizing the view that human extinction is a genuinely plausible result of contemporary climate change and likely contributing to a overwhelmingly despairing view of the issue (Ritchie, H. 2021, Piper, K. 2022).

Since the release of the book “Climate Shock” by Wagner & Weitzman (2015), which put forth a terrifying tail risk of more than a 10% likelihood of 6°C of warming by the end of the century, subsequent probabilistic forecasts of warming scenario likelihoods have been more optimistic. One driver of this result is likely more aggressive global commitments to climate policy, including the signing of the Paris Agreement, and another is the narrowing of uncertainty bounds for Earth’s equilibrium climate sensitivity (Cox et al. 2018, Dunne, D. 2018). Evidence of this decrease can be seen in recent modeling from Raftery et al. (2017), where the likelihood of reaching 6°C or higher by 2100 is given as 1%, representing an order of magnitude decrease in the risk of exceeding 6°C of warming by the end of the century relative to the estimates from Wagner & Weitzman (2015). The likelihood of reaching temperatures greater than 4°C also declines from ⅓ to ⅕ in this model. Another recent working paper from Venmans and Carr (2022) reports probabilities for an “agnostic” calculation (a conservative technique, which weights the likelihood of all Representative Concentration Pathways (RCPs) between 1.9 and 6.0 equally). This model gives the odds of exceeding 5°C of warming this century a 1% chance, and the central estimate of the authors gives the probability as 0.2%. The author’s entire probability distribution lies in the 0-6°C range and the odds of exceeding 6°C aren’t even modeled, a fact suggesting a significant decrease in the expected intensity of end of century warming over the past decade. Simultaneously, the modeling literature has increasingly cemented the near impossibility of adhering to the 1.5-2°C warming targets of the Paris Agreement, making these benchmarks increasingly bizarre as baselines against which to assess climate policy (Raftery et al. 2017). Trajectories for emissions and expected warming based on pledges and current policies tracked by Climate Action Tracker (CAT) report a most optimistic scenario of 1.8°C, with 2.9°C as their most pessimistic projection as of November 2022, values that are in accordance with recent probabilistic forecasts from Venmans and Carr (2022) (CAT, 2022).

In sum, the forecasting literature on climate futures now enables us to make informed guesses about the state of future emissions, and that despite uncertainty some outcomes should be considered highly unlikely. In particular, two scenarios which are regularly modeled in climate impacts studies (that warming will exceed 6°C or fall within the 1.5-2°C goal of the paris agreement by the end of the century) are seen to be exceptionally unlikely. In spite of the uncertainty inherent in such predictions, these values make attempts to compare the (presumed to be fixed) emissions from long-lived assets to a baseline of overall emissions feasible. Though the estimates are subject to error, the fractional nature of the lock-in value which will later be derived implies that when measured this way the value can be at least internally consistent.

Given the recent narrowing of the distribution of future climate outcomes, it is increasingly possible to prioritize and target climate interventions based on the likelihood of different potential futures, and to move away from abatement cost minimization as the sole method for prioritizing interventions. In economic terms, investing in interventions with the lowest cost per unit of emissions reduction (abatement costs) should result in the most efficient abatement strategy, however, there are several reasons that this may not always be the case in actuality. Most generally, this arises from the fact that abatement costs measure the price of implementing a specific policy or technology, a metric which may fail to capture other costs and benefits associated with reducing emissions. This can easily occur as abatement costs are often estimated based solely on the costs of an initial investment and ongoing compliance with regulation, while any avoided costs of future damages were never considered (Kesicki, F. & Ekins, P. 2012, Hallegatte, 2023).

As compelling data about future climate scenarios becomes more available, there is– nearly for the first time– an alternative method to abatement costs for evaluating optimal emissions reduction policy. This arises because long term emissions scenario forecasts allow us to consider the long term repercussions of various emissions policies, and provide a more realistic counterfactual against which to compare the effects of different policies. As I will later argue, carbon lock-in is one of the metrics which is able to capture the newly available climate forecasting literature, and turn it into actionable suggestions for mitigation priorities.

3. Methods

The overarching goal of this research is to develop a technique by which carbon lock-in can be measured, or more specifically, generating a metric which quantifies carbon lock-in based on emissions data from long-lived fossil assets. Such a quantification is possible because carbon lock-in arises from the construction of long-lived fossil fuel infrastructure like power plants and factories, which generate considerable emissions over their lifetimes. As a result, replacing or avoiding the construction of highly carbon-intensive facilities is key to preventing lock-in. By assessing emissions from long-lived assets, I generate bottom-up estimates of those emissions which can be considered "locked-in" based on data for existing and planned assets, and typical plant lifetimes. To make relative statements about the scale of these emissions, I then reference this data against counterfactual emissions scenarios. These values are somewhat more challenging to derive than the emissions data for long-lived assets, and ultimately I rely on downscaled projections of future emissions under permutations of RCP and SSP scenarios.

Importantly, a quantified measure of lock-in may also provide a valuable prioritization tool with which to compare different possible interventions. Traditionally, the preferred intervention prioritization tool of climate economists has been abatement costs, but these fail to capture the longer term macroeconomic impacts of investing in different mitigation strategies, and are more suited to a marginal prioritization approach (Hallegatte, 2023). Ideally, a metric for carbon lock-in will better enable climate change mitigation prioritization by accounting for not only the present differences in the marginal abatement costs of different interventions, but also the potentially significant scale of future global emissions. Because most 21st century emissions remain ahead of us, accounting for future emissions is key to effective mitigation policy. This idea is also supported by recent work suggesting that efforts to avoid carbon lock-in could be a highly cost-effective climate change mitigation strategy, a result which is largely based on a respecification of the central optimization problem as a minimization of overall climate damage as opposed to emissions alone (Ackva, 2021). This shift in framing highlights the importance of influencing emissions trajectories over the long-term, which measures of lock-in account for unusually well by anticipating the emissions impact of each new asset's construction for the remainder of its lifetime. This section therefore aims to describe and define an alternative metric for prioritizing climate change interventions by quantifying carbon lock-in.

3.1 Data

The initial objective of this study was to identify the data varieties most relevant to measuring carbon lock-in, and classify them according to appropriate conceptual groupings, or "emissions streams". These categorizations were chosen to highlight the group of emissions from long-lived assets, emissions overall, and the difference between these values.

1. **Considered emissions**: these are the emissions which would result from the operation of assets which are currently in the planning phase, or in the process of permitting or construction. These are projected based on typical plant lifetimes, and asset specific construction data provided by Global Energy Monitor (2023).
2. **Committed emissions**: these emissions are those which will result from the continued operation of existing assets, assuming typical lifetimes. While it is also possible to derive these values from GEM's data, I rely on more comprehensive estimates given in Tong et al. (2019).
3. **Scenario based emissions**: this refers to emissions given by the downscaled projection of global emissions under different RCPs and SSPs. Taken from Gütschow et al. (2021), this provides counterfactual trajectories against which to compare emissions considered and committed emissions, and efforts to reduce them.

4. **Expectable emissions**: these represent the emissions expected in addition to considered and committed values, and are derived as the arithmetic difference between projected emissions in a particular scenario and the sum of considered and committed emissions. This is primarily a value calculated for plotting, but its magnitude also conveys the gap between the emissions in a given scenario and the measure of emissions from long-lived assets.

Critically, considered and committed emissions are derived empirically and at the country level, and do not change as a function of the scenario against which they are compared. In the ensuing plots, global considered and committed emissions are correctly depicted as unchanging across varying RCP and SSP projections.

The datasets included in the study are as follows:

1. **Global Energy Monitor (GEM):** An nearly comprehensive database compiling information on existing and planned energy infrastructure worldwide, including power plants, refineries, pipelines, and other assets. I utilize GEM's emissions estimates for coal plants, and production capacity data for gas plants.

2. **Tong et al. (2019):** Provides country-level estimates of future emissions from existing infrastructure, assuming typical asset lifetimes. While sectoral emissions are only disaggregated globally, I estimate country-specific sectoral emissions by assuming each country's relative sectoral contributions match the global fractions.

3. **Gütschow et al. (2021):** Contains country-level emissions trajectories for various RCP and SSP scenarios from integrated assessment models. Downscaling these global projections enables detailed cross-country comparison.

4. **Venmans and Carr (2022):** Estimates an unconditional probability distribution of future emissions and temperatures based on a review of literature on estimates of future emissions for current policy and pledge scenarios, as well as expert elicitations, abatement costs, learning rates, fossil fuel supply side dynamics, and geoengineering. I use the central estimate of the emissions scenario likelihoods provided in table 4.

Like the concept of emissions streams, credit for identifying the first three of these initial datasets is owed to Johannes Ackva.

Initially, I generate a dataset of considered emissions for electricity from GEM by totaling emissions from planned coal and gas assets. Planned assets are identified by their operational status, and plants classified as under ‘construction’, ‘permitted’, ‘planned’, etc. are identified and aggregated while plants listed as ‘retired’, ‘mothballed’, or ‘non-operating’ are removed from the data. Assets without a listed start year are assumed to have begun operating in the year given by the average of the start years for that asset and operational status (e.g. averaging the start years for plants with a status of “operating” and an asset type of “gas”, and applying this to operating gas assets with unlisted start years). Because gas assets in GEM’s data lack emissions estimates, I apply a conversion factor from Davis et al. (2014) to translate from megawatts of generation capacity to lifetime CO_2 emissions for each asset. The conversion factor suggests each gigaton of new gas generation capacity results in a twelfth of a single gigaton of CO2-eq emissions, which I assume is evenly distributed over the plant’s lifetime. I assume that plants operate for a typical lifetime of 40 years (Cui et al. 2019), and calculate considered emissions by projecting each plant’s yearly emissions out over this period.

I also estimate emissions from industry as the product of a given year's considered emissions from electricity and the ratio of committed electrical emissions to committed industrial emissions in the first year of the data, 2021. This assumes the historic split of asset construction between electrical and industrial plants matches the split indicated by data on planned assets, and that growth in each sector is proportional. While empirically less sound than other estimation methods, it's particularly difficult to derive emissions estimates from industrial production, and this method of estimation likely captures industrial trends to the first order. I also explored the possibility of using global steel production data as a proxy for industrial emissions, but failed to generate believable estimates based on the available data and ultimately chose to exclude these results.

Committed emissions data is derived independently of considered emissions, and is borrowed from Tong et al. (2019). While this data was largely comprehensive and did not require backfilling, the division of committed emissions across sectors was only provided at the global rather than national level. However, the authors also provide estimates of total committed emissions per country, so it is possible to obtain sectoral committed emissions per country if one assumes that the global distribution of emissions across sectors applies to all countries. I implement this assumption, and although it may be seen as a limitation, this is strongly mitigated by the use of regional and global level data aggregation for the purposes of plotting and analysis.

To determine the total considered and committed emissions, I combine the data on considered emissions from electricity (gas and coal) and industrial sectors with committed emissions data. Notably, while considered emissions reflect only the emissions from sectors where nearly all assets are considered "long-lived", committed emissions values encompass assets with shorter lifetimes, specifically emissions from buildings, transportation, and other energy production (in addition to electricity and industry). While this makes the two values less comparable, it results in the sum of considered and committed emissions more accurately accounting for all possible information from which one can estimate emissions futures. Other data processing of considered and committed emissions data included the standardization of country names, converting emissions units into Megatonnes CO_2-eq across datasets, and omitting faulty values.

To generate data on background emissions scenarios against which to compare considered and committed emissions, I use data from Gütschow et al. (2021) to provide country-level trajectories across various RCP and SSP combinations specified by the IPCC. While RCPs model emissions literally, and are named with a number of watts per square meter of radiative forcing reached by the end of the century, SSPs describe the interaction of challenges to mitigation and adaptation respectively, and their values represent the magnitude of these challenges. Gütschow et al. (2021) provides downscaled versions of Integrated Assessment Model outputs, which allows for comparing committed emissions to projections under different scenarios to assess lock-in risks. The scenario data also relies on a particular choice of downscaling parameters, which in this case includes harmonization of projected trends with historical emissions data, and the exclusion of emissions from bunkers (international shipping and aviation), as these are challenging to attribute nationally. The convergence downscaling method also assumes an exponential convergence of national emissions intensities before a transition to negative emissions. These specifications were chosen based on the respective goals of focusing emissions models on long-lived assets (which exclude bunkers) and being informed by historical trends. The other relevant parameter choice is that of the gas "basket" which is being modeled, or, whether the projected emissions should include the total CO_2-eq emissions from all gasses named by the Kyoto protocol, or CO_2 alone. Because committed emissions data is specified in CO_2 equivalent emissions, I use the emissions given for the basket of gasses used in IPCC AR4 (Eurostat 2015).

After compiling each dataset, considered emissions from coal and gas are aggregated with committed emissions data and projected scenario emissions. This results in a single data file containing a time series of each emissions type (considered, committed, and background scenario) for each combination of country, RCP, and SSP in the data. Notably, some permutations of RCP and SSP values are implausible and not included by Gütschow et al. (2021) (e.g. low barriers to cooperation and innovation (SSP1), but still reaching 6 W/m2 radiative forcing by end of century (RCP 6)), so are therefore excluded from the final data. As stated, considered and committed emissions are empirically derived independently of the scenario data, and are therefore constant across RCPs and SSPs for a given country. To mitigate the noise observed as low levels of downscaling and for the ease of presentation on the page, the majority of results presented in this thesis are given at the aggregated regional and global levels (see appendix for regional definitions).

Aggregating data for 178 countries and 28 SSP-RCP scenario combinations results in a final dataset with more than 5,000 emissions time series, making it challenging to analyze the results of this exercise without some level of abstraction. I aim to address this by reducing the dimensionality of the data, both in terms of geographic units and number of emissions scenarios. This is possible to do on a geographic basis through a simple regional or global aggregation of the country level datasets, but this does little to reduce the scenario dimension.

Fortunately, the number of scenarios under consideration can also be reduced. One method to do this is by "taking the expectation" of future emissions as a weighted average of the likelihoods assigned to different scenarios under an unconditional probability distribution across future emissions scenarios. This collapses the scenarios for which probabilities are provided into a single global projection of emissions futures. In this study I use the central estimate from the probability distribution published in Venmans and Carr (2022), and produce a single plot for each country and region. Additional benefits of this reduction in dimensions include the faster computational speed of the model, as the number of outputs being generated decreases, and the fact that it enables statements about the future to be made in absolute terms rather than conditional on particular emissions scenarios.

After completing all data cleaning, aggregation, and simplification steps I plot the various time series for considered, committed, and scenario emissions. This allows for an assessment of whether planned and existing infrastructure will result in emissions overshooting a particular emissions scenario target, and a comparison of each country and region's committed and considered emissions values to scenario emissions taken from the downscaled RCP-SSP scenarios. This allows for the comparison of future emissions from existing assets to emissions reduction targets compatible with global climate policy, e.g. the Paris Agreement goal of limiting warming to less than 2°C, which roughly translates to RCP scenarios below 2.6 W/m^2 (Sousounis, 2019), and for the derivation of a metric for carbon lock-in. The comparison of considered and committed emissions (representing long-lived asset emissions) to scenario projections, and the relationship of this fraction to carbon lock-in, are covered in the next section.

Because the results of this analysis rest on comparing the relationship between considered and committed emissions to the emissions projected under particular future climate change scenarios, I will note that while the scenario data used account for CO_2-equivalent emissions from all economic sectors with the exception of land use, land-use change and forestry (LULUCF), the data used for considered emissions only attempts to account for emissions from sectors with long-lived assets. Given that LULUCF accounts for 5-10% of global greenhouse gas emissions, one plausible interpretation of absolute global emissions trajectories could be to increase them by 5-10%. I refrain from this implementation given (1) the largely relativistic nature of these findings, for which such an adjustment would make little difference, and (2) the uniquely high uncertainty and variability applicable to this sector (Climate Action Tracker, 2023).

3.2 Quantifying Carbon Lock-In

For the purpose of this study, the term "long-lived assets" refers to physical infrastructure which, once implemented, has an extended operational lifetime relative to other products with emissions relevance such as small scale machinery, consumer electronics, heating systems, and automobiles. Long-lived assets include energy production and industrial facilities such as power plants and factories, and tend to generate significant amounts of emissions over their lifespan. This characteristic results in 'carbon lock-in', and presents a considerable challenge for emissions reduction efforts as older and more fossil intensive facilities are rarely retired before reaching total obsolescence.

In this thesis carbon lock-in is quantified as the fraction of total emissions from long-lived assets. The numerator of this value is cumulative the sum of yearly considered and committed emissions, and the denominator is a cumulative sum of yearly scenario emissions (or "expected" scenario emissions, for the case which uses a likelihood weighted average of emissions scenarios). The cumulative nature of the fraction is justified by the fact that cumulative emissions are a more appropriate proxy for temperature than point emissions, however, this cumulative approach to measurement results in carbon lock-in fractions being fairly time dependent, and specific to a given year. Much of this specificity is the result of declines in the magnitude of emissions from long-lived assets which are not matched by declines in the background scenario emissions. These occur because of limited planning horizon for considered emissions, and the expiration of those assets responsible for committed emissions.

Although as specified in this study carbon lock-in can be calculated for any given year, it may be particularly interesting to investigate lock-in on shorter timelines as this is arguably more relevant for climate policy. However, comparing lock-in fractions across countries is also of interest, and longer timelines may be helpful for capturing the variable development patterns of countries which affect their lock in fractions on different time horizons. Still, the nature of planning means that considered and committed emissions decline sharply in the 2070s, as little future infrastructure currently planned to start in the 2030s is listed in GEMs data (because energy infrastructure planning is not conducted indefinitely far into the future). As a result of these considerations, several possible timelines on which to consider lock-in are presented in the results.

4. Results

4.1 Scenario Interpretation

The results of this study are typically presented in terms of a particular emissions scenario, which is defined by the combination of a Shared Socioeconomic Pathway (SSP) and a Representative Concentration Pathway (RCP). Understanding the assumptions inherent to each of these scenarios is key for interpreting the results of this work. This subsection therefore aims to better define these scenarios as the backdrop against which changes to emissions from long-lived assets takes place.

Firstly, while related, SSP and RCP pathways are modeled independently and refer to distinct variables. RCPs specify greenhouse gas concentrations at the end of the century, while SSPs correspond to storylines illustrating a range of demographic, economic, and technological futures. Each RCP indicates a specific radiative forcing value measured in watts per square meter (W/m^2) reached by 2100, and each SSP has an arbitrary number that refers to a set of qualitative assumptions which can be translated into predictions about potential societal developments that could influence greenhouse gas emissions (IPCC AR6).

The RCPs included in this study include stringent mitigation scenarios (RCP 1.9 and 2.6), intermediate scenarios (RCP 3.4 and 4.5), and high greenhouse gas emissions scenarios (RCP 6.0), as well as the "business as usual" case (RCP 8.5). The SSPs modeled span from a world with rapid and inclusive economic growth and strong global cooperation (SSP1) to a world characterized by intense geopolitical rivalries, slowed economic growth, and less concern for the environment (SSP5). RCPs can be viewed as reflecting the physical dimension of the climate problem, and their increasing values can be seen as corresponding to an increase in the amount of mitigation which must be conducted in a given future. In parallel, SSPs are viewed as the socioeconomic dimension of climate change, and the narratives they construct can be characterized as determining the challenges which mitigation efforts will face rather than the overall amount of mitigation which need be conducted, which is better captured by the physical dimensions of climate change that RCPs aim to parametrize (Hausfather, 2018). The span of the emissions scenarios captured by this study is presented above, with highlighted lines indicating the trajectories closest to the emissions implied by trends in long-lived assets.

Together, RCPs and SSPs work in tandem to provide a fairly comprehensive view of plausible future climate change scenarios. For the purpose of this analysis, the emissions trajectory specified by a particular combination of RCP and SSP pathways is referred to interchangeably as a "scenario". Each scenario can be interpreted based on its component parts, and by understanding the unique pieces of information they encompass. For instance, modeling an SSP2-RCP4.5 scenario can be thought of as reflecting a "middle of the road" future for societal and economic trends (SSP2) combined with a moderate emissions trajectory, leading to a radiative forcing level of 4.5 W/m^2 by the year 2100 (RCP4.5). This case implies a world broadly similar to current trends, where emissions peak around mid-century, and there are medium challenges to both mitigation and adaptation. Importantly, some combinations of RCP and SSP scenarios are not modeled at all because certain scenario combinations are considered incompatible. Specifically, RCP 1.9 and 2.6 and viewed as unreachable under the assumptions driving the geopolitically fraught SSP 3 storyline, thus downscaled emissions data and plots for this scenario combination are not included in the analysis (Gütschow et al. 2021).

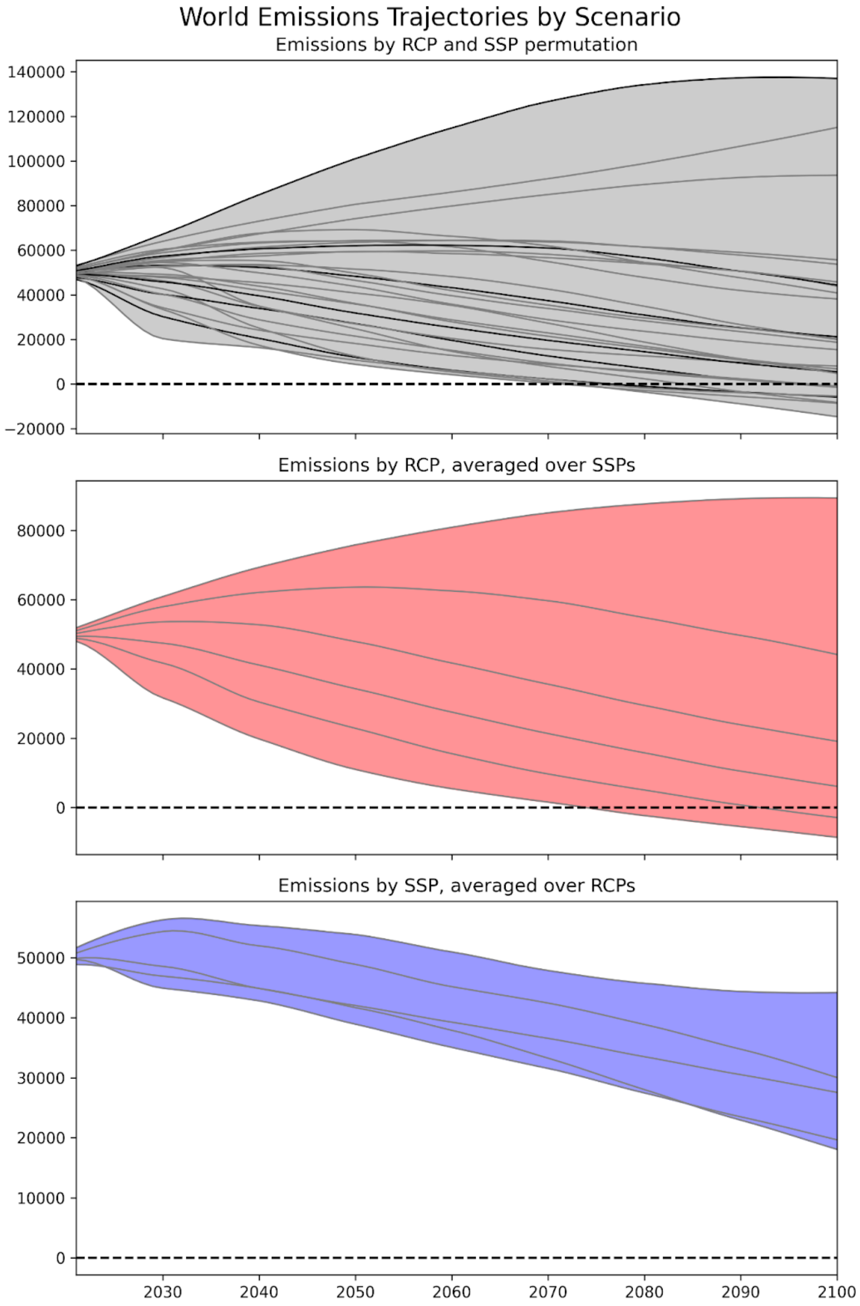


Figure 1. World emissions trajectories by scenario. Global CO_2-eq emissions under the pathways specified by Guetschow et al. (2021) for (from top to bottom): every permutation of RCP and SSP, each RCP averaged across all corresponding SSPs, and each SSP averaged across all corresponding RCPs.

4.2 Trends in Emissions from Long-Lived Assets

4.2.1 Long-lived asset data composition

The investigation of carbon lock-in conducted by this study is dependent on the ratio of empirical data on emissions from long-lived assets to the emissions specified by the range of RCP and SSP scenarios previously discussed. Examining the composition of data on long-lived assets may therefore yield insights into what this metric does and does not capture, and how the information it conveys is qualitatively different across regions. The plot below indicates the relative and absolute contributions of different asset types to each region's total emissions from long-lived assets through the end of the century.

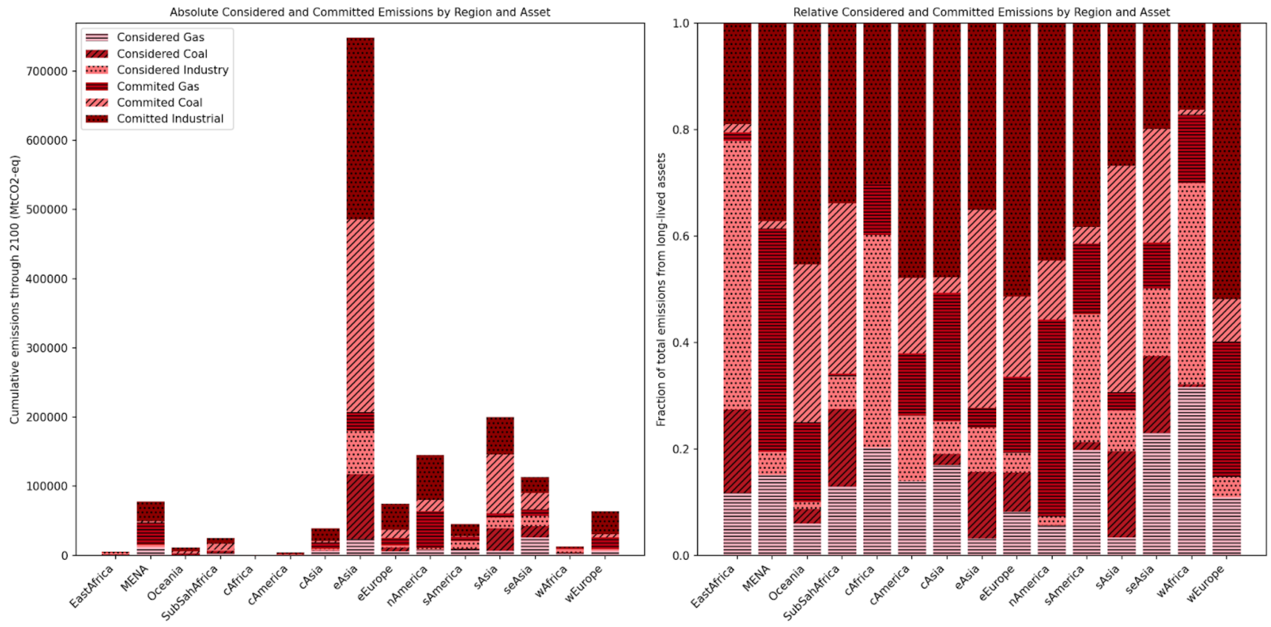


Figure 2. Absolute (left) and relative (right) contributions to emissions from long-lived assets. $MtCO_2$-eq cumulative global considered and committed emissions through 2100, as implied by Tong et al. (2019) and Global Energy Monitor (2023) broken down by region and asset type.

This breakdown reveals that committed emissions from coal and industry together makeup the majority of emissions from long-lived assets in most regions, and that of the two, coal emissions generally dominate. Except in East Africa, considered emissions are also primarily coal related. Overall, emissions from long-lived assets are the highest in East Asia, which is only distantly followed by South Asian, North American, Southeast Asian, and Middle Eastern and North African emissions. In all regions besides East Asia, considered emissions favor gas over coal. Of course, the regional aggregations used are purely geographic, and say little about the emissions per capita or per GDP of each region.

A surprising finding of this analysis is the relatively high fraction of emissions related to industry, which is likely an artifact of the estimation technique used to generate this data producing results which are a function of growth in the electricity sector of each region. Unfortunately, empirical data on global emissions from industry is difficult to derive, and initial attempts to estimate these values based on steel production yielded results which seemed even less realistic. Although the uncertainty surrounding this estimate introduces some limitations, this detracts little from the final result, because carbon lock-in is defined as a fraction of total emissions and used only for relative prioritization among regions, rather than to make absolute statements about the magnitude of interventions needed in various jurisdictions.

Although considered and committed emissions are often treated in aggregate in this analysis, there is an important qualitative difference between the two with significant implications. Because considered emissions are merely planned, it's highly likely that not all such assets will in fact be built, and measured emissions could theoretically be much lower than the data on projected construction indicates. However, this could easily be negated by a lack of data on planned assets which are likely to be built. Unfortunately, lack of data on the fraction of planned assets listed by GEM which fail to be constructed relegates this uncertainty to a fundamental limitation, one which is common in empirical analyses.

4.2.2 Global emissions trends

After aggregating data on global emissions from long-lived assets, I model future emissions trajectories and compare these to a range of possible future emissions scenarios. In Figure 3, I present stacked plots of considered, committed, and modeled scenario emissions through the end of the century for a representative range of RCP and SSP specifications, where the specific scenarios shown are those for which probabilities are assigned by Venmans and Carr (2022). The segments of the plots represent considered and committed emissions, as well as the difference between the sum of these values and the total emissions predicted by Gütschow et al. (2021) for a particular scenario. These time series of global emissions are designed to illustrate the relationship between emissions in a given scenario, and the emissions from long-lived assets.

In every scenario except for a "business as usual" baseline, global emissions are found to be lower at the end of this century than in the present day, and in a handful of scenarios global emissions reach net negative values before the end of the century. However, the majority of cases indicate global emissions to peak in the next twenty years before beginning a more gradual decline. Taking into account planned and imminent emissions from long-lived assets, it seems likely that several emissions pathways are incompatible with currently planned infrastructure, as is seen in SSP1 RCP 1.9 above. This is evident from the fact that, taken together, considered and committed emissions exceed the black line indicating the projected time series of emissions for the scenario. If emissions from long-lived assets are viewed as fixed because of the difficulty of decommissioning these assets before the end of their natural lifetimes, it is possible to essentially rule out these particular trajectories even without accounting for the fact that long-lived assets make up only a fraction of total emissions. However, the feasibility of a particular RCP or SSP is not necessarily ruled out by having it exceeded by emissions from long-lived assets because of the limitations of downscaling methods used to obtain the scenario emissions trajectories. To derive country-level or regional emissions estimates, global emissions futures are combined with country-level socioeconomic and emissions data from 2018, which happens to be somewhat outdated at this point (Gütschow et al., 2021). Furthermore, it is technically possible that assets might be retired before their natural lifetimes, although this is not normally assumed to be the case in energy modeling literature (Cui et al. 2014, GEM 2023). Despite these limitations, it seems quite likely that an emissions scenario which is exceeded by projected emissions from existing and planned long-lived assets is largely infeasible.

Furthermore, the divergence of scenario emissions pathways from the growth trajectory of considered and committed emissions may easily be misinterpreted. The decline of emissions from long-lived assets around 2070 is largely an artifact of the data, and it should not be assumed that these emissions will genuinely cease. This appearance results from the fact that available data on planned and existing infrastructure only extends to the planning horizon for such projects, yielding universally declining trends in emissions from long-lived assets. Given the limited window of time into which future emissions are planned and the consistently assumed cessation of their emissions after 40 years (upon their retirement), future emissions from long-lived assets will always appear to decline over time in this model. It is therefore key to appropriately interpret this data as a snapshot of future emissions from long-lived assets which does not account for the coal, gas, and industrial assets which will be planned and constructed during the remainder of the century.

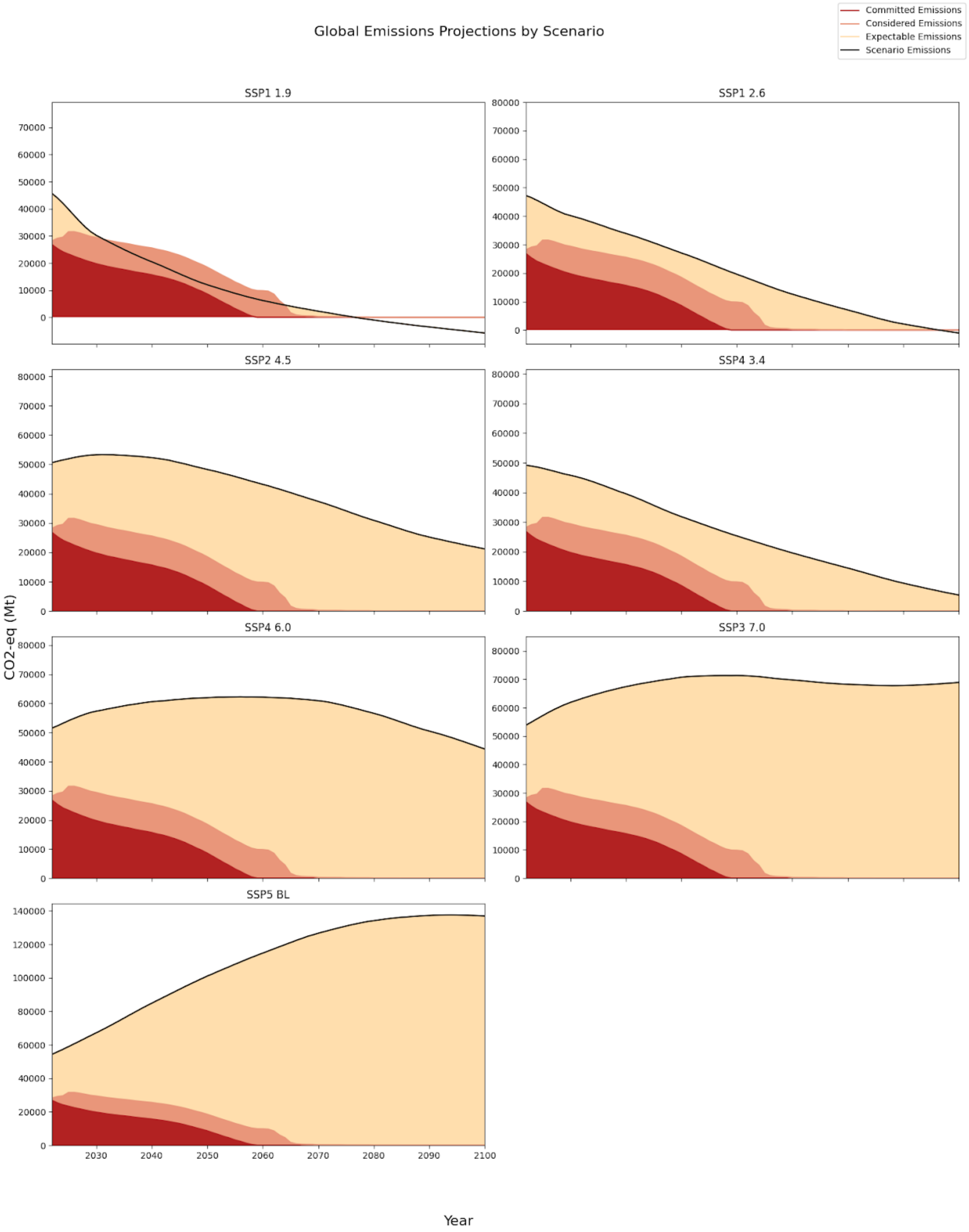


Figure 3. Modeled global emissions projections for the RCP-SSP specifications given by Venmans and Carr (2022). $MtCO_2$-eq considered and committed emissions plotted against scenarios given by Gütschow et al. (2021). Explanation of plotted variables is given by section 3.1, Data.

In addition to a breakdown of future emissions across scenarios, it's helpful to explore the trajectory of global emissions under a single future scenario. By taking a weighted average of the emissions scenarios described above and plotting them against the global totals of emissions from long-lived assets it's possible to model all of these scenarios on a single plot. Above, the expectation of global emissions is defined by the central probability estimates of Venmans and Carr (2022) is plotted along with global emissions from long-lived assets. While failing to reach net zero before the end of the century, this trajectory shows a continual decline of emissions, which emissions from long-lived assets do not appear to exceed. Interestingly, a continual decline of this nature suggests that annual global emissions have already peaked, which might first be viewed skeptically, but is in line with the first decrease in global emissions trends to have been seen in recent years, occurring from 2021 to 2022 (IEA). In the case of this model, the observed decrease is likely to be the product of Venmans and Carr (2022) weighting scenarios with sharp and imminent emissions declines more heavily than those with slower declines, or even increases, over the course of the century. Regardless of the optimistic pattern of decline, the aggregate global view does not suggest that net zero targets can be reached anytime this century, and is suggestive of considerable continued challenges to making this a reality. That this is the case could be taken as evidence of the need for even more stringent mitigation policies, and supports the consideration of long-term emissions patterns today– such as by measuring and mitigating carbon lock-in.

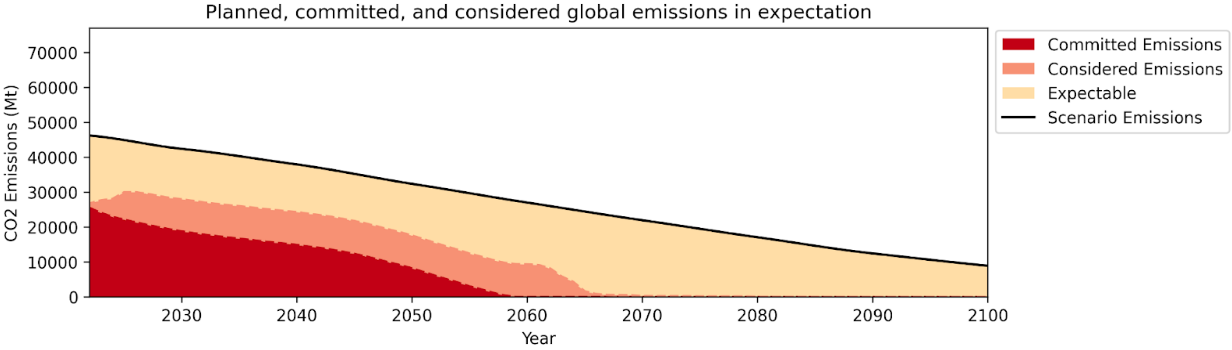


Figure 4. Modeled global emissions projections for the weighted average of the scenarios in Figure 3, according to the probabilities given in the central estimate of Venmans and Carr (2022).

A final consideration is that the overall scenario emissions indicated by this plot are not perfectly representative of reality. The 2021 emissions under the global expectation exceed 4 million metric tonnes (Mt), while real emissions were below this value in 2021 and 2022. That is, the 2021 and 2022 data already demonstrate the inaccuracy of the average scenario emission estimate. However, the impact of this discrepancy on the conclusions is minimized due to the fractional nature of carbon lock-in. Although the total scenario emissions value might influence whether a country's lock-in fraction surpasses 1, this is not a central indicator for significance. Irrespective of whether any country has a lock-in fraction exceeding one, the focus for emissions reduction should remain on the countries with the highest lock-in fractions. Furthermore, the Gütschow data which comprises the lock-in denominator need only be relative rather than absolute, and manipulations to correct its divergences could create an unwarranted illusion of precision or other confounding effects.

4.2.3 Regional emissions trends

While data on global emissions trends is valuable for understanding the assumptions underlying the model, it cannot produce local measures of lock-in to be used for prioritization among regions or countries. Because most of the value in measuring the fraction of emissions from long-lived assets lies in comparing trends around the world, regional analyses are more illustrative for the purpose of this study.

Below I model the emissions for all global regions in the data under the expectation of global emissions given by the central probability of Venmans & Carr 2022.

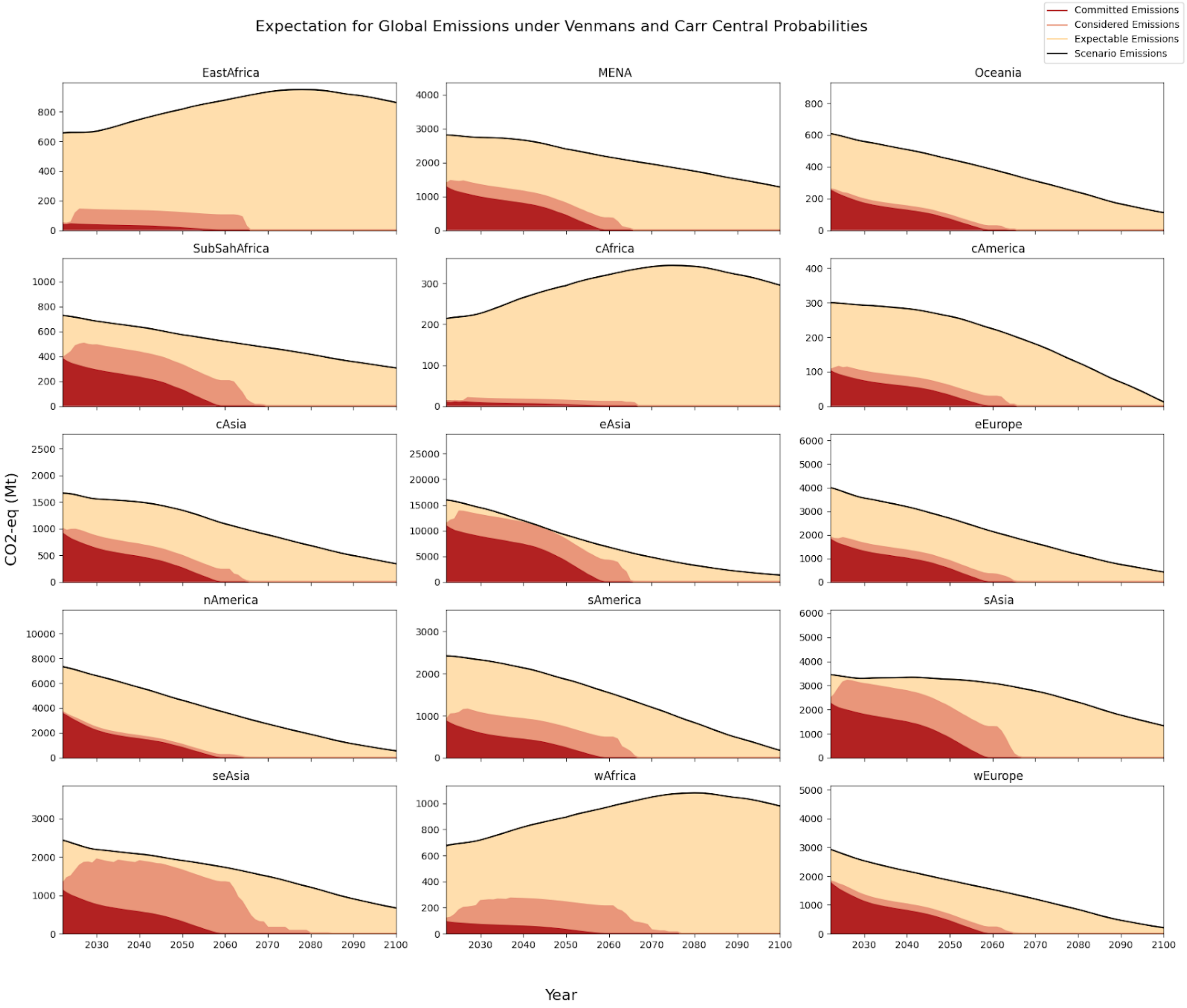


Figure 5. Modeled global emissions projections by region for the weighted average of the trends in the scenarios listed in Figure 3, according to the probabilities given in the central estimate of Venmans and Carr (2022). Data is the same as included in Figure 4, but is grouped by regions rather than aggregated globally.

In examining the global expectation for emissions across scenarios, emissions can be seen to decline over the course of the century in every region except East, West, and Central Africa. Considered and committed emissions fail to exceed the scenario in any region, which can be taken as weak evidence of these expectations being reasonable estimates for future emissions. Regions with emerging economies including South, Southeast, and East Asia, as well as Sub Saharan Africa have considered and committed emissions totals which approach the scenario, making these economies relatively more likely to exceed the emissions expected of them under projections.

Breaking down emissions projections by region also highlights the distinction between considered and committed emissions around the world, which are largely in congruence with expected development patterns of various regional economies. In developing economies with fewer fossil assets, considered emissions are more likely to dominate than committed emissions as planned assets outstrip emissions from existing ones, while the opposite is true for developing countries. Importantly, the projections of emissions from long-lived assets may be somewhat too low for optimistic projections of industrialization and development in less developed regions (Ezeh et al. 2020).

4.2.4 Within region variation in Southeast Asia

While regional analyses are largely sufficient for the goals of this study, detailed case studies of country-level trends in emissions are also informative for understanding carbon lock-in. The subsequent analysis focuses on Southeast Asia in particular, under the assumption that the region's unusually high cross-country variation in economic development and energy mixes (as the result of natural resource variability) would produce heterogenous results, highlighting the importance of a granular approach to determining effective emissions reduction strategies (Symon, 2004). Relative to other regions in this study, Southeast Asia has the highest fraction of its overall emissions from long-lived assets attributable to considered coal and gas infrastructure, indicating plans for imminent growth in its energy sector. If this data is well founded, it suggests that Southeast Asia may be a key region in which to focus on avoiding carbon lock-in.

In Figure 6, Southeast Asian emissions are modeled below at the country level for the weighted average of emissions trends based on the central probability estimates for scenarios given in Venmans and Carr (2022). This result is consistent with the trend of wealthier countries having vastly fewer considered emissions than poorer countries with higher growth rates, and it visually demonstrates the variation in relationships between scenario emissions trajectories and emissions from long-lived assets. Between the scenarios, empirical emissions data derived based on extrapolation of the lifetimes of planned and existing assets is unchanged, while the scenario trajectories change substantially. The plots are additionally useful for illustrating how the fractional nature of carbon lock-in could result in a lower value for scenarios with higher emissions overall (which is a reason to disregard scenario dependent measures of carbon lock-in).

At the country level, emissions from long-lived assets appear somewhat noisy, illustrating the disjointed nature of the underlying data resulting from its annual specification, and the uniform forty year lifetimes assigned to long-lived assets based on their start dates. While regional aggregation serves as a useful tool for reducing heterogenous trends within a region into a coherent, comprehensible overview of likely future emissions, the diversity of trends within a single region still underscores the importance of a granular, country-level approach in order to encompass as much information about existing trends as possible when modeling future emissions.

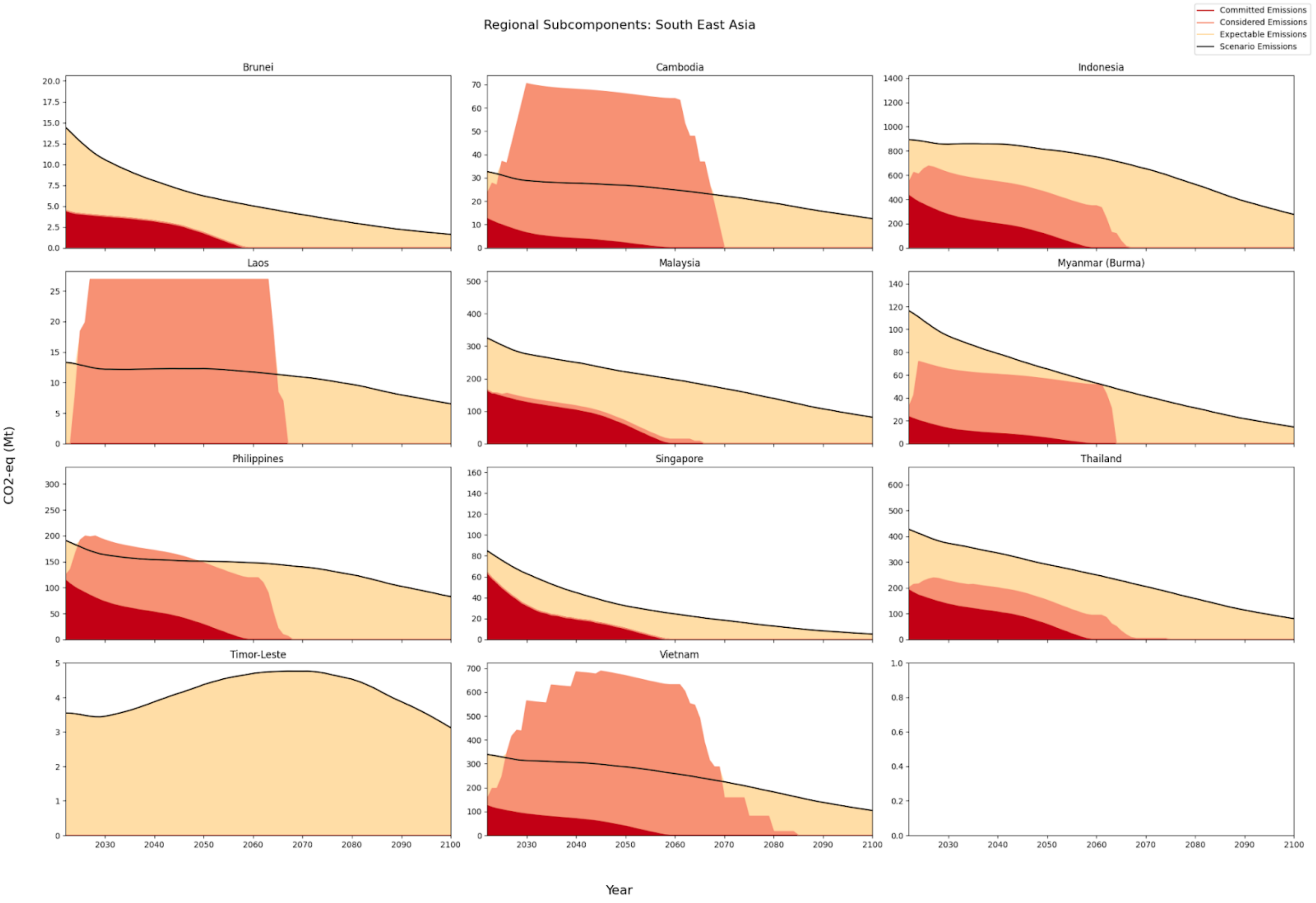


Figure 6. Modeled global emissions projections for countries in South East Asia, for the weighted average of the scenarios in Figure 3, according to the probabilities given in the central estimate of Venmans and Carr (2022). Data is the same as included in Figures 4 and Figure 5, but is grouped by country rather than aggregated regionally or globally.

4.3 Fraction of Total Emissions from Long-Lived assets

4.3.1 Geographic distribution

Table 1 presents the fraction of cumulative emissions from long-lived assets in different global regions for the years 2030, 2050, 2070, and 2100. This metric roughly accounts for the magnitude of carbon lock-in under various time frames, and is calculated as the cumulative amount of emissions from long-lived assets (the cumulative sum of each year's considered and committed emissions values) divided by the cumulative sum of scenario emissions. A mapping from regions to countries is available in the appendix

In 2030, South Asia and East Asia hold the highest fractions at 0.80 and 0.76 respectively. However, by 2050, the situation changes slightly, as East Asia rises to the top with a fraction of 0.87, while South Asia drops marginally to 0.81. By 2070, a general trend of declining fractions is observed across most regions. This continues into 2100, with every region exhibiting significantly reduced fractions compared to their 2030 levels. Throughout all the periods, Central Africa consistently shows the lowest fractions, with the value decreasing from 0.06 in 2030 to a mere 0.03 by 2100. The highest fractions are generally found in the Asian regions throughout the years, indicating a relatively high level of carbon lock-in. Conversely, African regions tend to exhibit the lowest fractions, indicating lower carbon lock-in levels. North America and Oceania see a consistent decrease over time, falling from 0.39 to 0.23 and from 0.35 to 0.19 respectively between 2030 and 2100. This data indicates a clear temporal trend of declining carbon lock-in fractions across all regions over the 70-year span. The differences between regions suggest regional disparities in the extent of carbon lock-in, with some regions more heavily affected than others.

Importantly, although a data column for 2100 is given in Table 1, this should generally be considered as beyond the relevant timeframe for this model's predictive capacity (as well as for preventing worst-case climate outcomes more generally). Because the planning horizon for long-lived assets is at most ten to fifteen years, the greatest extent of modeled emissions from long-lived assets in this study is the late 2060s. Values measured far beyond this time threshold are deeply skewed by the fact that the denominator of the lock-in metric continues to evolve (and is non-zero), while the emissions from long-lived assets are effectively zero due to constraints of the planning horizon for emissions intensive assets. Peak cumulative lock-in values appear in 2043 according to the data modeled, but as lock-in is a function of both considered and committed emissions, much of the contribution to lock-in in 2043 results from assets which were constructed prior to the timespan of this study and are assumed to be unaffectable. I therefore also consider years with lower lock-in values which are further into the future, since more of the lock-in measured for these years is determined by planned assets whose existence may still be influenceable with present action.

Fraction of cumulative emissions from long-lived assets by year

	2030	2050	2070	2100
eAsia	0.76	0.87	0.78	0.68
sAsia	0.8	0.81	0.62	0.45
seAsia	0.65	0.8	0.74	0.57
SubSahAfrica	0.59	0.64	0.53	0.38
cAsia	0.52	0.49	0.39	0.31
wEurope	0.52	0.48	0.38	0.32
MENA	0.46	0.43	0.33	0.24
eEurope	0.42	0.42	0.34	0.28
sAmerica	0.4	0.42	0.36	0.3
nAmerica	0.39	0.34	0.27	0.23
Oceania	0.35	0.31	0.24	0.19
cAmerica	0.33	0.3	0.24	0.19
wAfrica	0.24	0.29	0.24	0.14
EastAfrica	0.15	0.16	0.13	0.08
cAfrica	0.06	0.06	0.05	0.03

Table 1. Fraction of cumulative emissions from long-lived assets (carbon lock-in fraction) by year and region. Given by the ratio of considered plus committed emissions to background scenario emissions under expectation, or, according to the probability weights from Venmans and Carr (2022). Values roughly decrease from top to bottom.

4.3.2 Dependence on scenario emissions trajectories

For the sake of this study, carbon lock-in is quantified as the fraction of cumulative 21st century emissions from long lived assets. Therefore, in scenarios with higher background emissions, carbon lock-in values may appear deflated because the numerator of the carbon lock-in fraction (emissions from long lived assets) is empirically derived and invariable across scenarios, while the denominator (total emissions) is dependent on a variable forecast made based on SSP and RCP values. An important result of this methodology is that, in some cases, carbon lock-in values actually decline under higher emissions relative to lower emissions scenarios, which is a seemingly counterintuitive result given that one typically expects a measure designed to capture climate impacts to increase with rising emissions. The basic implication of this tendency is that presenting carbon lock-in results by scenario is misleading, and the carbon lock-in fractions presented in this work should therefore only be used for establishing a sense of the lock-in risks within a particular scenario, or in an expectation drawn across scenarios. The carbon lock-in metric derived in this study is therefore primarily useful for geographic prioritization, and shouldn't be considered as a function of any particular emissions future. Still, the inclusion of information on general emissions futures in addition to emissions from long-lived assets is essential, because only by amalgamating a range of scenario projections into a single trajectory based on probabilistic models of emissions futures does it become possible to calculate a global lock-in fraction.

The relevance of the scenarios to defining lock-in cannot be understated, as the lock-in fraction is fundamentally contingent on a denominator specified by the scenario. In scenarios characterized by high growth, the numerator—emissions from long-lived assets—could be larger, whereas in unequal growth scenarios, it could be smaller. Analogously, the denominator—total emissions—could be larger in high growth scenarios, and potentially smaller in unequal growth scenarios. In some regions, there are particular, narrow, time periods where the lock-in fraction increases due to rapid construction of new infrastructure (or sharp declines in counterfactual emissions trajectories). Targeting intervention timing to avoid the lock-in which results from these periods may be one valuable piece of evidence for prioritizing not only the geography of climate interventions, but also their timing. Yet, I view this tendency as an indication of robustness, since it implies that the lock-in metric measures more than counterfactual emissions, and is therefore not obviously a worse proxy for climate change than emissions themselves.

4.3.3 Correlation with other variables

To further explore the validity of carbon lock-in as a metric, I performed a regression analysis with country country characteristics that may be predictive of carbon lock-in as independent variables (GDP per capita and population density values are taken from 2023). Of course, this is essentially a correlation analysis, and as such, it is susceptible to spurious correlations and does not establish causality. However, it could still generate insights into the kinds of countries which may be more susceptible to carbon lock-in.

The results of the analysis (below) suggest a limited correlation between carbon lock-in and the predictor variables, with GDP per capita being the only significant (positive) predictor of lock-in. However, no significant correlations were observed with either population density or the past increase in renewable energy usage (indicated by the change in the fraction of total TWh from fossil fuels between 2010 and 2021). The coefficients, standard errors, and p-values for these variables at different years, as shown in the Table 2, further underscore this observation.

To reconcile this lack of association, I further examined the relationship between carbon lock-in and the predictor variables in the Figure 7, below. In all cases, the independent variables appear abnormally distributed. Perhaps this is related to the systemic exclusion of small nations from the plots due to missing emissions reporting, but this is unlikely to fully account for the lack of correlation. Notably, Figure 7 and

Table 2 take the log of population density to adjust for its non-linear distribution, but still the correlation is insignificant. One possible reason for the lack of correlation could be related to the downscaling assumptions embedded in the scenario data, which perhaps could be orthogonally correlated with the implementation of these variables for lock-in calculation. While other scaleless variables related to energy sector data could perhaps be more illuminating, data acquisition is generally non-trivial, and a precursory exploration of other variables failed to yield meaningful associations. Arguably, the difficulty of deriving meaningful associations underscores some of the inherent challenge in pinpointing the drivers of carbon lock-in, and suggests that a multitude of factors, many potentially interrelated, could influence the metric.

Fraction of cumulative emissions from long-lived assets by year		**coef**	**std err**	**t**	**P>|t|**	**[0.025**	**0.975]**
2030	const	0.2821	0.085	3.333	0.001	0.115	0.449
	log(population density)	0.0061	0.018	0.329	0.743	-0.03	0.043
	Change in fraction of total TWh from fossil fuels between 2010 and 2021	-0.0925	0.177	-0.523	0.602	-0.442	0.257
	GDP per capita (ten thousand HKD)	0.0365	0.013	2.782	0.006*	0.011	0.062
2050	const	0.3038	0.106	2.855	0.005	0.094	0.514
	log(population density)	0.0112	0.023	0.481	0.631	-0.035	0.057
	Change in fraction of total TWh from fossil fuels between 2010 and 2021	-0.1044	0.223	-0.469	0.64	-0.544	0.335
	GDP per capita (ten thousand HKD)	0.0237	0.016	1.438	0.152	-0.009	0.056
2070	const	0.2594	0.098	2.651	0.009	0.066	0.453
	log(population density)	0.0091	0.021	0.427	0.67	-0.033	0.051
	Change in fraction of total TWh from fossil fuels between 2010 and 2021	-0.0573	0.205	-0.28	0.78	-0.461	0.347
	GDP per capita (ten thousand HKD)	0.0158	0.015	1.041	0.299	-0.014	0.046

Table 2. Regression table demonstrating the effects of independent variables on the fraction of cumulative emissions from long-lived assets by year in 2030, 2050, and 2070. Nearly no values are significant, and these variables are limited in their ability to capture lock-in.

Still, the stark lack of correlation between carbon lock-in and the independent variables is surprising, as one would typically expect a connection between metrics which evaluate climate change and things like GDP per capita or trends in renewable energy. To investigate this, the image below considers the relationship between GDP per capita and renewable energy use, which is positively correlated, as one might expect.

Figure 7. Correlation between carbon lock-in fractions and the independent variables included in the regression (Table 2). R^2 values suggest weak correlation of GDP with lock-in, and little relationship elsewhere.

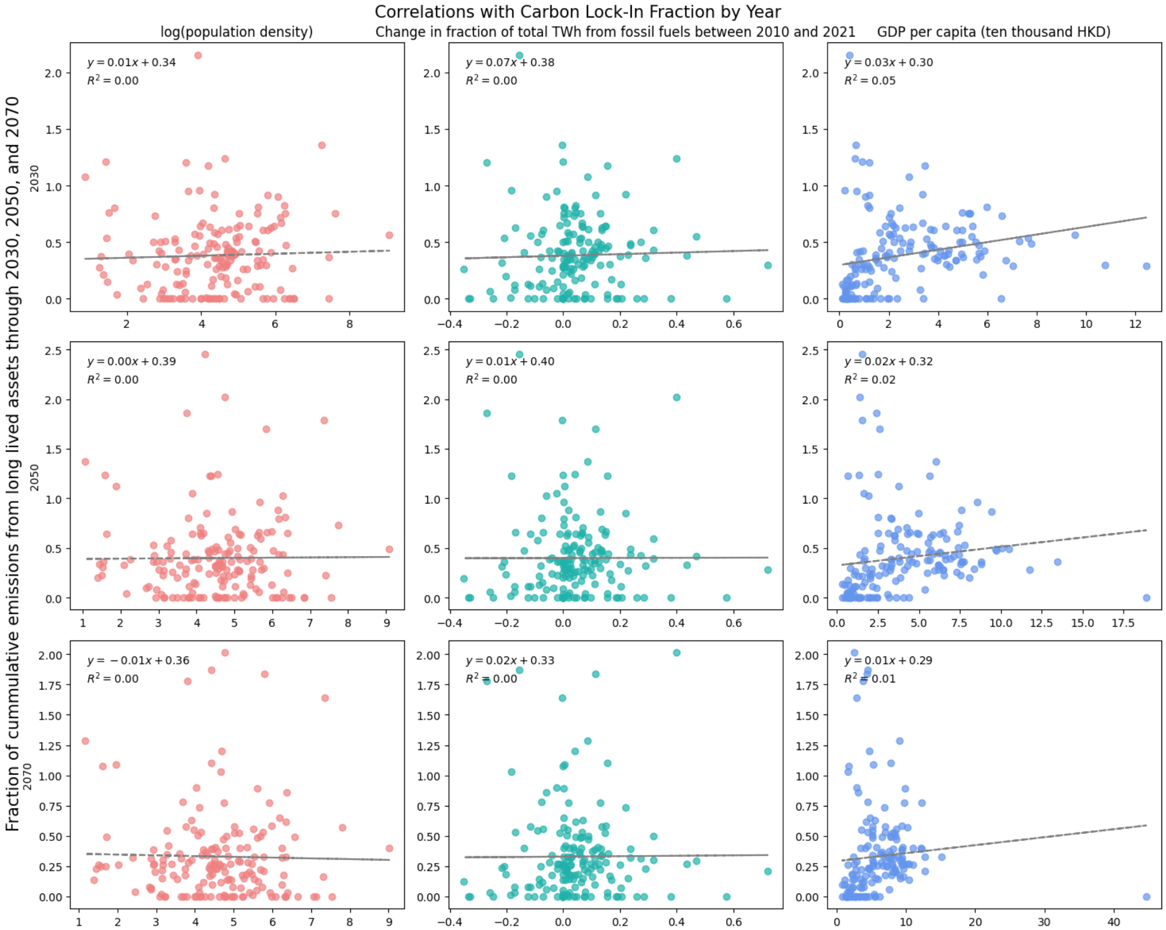
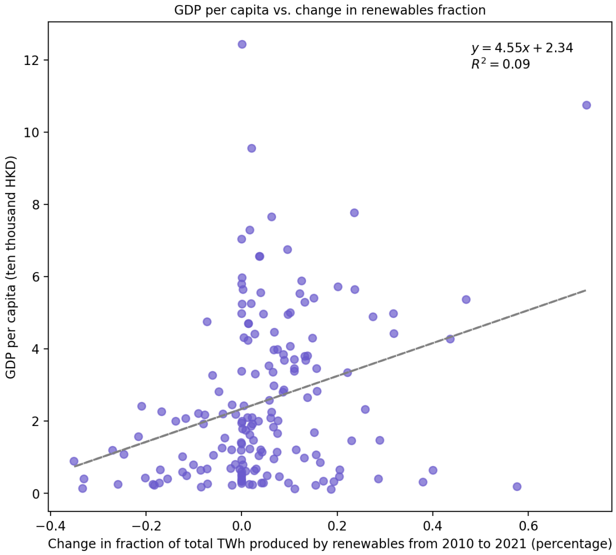


Figure 8. Correlation between GDP per capita and the change in the fraction of a country's total TWh produced by renewable energy between 2021 and 2010.



4.4 Model Validation

4.4.1 Evaluating the geographic distribution of lock-in

Carbon lock-in represents the fraction of cumulative 21st century emissions which are expected to come from existing or planned long-lived assets. Figure 9 displays the global distribution of carbon lock-in fractions at their highest point, in 2043. Values vary over time because they measure lock-in on a cumulative basis, and emissions evolve year to year. Displaying the year with the highest global ratio of emissions from long-lived assets to total emissions both captures the fullest extent of lock-in risk currently measured, and creates the greatest possible visual contrast between plotted lock-in values. The majority of countries with fairly high lock-in fractions are found in Asia, and Sub Saharan Africa, and countries without available data are marked in gray. The countries with the highest lock-in fractions, all greater than two, are Zimbabwe, Hong Kong (SAR China), and Taiwan.

Any country with a lock-in fraction greater than one is of particular interest, because this is indicative of emissions from long-lived assets outpacing the projected overall emissions of that country. It's plausible that in these localities, unless committed assets are retired early or strong lobbying leads to a reduction of currently considered plans, real life emissions will exceed the values allocated by RCP-SSP scenarios. However, this result is not necessarily only the effect of the lock-in fraction's numerator, with excessively high emissions from long-lived assets. It could also be the case that the denominator (future emissions trajectories derived through downscaling) against which long-lived assets emissions are being compared is less robust for particular countries. This is somewhat supported by Table 3, which explores emissions from countries with high lock-in fractions in more detail, and finds that the most anomalous lock-in values come from countries which capture exceptionally small fractions of global emissions. Zimbabwe has a lock-in fraction of 2.53 in 2043, yet it only contributes 0.001% to global emissions totals for the years 2021, 2043, and a slightly higher 0.002% in 2100. Similarly, Hong Kong (SAR China) and Taiwan, despite having lock-in fractions of 2.29 and 2.04, respectively, also account for relatively small percentages of global emissions. This pattern is also observed in countries like Bangladesh, Vietnam, and the Philippines, where, despite higher lock-in fractions, contributions to global emissions remain notably low.

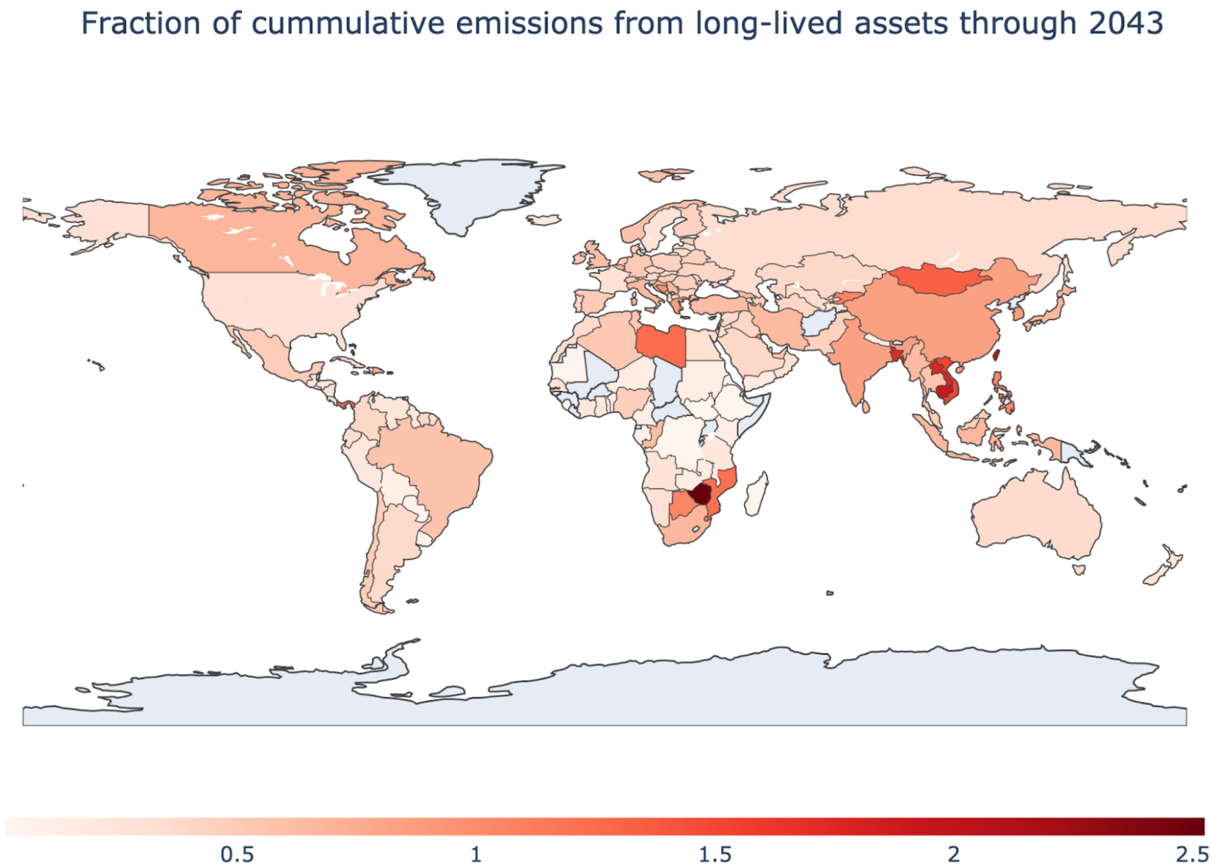


Figure 9. Choropleth plot of global carbon lock-in fractions, cumulative through 2043. Darker red indicates higher lock-in fractions, no data is available for countries in white.

There are several plausible reasons why this could be the case. Namely, differences in asset reporting and unintended effects of downscaling. By asset reporting, I am referring to the fact that considered emissions values (which also contribute to lock-in) are derived from documented construction plans, and that tendencies in documentation could vary across countries. For example, the existence of documentation in one locality might imply construction of a plant with near certainty, while in another it implies a very low chance. However, it seems most likely that the effects of downscaling would drive country-level anomalies in lock-in fractions. In general, the lower a country's emissions are, the smaller the error in the model's prediction of that value needs to be in order to be wrong. As a result, it is likely harder to precisely predict the future emissions of countries with relatively low emissions today via downscaling. Overall, while lock-in fractions are useful for understanding the impact of existing infrastructure, they should be interpreted in light of the limitations of downscaling.

		Lock-in fraction	Fraction of global emissions by year		
		2043	2021	2043	2100
Zimbabwe	SubSahAfrica	2.53	0.001	0.001	0.002
Hong Kong (SAR China)	eAsia	2.29	0.002	0.001	0
Taiwan	eAsia	2.04	0.012	0.006	0.001
Cambodia	seAsia	1.89	0.002	0.001	0.001
Laos	seAsia	1.76	0.001	0.001	0
Bangladesh	sAsia	1.72	0.007	0.006	0.002
Vietnam	seAsia	1.52	0.016	0.014	0.005
Mongolia	eAsia	1.33	0.002	0.002	0.001
Libya	MENA	1.25	0.002	0.003	0.001
Panama	cAmerica	1.23	0.001	0.001	0
Mozambique	EastAfrica	1.22	0.002	0.003	0.002
Eswatini	SubSahAfrica	1.17	0	0	0
Kyrgyzstan	cAsia	1.06	0.001	0.001	0
Botswana	SubSahAfrica	1.05	0.001	0	0
Philippines	seAsia	1.02	0.009	0.007	0.004

Table 3. Fraction of global emissions attributable to countries with lock-in fractions greater than 1. Lock-in fractions listed for the peak of modeled lock-in values (2043) and the beginning (2021) and end of the dataset (2100).

4.4.2 Adjustments for scenario comprehensiveness

Because electrical and industrial emissions account for the bulk of emissions from hard to decarbonize sectors, my data collection efforts were focused on gathering highly granular data for these sectors in particular since the difficulty of decarbonization in the presence of these assets is a key implication of carbon lock-in (Davis et al. 2010). Because this is not comprehensive of global emissions, one important subcomponent of this analysis is an adjustment of the scenario projections taken from Gütschow et al. (2021) based on updates to our knowledge of real world emissions.

The emission projections from Gütschow et al. (2021) were published in 2020 (indeed a year before the cited paper's release), so it's now possible to compare projected emissions for 2021 to actual emissions from Ritchie et al. (2020) as a measure of the reliability of the author's projections. It's important to note that 2021 was still impacted by the COVID-19 pandemic, but as 2021 is the only year for which modeled data and real estimates are available, it's used regardless. To examine any differences, I compute an additional data specification which weights the scenario data by the ratio between each country's real emissions in 2021 and its projected emissions. Then, for each projection, yearly emissions values were adjusted upwards or downwards by this ratio to better account for the difference between each projection and know facts about real world emissions. The resulting trend in scenario emissions is given by the red line in Figure 10.

Figure 10 suggests that anchoring my modeled values for future emissions to real emissions data for 2021 results in an overall increase in my predicted values. However, the increase was sufficiently small and the weighted values sufficiently similar to the initial data specification that I've excluded it from other results presented in this study. Because all modeled global scenario emissions trajectories are continuously declining, and because carbon lock-in is a fraction, using a scaled measure of the scenario data wouldn’t impact any relative prioritization decisions made based on the lock-in metric.

However, examining the global case could be misleading, as it’s possible that more dramatic adjustments to projected emissions would be seen if applying the real emissions based scaling to country-level emissions trajectories. To explore whether this could be the case, I analyze the ratio between modeled emissions in 2021 and the real global emissions values more closely in Figure 11, which depicts the spread of the ratio of modeled to real emissions for expected emissions across all countries under the weighted average of scenarios taken from Venmans and Carr (2022). While the ratio between real and modeled emissions varies across countries considerably ranging from 0 to 2.2, the mean ratio of 0.84 suggests that scenario emissions from Gütschow et al. (2021) account for 84% of modeled emissions on average. Critically, the closer the modeled to real emissions ratio is to 1 the better predictor of reality scenario emissions are assumed to be. Overall, it appears that the country-level emissions could in fact be fairly influenced by such anchoring, but that the overall global expectation is likely to be reasonable without any such adjustment.

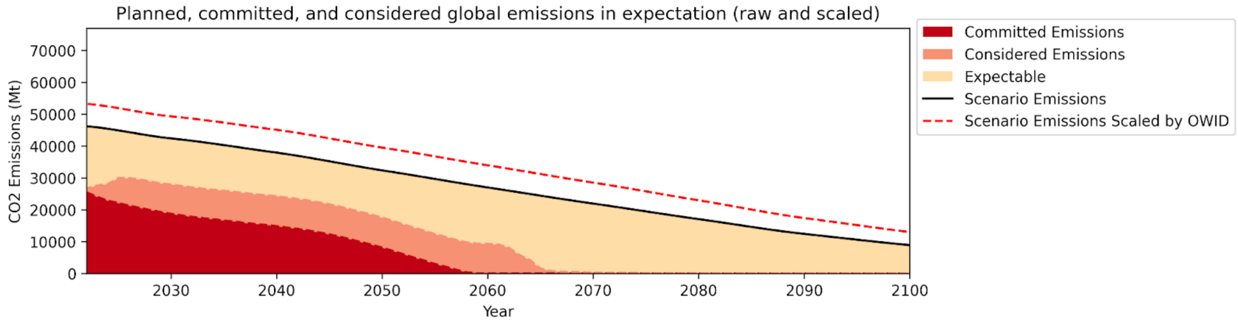


Figure 10. Modeled global emissions projections for the weighted average of the scenarios in Figure 3, according to the probabilities given in the central estimate of Venmans and Carr (2022) (see Figure 4). The effect of scaling Gütschow et al. (2021) emissions trajectories by real emissions in 2021 is given by the dashed red line.

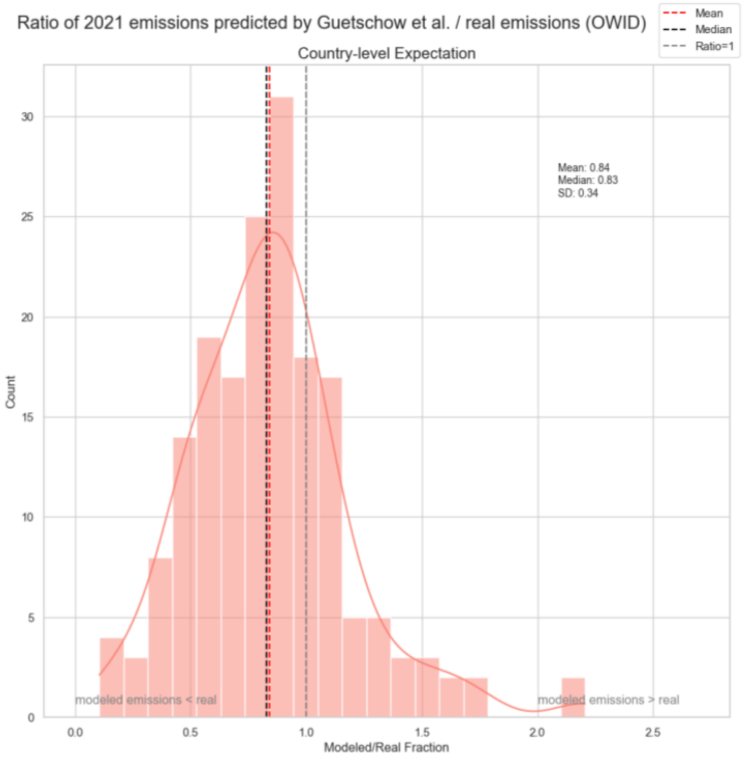


Figure 11. Distribution of the ratio between real 2021 emissions and the emissions predicted by taking a weighted average of the emissions from Gütschow et al. (2021) according to the central probability estimate of Venmans and Carr (2022). Ratio equal to one indicates perfect correspondence.

5. Discussion and limitations

Ultimately, this study presents country-level estimates of future emissions through the end of the 21st century, and uses the proportion of emissions attributable to long-lived fossil assets as a proxy for the technical component of carbon lock-in. I use assumptions about plant lifetimes from the energy economics literature and probabilistic forecasts of RCP-SSP scenario likelihoods to produce bottom-up estimates of emissions trajectories, and suggest that for many regions existing and planned fossil intensive assets threaten emissions reductions goals. The comparison of likely emissions from long-lived assets to the total emissions forecasted under a particular scenario shows that some optimistic climate futures are incompatible with existing infrastructure, and captures a discrepancy between stated climate pledges and the construction of long-lived fossil assets.

The research which resulted in this work focused on designing a metric for carbon lock-in, and resolving the relevant empirical challenges to determining carbon lock-in values. In particular, the cleaning, aggregation, and projection of emissions data from long-lived assets and background scenarios required the development of the codebase which enables the generation of the images included here. While the assumptions required to make the data workable create additional uncertainties, this thesis makes the novel contribution of attempting to quantify the technical component of carbon lock-in.

The carbon lock-in values generated in this analysis quantify the proportion of total emissions expected to originate from existing and planned fossil assets at various future points. As such, higher lock-in values suggest greater challenges to decarbonization as the result of carbon intensive infrastructure commitments. Lock-in also serves to capture opportunities to reduce emissions irrespective of location, and by using cumulative rather than current emissions it accounts for challenges to decarbonization over a relatively long timescale. The result of taking a global, long-term perspective when calculating a metric that captures something akin to the difficulty of abating emissions is a tool which can arguably be used to prioritize emissions reduction efforts by considering where the greatest magnitude of emissions which might be avoided lies (in combination with information about how difficult avoiding the construction of or decommissioning assets is in a given region). This is a valuable additional tool for intervention prioritization, which is otherwise limited to abatement costs. Often, these focus too narrowly on the local, marginal costs of emissions reductions, and may fail to capture the value of early investments that drive significant cost declines. While marginal abatement cost curves were central to mitigation discussions of the early 2000s, which were primarily concerned with marginal changes, today's search for longer-term mitigation strategies may be better off using other metrics and seeking to minimize the total costs of mitigation and damages (Vogt-Schilb et al. 2018, Hallegatte, 2023).

Coincidental findings of this study include the ability for bottom-up estimations of emissions from long-lived assets to be contrasted against particular future emissions trajectories as a rough study of a scenario's feasibility. Specifically, it is possible to nearly "rule out" the occurrence of scenarios which suggest lower emissions than those which are likely to result from existing infrastructure alone. Because the sum of considered and committed emissions only represents a fraction of an economy's total emissions from long-lived assets, it seems highly implausible that a future scenario which suggests total emissions levels below that of considered and committed values could be at all possible. Based on comparing global long-lived asset emissions to the emissions in scenarios prescribed by Gütschow et al. (2021), every emissions pathway by which the world reaches RCP 1.9, and the SSP4 pathway to RCP 2.6, should be seen as highly improbable. For these to occur would require either profound flaws in the underlying data, or the premature elimination of emissions from long-lived assets and halt of the construction of new fossil-intensive assets.

An additional result of this analysis was the finding that upon weighting the global Gütschow et al. (2021) scenario trajectories with credences from Venmans and Carr (2022), it appears as if global emissions are set to continually decline over the course of the century, Whether or not this seems feasible may be a sensible check against which to evaluate the results. Unfortunately, evidence for whether emissions could genuinely have peaked is still uncertain, and too little data is available to say. However, if emissions develop in the general mode suggested by these credences, forecasts of this kind should perhaps be seen more widely as valuable indicators about likely climate futures.

Of course, these and other findings of this study should be considered in light of their limitations. In particular, the fact that any empirical work is prone to data error, and that the bottom-up estimation of considered and committed emissions performed in this study could be subject to any number of mistakes. In this case, both systemic bias in the data and author error are possible. While various checks performed somewhat negate the possibility of the extreme mistakes (e.g. the emissions projected are almost certainty correct to within an order of magnitude), their precision is clearly limited. Overall, the results discussed are better interpreted as a feasibility study for the underlying methodology than as a definitive claim about emissions futures. Some specific uncertainties include the estimation of gas emissions based on megawatt capacity of these assets, and the estimation of considered emissions from industry as a direct function of considered electrical emissions. The reconstruction of scenario emissions for country-level emissions under SSP 3, RCP 7 could also been viewed as spurious, as it required taking a weighted average of SSP 3 data for RCP 6 and RCP 8.5 to approximate the trajectory of an intermittent scenario (this was necessary due to a mismatch in the scenario specifications given by of Gütschow et al. (2021) and Venmans and Carr (2022)). Furthermore, the credences of Venmans and Carr (2022) are only the model result of probabilistic forecasts– they're unlikely to perfectly predict the future of emissions. It's also worth addressing the underlying assumption that avoiding carbon lock-in is valuable, and not inevitable. Underestimates of clean energy progress and pricing are ubiquitous, and it's possible this could continue to be the case to such a degree that worries about the emissions of quickly industrializing economies will be seen as misplaced in retrospect (Ritchie & Roser, 2021).

The results of this research suggest that developing countries (particularly in Asia) have high emissions reduction potential by means of avoiding carbon lock-in, which is largely the result of the abundance of coal infrastructure currently planned. It seems plausible that this could also become the case for sub Saharan Africa, if the relatively conservative growth estimates used in IAMs are exceeded and it comes to emulate Asia's current status as a rapidly industrializing region facing the threat of lock-in (Ezeh et al. 2020). Based on the disproportionately high fraction of long-lived assets categorized as considered emissions, West Africa may also be a valuable target for interventions. As the bulk of the potential for mitigation emissions from carbon lock-in occurs in developing countries due to their relatively quickly expanding infrastructure, it is possible to uncharitably interpret the recommendation implied by this metric as an attempt to pass emissions burdens onto nations who are not responsible for them. Contrary to this, I view the risk of carbon lock-in abroad as a strong argument for the investment of wealthy nation's efforts to reduce emissions from foreign infrastructure. In general, locally isolated abatement is economically inefficient, and it makes sense for wealthy nations to take actions which enable abatement abroad, e.g. through climate finance or investments in the research which drives the cost declines of renewable technologies.

Overall, quantifying carbon lock-in provides a background against which to measure mitigation effects on cumulative global emissions, instead of only considering the local and marginal emissions reductions prioritized by abatement costs and other measures. As a result the metric somewhat demonstrates the differences in priorities which may emerge when taking a longer term perspective on mitigation, and suggests local marginal abatement may not always be strictly preferable to preventing the further construction of long-lived assets. With this in mind, the aim of this thesis is to make action-guiding the compelling theoretical basis for the entrenchment of long-lived assets: carbon lock-in, and set forth an empirical metric which can assist policymakers in identifying global decarbonization objectives.

6. Conclusion

The result of this thesis is essentially a back-of-the-envelope estimation of carbon lock-in, which in this context, refers to the future greenhouse gas emissions from existing or planned energy infrastructure that would be emitted if the infrastructure was used as usual until the end of its life cycle. The significance of carbon lock-in lies in the barrier it creates for future decarbonization, and the barrier it poses to mitigation efforts. The bulk of this research focused on developing a codebase able to produce the visualizations presented in the results.

Reflecting on the findings presented, I expect the primary contribution of this work is the availability of the carbon lock-in fraction as a value which can be used for prioritization. As the metric is provided at the country-level, it could easily be used to compare the value of investing in avoiding lock-in (e.g. by funding clean energy infrastructure construction) between specific countries or regions. Another potentially useful finding comes from considering the qualitative difference in the types of modeled emissions from long-lived assets, and explicitly generating estimates of considered emissions. These are emissions that result from assets currently in the planning phase, which serve as ideal targets for policy action because they identify a discrete construction proposal which can be lobbied for or against. The ability to affect considered emissions likely varies as a function of how plausible such lobbying is to be heeded in a particular political regime (specifically how well it responds to democratic pressures), thus the alterability of these emissions is somewhat a function of where they occur. Some combination of this alterability with the overall scale of considered emissions in a particular jurisdiction can estimate the amount of emissions which can be reduced through more feasible means than the premature retirement of existing fossil assets. Notably, under an efficient emissions reduction regime, abating considered emissions will likely occur before abating committed emissions, simply because it is easier to prevent construction than to decommission existing assets.

In future work, it would be especially valuable to distinguish between considered and committed emissions as proxies for lock-in, rather than treating them as a singular category of long-lived assets. It would also be useful to perform a quantitative comparison of lock-in metrics and abatement costs, in order to validate the claims this thesis makes about the substitutability of considered and committed emissions. A final implication of this work is that once aggregated, existing data can be used to generate bottom up estimates of future emissions which serve as useful checks against planned emissions pathways or emissions reduction goals, and examining this claim more closely would provide further area for future work. For policymakers, it would also be useful to compare suggested emissions targets to data from existing and planned assets as a feasibility study for a given proposal. Further analysis would aim to make this more easily possible for such policymakers.

Finally, this work sits within a larger body of research on cause prioritization, which combines the principles of optimization with the aim of comparing interventions designed to generate positive change. Specifically, this thesis contributes to an ongoing dialogue about the optimal allocation of resources for maximal reduction of harms from climate change, and regardless of its empirical uncertainties it provides evidence of the benefits a cause prioritization framework might bring to climate change mitigation efforts. Namely, it offers a new metric under which to measure emissions reduction potential. While further research could very plausibly suggest that carbon lock-in is not, in fact, superior to the classical approach, it is still worth considering whether the existing paradigm may be insufficient for capturing the relevant considerations for emissions reduction prioritization, and therefore worth attempting to quantify carbon lock-in.

Data and Code Availability Statement

Data and code used in this analysis are available upon request.

Appendix

country	**region**	**country**	**region**	**country**	**region**
Afghanistan	cAsia	Canada	nAmerica	Gabon	cAfrica
Albania	eEurope	Cape Verde	wAfrica	Gambia	wAfrica
Algeria	MENA	Central African Republic	cAfrica	Georgia	cAsia
Angola	SubSahAfrica	Chad	cAfrica	Germany	wEurope
Argentina	sAmerica	Chile	sAmerica	Ghana	wAfrica
Armenia	cAsia	China	eAsia	Greece	eEurope
Aruba	cAmerica	Colombia	sAmerica	Grenada	cAmerica
Australia	Oceania	Comoros	EastAfrica	Guatemala	cAmerica
Austria	wEurope	Congo - Brazzaville	cAfrica	Guinea	wAfrica
Azerbaijan	cAsia	Congo - Kinshasa	cAfrica	Guinea-Bissau	wAfrica
Bahamas	cAmerica	Costa Rica	cAmerica	Guyana	sAmerica
Bahrain	MENA	Côte d'Ivoire	wAfrica	Haiti	cAmerica
Bangladesh	sAsia	Croatia	eEurope	Honduras	cAmerica
Barbados	cAmerica	Cuba	cAmerica	Hong Kong SAR China	eAsia
Belarus	eEurope	Cyprus	MENA	Hungary	eEurope
Belgium	wEurope	Czechia	eEurope	Iceland	wEurope
Belize	cAmerica	Denmark	wEurope	India	sAsia
Benin	wAfrica	Djibouti	EastAfrica	Indonesia	seAsia
Bhutan	sAsia	Dominican Republic	cAmerica	Iran	cAsia
Bolivia	sAmerica	Ecuador	sAmerica	Iraq	MENA
Bosnia & Herzegovina	eEurope	Egypt	MENA	Ireland	wEurope
Botswana	SubSahAfrica	El Salvador	cAmerica	Israel	MENA
Brazil	sAmerica	Equatorial Guinea	cAfrica	Italy	wEurope
Brunei	seAsia	Eritrea	EastAfrica	Jamaica	cAmerica
Bulgaria	eEurope	Estonia	eEurope	Japan	eAsia
Burkina Faso	wAfrica	Eswatini	SubSahAfrica	Jordan	MENA
Burundi	EastAfrica	Ethiopia	EastAfrica	Kazakhstan	cAsia
Cambodia	seAsia	Fiji	Oceania	Kenya	EastAfrica
Cameroon	cAfrica	Finland	wEurope	Kuwait	MENA
Laos	seAsia	France	wEurope	Kyrgyzstan	cAsia
Latvia	eEurope	Nigeria	wAfrica	Sri Lanka	sAsia

Lebanon	MENA	North Macedonia	eEurope	Sudan	EastAfrica
Lesotho	SubSahAfrica	Norway	wEurope	Suriname	sAmerica
Liberia	wAfrica	Oman	MENA	Sweden	wEurope
Libya	MENA	Pakistan	sAsia	Switzerland	wEurope
Lithuania	eEurope	Panama	cAmerica	Syria	MENA
Luxembourg	wEurope	Papua New Guinea	Oceania	Taiwan	eAsia
Macao SAR China	eAsia	Paraguay	sAmerica	Tajikistan	cAsia
Madagascar	EastAfrica	Peru	sAmerica	Tanzania	EastAfrica
Malawi	EastAfrica	Philippines	seAsia	Thailand	seAsia
Malaysia	seAsia	Poland	eEurope	Timor-Leste	seAsia
Maldives	sAsia	Portugal	wEurope	Togo	wAfrica
Mali	wAfrica	Qatar	MENA	Trinidad & Tobago	cAmerica
Malta	wEurope	Romania	eEurope	Tunisia	MENA
Mauritania	wAfrica	Russia	eEurope	Turkey	eEurope
Mauritius	EastAfrica	Rwanda	EastAfrica	Turkmenistan	cAsia
Mexico	nAmerica	Samoa	Oceania	Uganda	EastAfrica
Moldova	eEurope	Saudi Arabia	MENA	Ukraine	eEurope
Mongolia	eAsia	Senegal	wAfrica	United Arab Emirates	MENA
Montenegro	eEurope	Serbia	eEurope	United Kingdom	wEurope
Morocco	MENA	Sierra Leone	wAfrica	United States	nAmerica
Mozambique	EastAfrica	Singapore	seAsia	Uruguay	sAmerica
Myanmar (Burma)	seAsia	Slovakia	eEurope	Uzbekistan	cAsia
Namibia	SubSahAfrica	Slovenia	eEurope	Vanuatu	Oceania
Nepal	sAsia	Solomon Islands	Oceania	Venezuela	sAmerica
Netherlands	wEurope	Somalia	EastAfrica	Vietnam	seAsia
New Zealand	Oceania	South Africa	SubSahAfrica	Yemen	MENA
Nicaragua	cAmerica	South Korea	eAsia	Zambia	SubSahAfrica
Niger	wAfrica	South Sudan	EastAfrica	Zimbabwe	SubSahAfrica
Kosovo	eEurope	Spain	wEurope	Isle of Man	wEurope
Curaçao	cAmerica	Palestinian Territories	MENA	North Korea	eAsia

References

Ackva, J. et al. (2021) ‘A guide to the changing landscape of high impact climate philanthropy’, Founders Pledge.

Caldecott, B. et al. (2018) Carbon Lock-in Curves and Southeast Asia: Implications for the Paris Agreement, Smith School of Enterprise and the Environment, University of Oxford.

Climate Action Tracker (2022) '2100 Warming Projections: Emissions and expected warming based on pledges and current policies', November.

Climate Action Tracker (2023) 'Land-use, land-use change and forestry’.

Climate Action Tracker (2023) 'Net zero targets’.

Cox, P., Huntingford, C. and Williamson, M. (2018) 'Emergent constraint on equilibrium climate sensitivity from global temperature variability', Nature, 553, pp. 319-322.

Cui, R.Y., Hultman, N., Edwards, M.R. et al. (2019) 'Quantifying operational lifetimes for coal power plants under the Paris goals', Nat Commun, 10, 4759.

Davis, S. J. et al. (2010) 'Future CO2 Emissions and Climate Change from Existing Energy Infrastructure', Science, 329, pp.1330-1333.

Davis, S. J. and Socolow, R. H. (2014) 'Environ. Res. Lett.', 9.

Dunne, D. (2018) 'New study ‘reduces uncertainty’ for climate sensitivity', Carbon Brief.

Erickson, P. et al. (2015) Environ. Res. Lett., 10, 084023.

Eurostat. (2015) ‘Glossary: Kyoto basket’.

Ezeh, A., et al. (2020) 'Why Sub-Saharan Africa Might Exceed Its Projected Population Size by 2100', The Lancet, 396(10258), pp. 1131-1133.

Global Coal Plant Tracker (2023) 'Global Energy Monitor', January.

Global Gas Plant Tracker (2023) 'Global Energy Monitor', February.

Gütschow, J. et al. (2020). Country resolved combined emission and socio-economic pathways based on the RCP and SSP scenarios (1.0) [Data set]. Zenodo.

Gütschow, J. et al. (2021) 'Country-Resolved Combined Emission and Socio-Economic Pathways Based on the Representative Concentration Pathway (RCP) and Shared Socio-Economic Pathway (SSP) Scenarios', Earth System Science Data, 13(3), pp. 1005–1040.

Hallegatte, S. (2023) 'Proper use of the abatement cost to steer the transition', Institute for Climate Economics, I4CE. Interview.

Hausfather, Z. (2018) 'Explainer: How 'Shared Socioeconomic Pathways' explore future climate change', Carbon Brief.

Hausfather, Z. and Peters, G.P. (2020) 'Emissions – the ‘business as usual’ story is misleading', Nat. Comment.

Kesicki, F. and Ekins, P. (2012) 'Marginal abatement cost curves: a call for caution', Climate Policy, 12(2), pp. 219-236.

Mattauch, L., Creutzig, F. and Edenhofer, O. (2015) 'Avoiding carbon lock-in: Policy options for advancing structural change', Economic Modelling, Volume 50, Pages 49-63.

Myllyvirta, Lauri, and Flora Champenois. “China Permits Two New Coal Power Plants per Week in 2022.” Centre for Research on Energy and Clean Air (CREA), 14 Mar. 2023.

O'Neill, B. et al. (2022) 'Key Risks Across Sectors and Regions. In: Climate Change 2022: Impacts, Adaptation and Vulnerability', Cambridge University Press, pp. 2411–2538.

O’Sullivan, J.N. (2018) 'Synergy between Population Policy, Climate Adaptation and Mitigation', In: Hossain, M., Hales, R., Sarker, T. (eds) Pathways to a Sustainable Economy, Springer, Cham.

Piper, K. (2022) 'Stop telling kids that climate change will destroy their world', Vox.

Raftery, A. E. et al. (2017) 'Less Than 2 °C Warming by 2100 Unlikely', Nat. Clim Change, 7, pp. 637-641.

Ricke, K. L. and Caldeira, K. (2014) 'Environ. Res. Lett.', 9, 124002.

Ritchie, H., Roser, M. and Rosado, P. (2020) 'CO_2 and Greenhouse Gas Emissions'. OurWorldInData.org. Available at: https://ourworldindata.org/co2-and-greenhouse-gas-emissions (Accessed: March 2023).

Ritchie, H. (2021) 'Stop telling kids they’ll die from climate change', WIRED UK.

Ritchie, H., and Roser, M. (2021) ‘Energy’. OurWorldInData.org. Available at: ourworldindata.org/energy (Accessed: July 2023).

Sousounis, P. (2019) ‘Climate Change: RCPs and the Emissions Gap’. Verisk.

Stips, A. et al. (2016) 'On the causal structure between CO2 and global temperature', Sci Rep, 6, 21691.

Sundqvist, T., Söderholm, P. and Stirling, A. (2004) 'Electric Power Generation: Valuation of Environmental Costs', In: Cutler J. Cleveland, Encyclopedia of Energy, Elsevier, pp. 229-243.

Symon, A. (2004) 'Fuelling Southeast Asia’s Growth: The Energy Challenge', ASEAN Economic Bulletin, 21(2), pp. 239-248.

Tong, D. et al. (2019) 'Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target', Nature, 572, pp. 373–377.

Unruh, G.C. (2000) 'Understanding carbon lock-in', Energy Policy, Volume 28, Issue 12, Pages 817-830.

Unruh, G.C. (2002) 'Escaping carbon lock-in', Energy Policy, Volume 30, Issue 4, Pages 317-325.

Unruh, G.C., Carrillo-Hermosilla, J. (2006) 'Globalizing carbon lock-in', Energy Policy, Volume 34, Issue 10, Pages 1185-1197.

Van Beek, L. et al. (2020) 'Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970', Global Environmental Change, 65, 102191.

Venmans, F. and Carr, B. (2022) 'The Unconditional Probability Distribution of Future Emission and Temperatures', Available at SSRN.

Vogt-Schilb, A., Meunier, G. and Hallegatte, S. (2018) 'When starting with the most expensive option makes sense: Optimal timing, cost and sectoral allocation of abatement investment', Journal of Environmental Economics and Management, 88, pp. 210-233.

Wagner, G. and Weitzman, M.L. (2015) 'Climate shock: The economic consequences of a hotter planet'.

World Resources Institute, 2021. ‘Statement: Brazil’s 2050 Climate Neutrality Goal Is an Important Gesture, but It Contradicts Climate Actions from the Administration’.

Zhu, J., Poulsen, C.J. and Otto-Bliesner, B.L. (2020) 'High climate sensitivity in CMIP6 model not supported by paleoclimate', Nat. Clim. Chang, 10, pp. 378–379.

Declaration of consent

on the basis of Article 30 of the RSL Phil.-nat. 18

Name/First Name: Buxton-Walsh/Violet

Registration Number: 21-117-742

Study program: MSc Climate Sciences

Bachelor ☐ Master ☑ Dissertation ☐

Title of the thesis: Quantifying Carbon Lock-In

Supervisor: Prof. Ralph Winkler

I declare herewith that this thesis is my own work and that I have not used any sources other than those stated. I have indicated the adoption of quotations as well as thoughts taken from other authors as such in the thesis. I am aware that the Senate pursuant to Article 36 paragraph 1 litera r of the University Act of 5 September, 1996 is authorized to revoke the title awarded on the basis of this thesis.

For the purposes of evaluation and verification of compliance with the declaration of originality and the regulations governing plagiarism, I hereby grant the University of Bern the right to process my personal data and to perform the acts of use this requires, in particular, to reproduce the written thesis and to store it permanently in a database, and to use said database, or to make said database available, to enable comparison with future theses submitted by others.

New York City, USA. 21st August 2023.

Place/Date

Violet Buxton-Walsh

Signature