SUSTAINABLE FINANCE PROGRAMME

UNIVERSITY OF OXFORD

Carbon Lock-in Curves and Southeast Asia: Implications for the Paris Agreement

Briefing Paper

October 2018

Authors: Ben Caldecott | Matthew McCarten | Charalampos Triantafyllidis

About the Oxford Sustainable Finance Programme

The Oxford Sustainable Finance Programme at the University of Oxford Smith School of Enterprise and the Environment is a multidisciplinary research centre working to be the world's best place for research and teaching on sustainable finance and investment. We were established in 2012 to align the theory and practice of finance and investment with global environmental sustainability.

We research environment-related risks, impacts, and opportunities across different sectors, geographies, and asset classes; how such factors are emerging and how they positively or negatively affect asset values; how they might be interrelated or correlated; their materiality (in terms of scale, impact, timing, and likelihood); who will be affected; and what affected groups can do to pre-emptively manage risk. Since our inception we have conducted pioneering research on stranded assets and continue to undertake significant research on the topic.

The production of high-quality research on the materiality of environment-related factors is a necessary, though insufficient, condition for these factors to be successfully integrated into decision-making. Consequently, we develop the data, analytics, frameworks, and models required to enable the integration of this information.

We are pioneers and advocates of 'spatial finance', a term we have coined that refers to efforts to bring geo-spatial capabilities into financial analysis. As such we are developing new asset-level datasets through data science and combining these with new approaches to spatial analysis, scenarios, and stress tests.

We also research barriers to the adoption of practices related to sustainable finance and investment. This includes the role of governance, norms, behaviour, and cognition, as well as policy and financial regulation in shaping investment decisions and capital allocation.

The Oxford Sustainable Finance Programme is based in a world leading university with a global reach and reputation. We work with leading practitioners from across the investment chain (including actuaries, asset owners, asset managers, accountants, banks, data providers, investment consultants, lawyers, ratings agencies, stock exchanges), with firms and their management, and with experts from a wide range of related subject areas (including finance, economics, management, geography, data science, anthropology, climate science, law, area studies, psychology) within the University of Oxford and beyond.

The Global Sustainable Finance Advisory Council that guides our work contains many of the key individuals and organisations working on sustainable finance. The Council also has a role in helping to informally co-ordinate and share information on sustainable finance and stranded assets work internationally. The Oxford Sustainable Finance Programme's founding Director is Dr Ben Caldecott.

About the Authors

Ben Caldecott is the founding Director of the Oxford Sustainable Finance Programme. He is concurrently an Academic Visitor at the Bank of England and a Visiting Scholar at Stanford University. Ben specialises in environment, energy, and sustainability issues and works at the intersection between finance, government, civil society, and academe, having held senior roles in each domain. He holds a doctorate in economic geography from the University of Oxford. Ben initially read economics and specialised in development and China at the University of Cambridge and the School of Oriental and African Studies, University of London.

Matthew McCarten is a Postdoctoral Research Associate in the Oxford Sustainable Finance Programme. Prior to joining the Oxford Sustainable Finance Programme he gained a PhD in finance at the University of Otago, New Zealand in 2017. His thesis examined the determinants and consequences of securities class actions. In particular, it investigated the association between securities class actions and various corporate characteristics, including debt financing, political lobbying and innovation. He also holds an MBus (with distinction) and a BCom from the University of Otago.

Charalampos P. Triantafyllidis is a Postdoctoral Research Associate in the Oxford Sustainable Finance Programme. He holds a PhD in Operations Research (OR) and has previously been a Postdoctoral Research Associate with Imperial College and University College London, on Sustainable Development and Mathematical Modelling/Optimisation respectively. His main remit is in Applied OR for Sustainability.

Acknowledgements

We would like to thank HSBC for providing a grant to support this briefing paper and the reviewers for their feedback.

We also acknowledge the support of the Oxford Martin School Post-Carbon Transition Programme.

Briefing Paper Series

This Briefing Paper is intended to frame an issue and stimulate discussion among users of research. The views expressed in this paper represent those of the author(s) and do not necessarily represent those of the host institutions or funders.

University of Oxford Disclaimer

Executive Summary

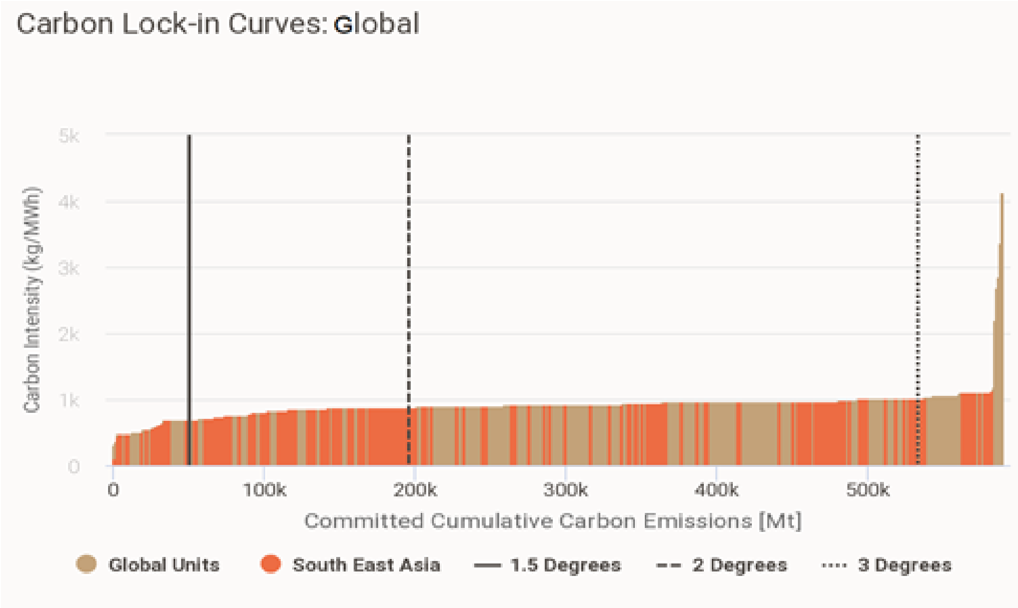
In the last 15 years energy demand in Southeast Asia has grown by over 60% and the IEA anticipates its energy demand to grow by two-thirds by 2040. Increasing energy demand coupled with a reliance on fossil fuels will have major implications for the ability of the region and its constituent countries to deliver on Paris Agreement compatible carbon budgets. All of the countries of Southeast Asia (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, and Vietnam) have ratified the Paris Agreement.

Carbon Lock-in Curves (CLICs) are a new method we have created to objectively assess the carbon budget implications of current and planned assets. CLICs create a way to order, optimise, and represent portfolios of assets based on their committed emissions or future 'carbon lock-in'. Cumulative committed emissions across assets are compared to carbon budgets to determine which assets are compatible (or incompatible) with a given budget.

Assets that are incompatible with carbon budgets face a higher risk of stranding due to action on climate change. CLICs allow companies, policymakers, financial institutions, governments, regulators, and civil society to see whether current or proposed assets are compatible with different climate pathways and how this could change over time.

This report introduces CLICs and applies the approach to analyse the compatibility of power generating assets in Southeast Asia with global and country-level carbon budgets. Figure 1 presents a global CLIC with all Southeast Asian power assets. We have undertaken an analysis, using IPCC AR5, of carbon budgets with a 66% probability of keeping global temperature increased above pre-industrial levels below a given temperature (1.5°C, 2°C, and 3°C). We then allocate a share of the global carbon budget to the sector we are analysing (in this case power). We can also make allocations to specific countries or even companies. The methodologies we employ are set out later in the report in Section 2.

Figure 1: Global Carbon Lock-in Curve
This figure plots a Global Carbon Lock-in Curve. All current and planned Southeast Asia power assets are in orange and other global power assets are in brown. The width of each bar represents the estimated committed cumulative carbon emissions (CCCEs) for each asset.



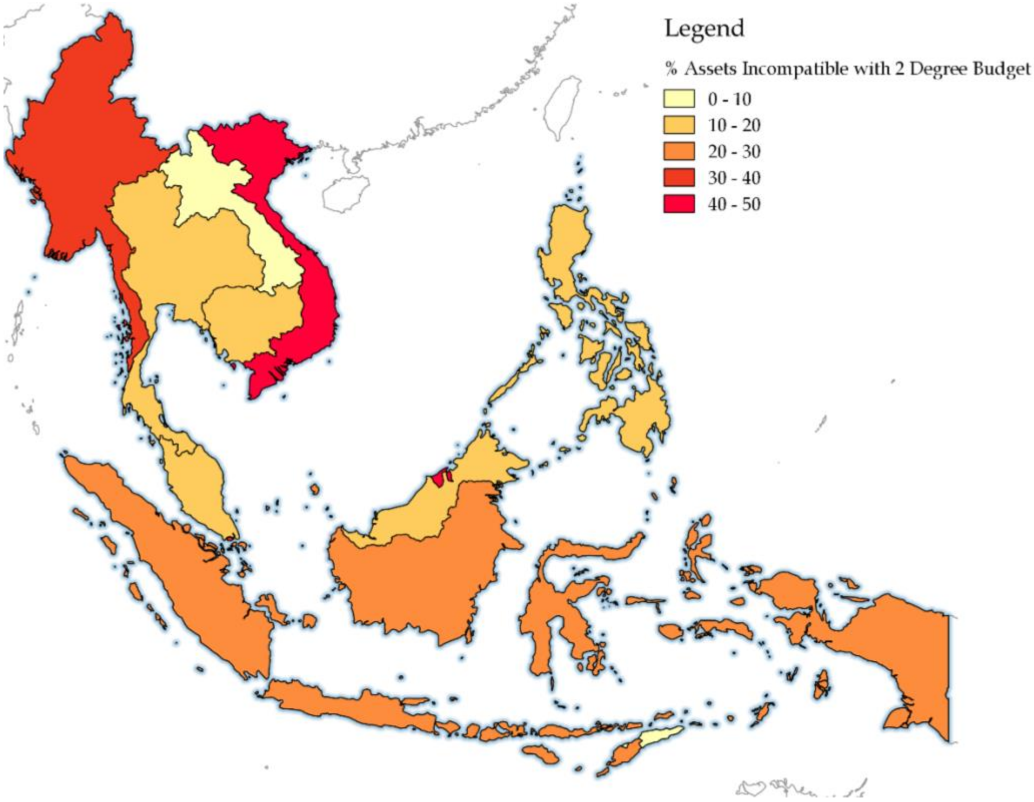
N.B. To improve rendering, assets with the same efficiency are aggregated and plotted as one. Therefore, each bar may represent the CCCEs of many individual assets. Using this rendering any bar with at least one Southeast Asian asset is coloured orange. Power generating assets are ordered by asset efficiency (carbon intensity (kg/MWh). The vertical lines represent the global emissions budget allocated to the global power sector for each warming scenario.

Table 1: Current and Planned Emitting Units Position Relative to the Global Budgets by Country
This table reports the emitting units position relative to the global budget for the countries in Southeast Asia, the percentage and number of emitting units that are incompatible with each warming scenario for each country, as well as a total representing the units across all Southeast Asian countries.

	Total Emitting Units			Units Incompatible with 1.5°C Budget	Units Incompatible with 1.5°C - 2°C Budget	Units Incompatible with 2°C - 3°C Budget
Country	Current	Planned	Total			
Brunei	55	7	62	88.7% (55)	45.2% (28)	0.0% (0)
Cambodia	155	13	168	94.6% (159)	10.1% (17)	1.8% (3)
Indonesia	2478	287	2765	89.0% (2460)	26.4% (730)	3.5% (97)
Laos	61	3	64	98.4% (63)	7.8% (5)	0.0% (0)
Malaysia	803	54	857	88.8% (761)	14.2% (122)	2.5% (21)
Myanmar	100	34	134	65.7% (88)	35.8% (48)	0.7% (1)
Philippines	1303	195	1498	83.3% (1248)	13.4% (200)	3.8% (57)
Singapore	149	5	154	81.2% (125)	33.8% (52)	7.8% (12)
Thailand	541	130	671	52.8% (354)	14.3% (96)	1.9% (13)
Timor-Leste	54	22	76	96.1% (73)	0.0% (0)	0.0% (0)
Vietnam	198	116	314	86.9% (273)	50.0% (157)	19.7% (62)
Total	5897	866	6763	83.7% (5659)	21.5% (1455)	3.9% (266)

Figure 2: Global Carbon Lock-in Curve

This figure plots a heat map based on the percentage of current and planned fossil fuel generation assets that are incompatible with a 2°C global carbon budget in Southeast Asia.



Through our CLICs analysis for the Southeast Asian power sector we have found that:

- The vast majority (83.7%) of Southeast Asia's current and planned fossil fuel generation assets are incompatible with a Paris Agreement aligned carbon budget (1.5°C budget or 200 $GtCO_2$).
- 87.7% of Southeast Asia's current fossil fuel generation assets are incompatible with 1.5°C, 17.8% are incompatible with 2°C, and 2.3% with 3°C. 56.2% of Southeast Asia's planned fossil fuel generation assets are incompatible with 1.5°C, 46.5% are incompatible with 2°C, and 14.8% with 3°C. This highlights the scale of premature closures required to meet climate change objectives and the potential for significant asset stranding in the future.
- While many of the current and planned assets by capacity are coal (57.4%) and oil (7.8%), a significant proportion of gas plants are planned or operating (31.2%) and many of these gas assets are incompatible with different carbon budgets: 64.6% in 1.5°C, 11.0% in 2°C, and 0.3% in 3°C. This highlights how new gas assets, which are often pushed as a route to meeting climate mitigation objectives, are not necessarily a solution.
- Vietnam has the largest fleet of the region's fossil fuel generation assets. 86.9% of Vietnam's current and planned fossil fuel generation assets are incompatible with 1.5°C, 50% are incompatible with 2°C, and 19.7% the 3°C. All of Vietnam's current and planned gas plants, which account for 15.9% of assets by generation capacity, are incompatible with 1.5°C.
- We analysed the ten largest power utilities in Southeast Asia by capacity (Electricity Generating Authority Thailand (EGAT), PT PLN Persero, PetroVietnam Power Corp, Electricity of Vietnam, Ministry of Electric Power (MM), Tenaga Nasional Berhad (TNB), PT Indonesia Power, PT Pembangkitan Jawa-Bali, EVN Genco 3, and Sarawak Energy Berhad Group) and

found that on average 90.7% of their current and planned fossil fuel generation assets are incompatible with 1.5°C, 26.6% are incompatible with 2°C, and 4.9% the 3°C.

The datasets we have brought together to undertake this analysis can be used to assess current and planned assets globally, within regions, within countries, and within companies. We can also assess investor portfolios and bank loan books which contain these assets.

We have created an online tool to create bespoke CLICs. This enables users to generate global and country-level CLICs for any portfolio of power generation assets. Users can alter all assumptions (e.g. carbon budget thresholds, plant retirement ages, plant CO_2 efficiency etc.) and these can be adjusted by users to fit their own views of the present and the future. CLIC analysis can also be applied to other sectors and industries, including: cement, iron and steel, shipping, aviation, and the automobile sector.

The key point is that CLICs allow us to objectively assess whether assets or portfolios of assets are compatible with different carbon budgets. If companies, governments, or investors believe a project is compatible with their carbon budgets, they can disclose what assumptions they have used (e.g. what they believe a Paris Agreement carbon budget is and what operating assumptions they have for the asset). These can then be tested, and sensitivity analysis undertaken.

We are moving away from a situation where groups can make unsubstantiated claims about how assets are compatible with climate change mitigation. We can now verify and evaluate such claims, and this is essential if we are to move the power sector, and indeed other sectors, towards net zero carbon emissions (necessary to achieve any warming threshold) later in the century.

Table of Contents

1. Introduction

There are a wide range of stakeholders, including financial institutions, governments, and financial regulators, now interested in examining the extent to which investments, loan books, and investment portfolios are aligned with the carbon budgets implied by the Paris Agreement to keep global warming 'well-below 2°C'.[1]

So far much of the focus has been on securing public commitments from companies to adopt carbon reduction targets,[2] improve the disclosure of companies' annual CO_2 emissions,[3] and/or assess what these carbon budgets mean for listed fossil fuel reserves and resources.[4]

However, comparatively little attention has been paid to committed emissions or the 'carbon lock-in' of the current or planned capital stock embedded in company and investor portfolios, or indeed within country development plans.

Committed emissions are the cumulative carbon emissions that an asset is expected to emit over its remaining lifetime.[5, 6] This concept, and its application, is significant as it allows us to estimate carbon lock-in and when the current and planned stock of assets will breach carbon budgets.

Recent studies have found that, across all thermal power assets globally, committed emissions breached the 1.5°C to 2°C carbon budget in 2011 and the carbon budget for a 2°C to 3°C warming scenario was breached in 2014.[7] These global findings from periodic studies have not yet been translated to specific countries or companies, or indeed to sectors outside the power sector. Nor has there been a way of doing the analysis using continually updated datasets or in a way that is simple for potential users.

This paper introduces a new approach that takes committed emissions analysis to this next level of detail and sophistication: Carbon Lock-in Curves (CLICs).

The report is organised as follows: Section 2 sets out the methodology employed to create CLICs and the key assumptions used in these analyses. Section 3 provides a CLIC analysis for Southeast Asian countries and the largest Southeast Asian power utilities. Section 4 briefly describes our new online CLICs tool. Section 5 provides concluding remarks.

---

[1] Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environmental Research Letters*, 13, 1395-1408.

[2] Bui, B., & de Villiers, C. (2017). Carbon emissions management control systems: Field study evidence. *Journal of Cleaner Production*, 166, 1283-1294.

[3] Krabbe, O., Linthorst, G., Blok, K., Crijns-Graus, W., van Vuuren, Detlef P., Höhne, N., . . . Pineda, Alberto C. (2015). Aligning corporate greenhouse-gas emissions targets with climate goals. *Nature Climate Change*, 5, 1057-1060.

[4] McGlade, C., & Ekins, P. (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature*, 517, 187-190.

[5] Davis, S. J., Caldeira, K., & Matthews, H. D. (2010). Future CO_2 Emissions and Climate Change from Existing Energy Infrastructure. *Science*, 329(5997), 1330-1333.

[6] Davis, S. J., & Socolow, R. H. (2014). Commitment accounting of CO_2 emissions. *Environmental Research Letters*, 9(8), 1-9.

[7] Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environmental Research Letters*, 13, 1395-1408.

2. Methodological Approach and Assumptions

CLICs are built on a methodological approach that combines the concept of 'Committed Cumulative Carbon Emissions' (CCCEs) or 'carbon lock-in' (see Box 1) with the concept of marginal abatement cost (MAC) curves.[8] CCCEs are an estimate of the emissions that will result from an asset over the remainder of its expected lifetime. MAC curves provide a method of comparing specific abatement actions. MAC curves calculate the cost of specific abatement actions relative to a business-as-usual baseline. These abatement actions are then ranked using an estimate of the unit cost of emissions abated, thus providing a way of comparing the relative merit of each action.[9]

A CLIC plots the CCCE for each asset ordered by a particular ranking method (e.g. plant efficiency, marginal cost, plant age). The width of each bar represents the CCCEs and the ordering variable is plotted on the y-axis. The carbon budgets are then plotted as a vertical line. Assets that are on the left of these budget lines are compatible with that carbon budget, given various assumptions, whereas assets that fall to the right of these budget lines are incompatible with the carbon budget for a given warming threshold and are likely to face a higher risk of becoming stranded due to climate-related transition risks.

We have developed CLICs for initial use in the power sector for thermal assets. However, the methodology is applicable to other sectors with assets generating point source emissions.

The construction of global and country-level CLICs requires three sets of assumptions to be made: (1) the future CCCEs for each asset (for power this is each thermal power generating unit), (2) the carbon budget for each probability threshold for degrees of warming, and (3) the proportion of carbon allocated to each sector globally (and to each sector within each country).

All of the assumptions employed in CLICs are transparent and can, of course, be changed by users based on their beliefs and the sensitivity analysis they want to conduct.

This section provides an overview of the methods used to calculate each of the assumptions.

Box 1: What is Carbon Lock-in?

Carbon lock-in is defined as the tendency for carbon-intensive technologies to persist causing lower carbon alternatives to be 'locked out'.[10] Current reliance on carbon-intensive infrastructure, particularly in the energy sector, represents a significant commitment of emissions. The carbon lock-in stemming from the more carbon-intensive assets significantly increases the cost of transforming carbon-intensive industries to meet the Paris Agreement. Carbon lock-in increases substantially if stringent short-term carbon budgets are not enforced.[11]

[8] Kesicki, F., & Strachan, N. (2011). Marginal abatement cost (MAC) curves: confronting theory and practice. *Environmental Science & Policy*, 14(8), 1195-1204.
[9] Huang, S. K., Luo, K., & Chou, K. (2016). The applicability of marginal abatement cost approach: A comprehensive review. *Journal of Cleaner Production*, 127, 59-71.
[10] Erickson, P., Kartha, S., Lazarus, M., & Tempest, K. (2015). Assessing carbon lock-in. *Environmental Research Letters*, 10(8), 1-7.
[11] Bertram, C., Johnson, N., Luderer, G., Riahi, K., Isaac, M., & Eom, J. (2015). Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technological Forecasting & Social Change*, 90, 62-72.

Estimating Committed Emissions

CCCEs represent the total CO_2 emissions that are estimated to be emitted over the remaining lifetime of an asset, without substituting inputs, upgrading assets, retrofitting assets or refurbishments. CCCEs occur from both direct and indirect emissions[12] and arise from both existing assets and planned or under construction assets.[13]

CLICs are constructed based on the estimated committed emissions for each thermal unit using calculations in line with prior work.[14, 15, 16] The calculations of committed emissions and construction of the CLICs are dependent on access to good asset-level data. The database of power generating units that has been used for to build each CLIC in this report is the most up-to-date version of the Platts World Electric Power Plants Database (Platts, 2017), which provides relatively complete information on power generating assets.[17] This database consists of 90,150 emitting power units spread across 226 countries, of which 82,099 are operating, and 8,051 are either planned or under construction.

The calculation of committed emissions for each emitting asset requires two pieces of information: (1) the estimated future annual emissions and (2) the estimated remaining economic lifetime. The annual CO2 emissions for each power unit ($kgCO_2$/year) are calculated using the following formula:

$$Annual\ Emissions = Heat\ Rate\left(\frac{Btu}{kWh}\right) * Emissions\ Factor\ \left(\frac{kgCO_2}{Btu}\right) * Utilization\ Rate(\frac{kWh}{Year})$$

The annual emissions are calculated by multiplying the heat rate (in Btu/kWh) with the emissions factor (in $kgCO_2$/Btu) of the specific fuel type and the utilisation rate (in kWh/year). The historical data on heat rates and utilisation rates has been taken from the US Energy Information Administration, while the data on fuel type-specific emissions factors has been obtained from the US Environmental Protection Agency.

The expected economic lifetime for all power generating units is assumed to be 40 years. This life expectancy is based on the year the unit first went online. If the remaining life of a unit is greater than or equal to 40 years the future life expectancy is assumed to be five years. Finally, the cumulative committed carbon emissions for each asset is calculated by multiplying the estimated annual emissions with the expected remaining lifespan.

The use of a 40-year expected lifetime is consistent with prior work on committed emissions.[18] However, using a standardised expected lifetime across all global power assets does not take into account differences in lifetimes that are evident across countries. As such, some of the committed emissions calculations may over or underestimate what is actually emitted. Similarly, historical heat rates and utilisation rates may not reflect what happens in the future. This could also result in an over

[12] Carlson, K. M., Curran, L. M., Ratnasari, D., Pittman, A. M., Soares-Filho, B. S., Asner, G. P., . . . Rodrigues, H. O. (2012). Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia. *Proceedings of the National Academy of Sciences*, 109(19), 7559-7564.
[13] Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environmental Research Letters*, 13, 1395-1408.
[14] Davis, S. J., Caldeira, K., & Matthews, H. D. (2010). Future CO_2 Emissions and Climate Change from Existing Energy Infrastructure. *Science*, 329(5997), 1330-1333.
[15] Davis, S. J., & Socolow, R. H. (2014). Commitment accounting of CO_2 emissions. *Environmental Research Letters*, 9(8), 1-9.
[16] Pfeiffer, A., Millar, R., Hepburn, C., & Beinhocker, E. (2016). The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Applied Energy*, 179, 1395-1408.
[17] The version of the CLIC module that will be made available online will use publicly available non-proprietary datasets.
[18] Davis, S. J., Caldeira, K., & Matthews, H. D. (2010). Future CO2 Emissions and Climate Change from Existing Energy Infrastructure. *Science*, 329(5997), 1330-1333.

or underestimation of CCCEs. However, these historical estimates are a standard approach to calculating committed emissions in prior work.[19] The online CLIC module we have developed allows users to change the assumptions that are used in the calculations of committed emissions so that users can define their own expectations.

Estimating Carbon Budgets

To determine whether specific current or proposed assets are compatible with different climate pathways it is necessary to compare the CCCEs with global and country-level carbon budgets (see Box 2). The global carbon budgets used here represent the cumulative CO_2 emissions required to limit global average warming (with greater than 66% probability) to below 1.5°C (200 $GtCO_2$), 2°C (800 $GtCO_2$), and 3°C by 2100 (2200 $GtCO_2$). These carbon budgets are taken from the IPCC Fifth Assessment Report (2014).

This approach allows us to assess the compatibility of assets relative to a global carbon budget. But this approach ignores the presence of countries and therefore the differences between countries. Countries have different levels of ambition and some have already announced their own carbon budgets for certain sectors (for example, the United Kingdom as required as part of the Climate Change Act 2008). To assess the compatibility of assets within a country context, we need to establish country-specific carbon budgets.

A global carbon budget can be allocated to different countries in different ways. There are established climate mitigation burden sharing approaches in the extant literature.[20] The five main approaches for sharing a global carbon budget between countries are as follows: capability (CAP), equal per capita (EPC), greenhouse development rights (GDR), equal cumulative per capita (CPC) and constant emissions ratio (CER). These approaches were developed to assign mitigation burdens to different countries in the context of the international climate negotiations.[21]

Table 2 provides an overview of the five allocation methods. To create country-level carbon budgets for CLIC analysis in this paper we have allocated a weighting to each method. The weightings we have selected are our own assessment of what we consider to be the most likely allocation. The higher weighting for the CER budget reflects our view that the largest emitters are unlikely to accept highly restrictive carbon budgets. A sensitivity analysis based on different allocation methodologies is possible, but we have not done this as part of this paper.

[19] Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environmental Research Letters*, 13, 1395-1408.

[20] Robiou du Pont, Y., Jeffery, M. L., Gütschow, J., Rogelj, J., Christoff, P., & Meinshausen, M. (2016). Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, 7, 38-43.

[21] Robiou du Pont, Y., Jeffery, M. L., Gütschow, J., Rogelj, J., Christoff, P., & Meinshausen, M. (2016). Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, 7, 38-43.

Box 2: What are Carbon Budgets?

A 'carbon budget' is the cumulative quantity of CO_2 emissions that are allowed in order to keep global warming below a certain warming threshold. There is a linear relationship between each marginal tonne of CO_2 released and the resulting warming that occurs.[22] The warming that occurs from CO_2 emissions is also more or less permanent. It is, therefore, possible to determine the cumulative quantity of emissions or 'carbon budget' that will result in various warming scenarios.

Each carbon budget typically has an associated probability (e.g. for this analysis we use IPCC AR5 carbon budgets with greater than 66% probability). These probabilities represent the likelihood of keeping global temperature increases above pre-industrial levels below the given temperature threshold.

Table 2: Allocation of Country-level Budgets

This table presents the allocation approaches that have been used as well as the default weightings that have been applied by default to each allocation to calculate the country-level budgets.

Allocation code	*Allocation name*	*Allocation characteristics*	*Indicative Allocations (2°C budget) [GtCO2e]*					
			Asia	Ref. Econ	Middle East & Africa	OECD	Latin America	Weighting used in the analysis contained in this paper
CAP	Capability	High mitigation for countries with high GDP per capita, i.e. richer countries mitigate first	726	98	172	-226	29	5%
EPC	Equal per capita	Convergence towards equal annual emissions per person, i.e. most populated countries receive largest allocations	364	31	252	91	62	5%
GDR	Greenhouse development rights	High mitigation for countries with high GDP per capita and high historical per capita emissions, i.e. poorer nations with low historical emissions receive largest allocations	728	-24	410	-386	72	5%
CPC	Equal cumulative per capita	High mitigation for countries with high historical per capita emissions, i.e. largest share for nations with low historical emissions	731	-146	647	-546	115	5%
CER	Constant emissions ratio	Maintains current emissions ratios, i.e. largest emitters today receive largest allocations	256	99	53	352	40	80%

[22] Allen, M. R., Frame, D. J., Hutingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., & Meinshausen, N. (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, 458, 1163-1166.

Estimating Sectoral Carbon Budgets

Finally, in order to construct CLICs for specific sectors the country-level budgets need to be subdivided into sectoral budgets. The power sector budget for each country is calculated using a combination of the equity budgets outlined above, and the results from AMPERE, a cross-comparison Integrated Assessment Model (IAM) (see Box 3).[23] These energy models calculate efficient distributions of global mitigation across emitting sectors considering the effects of policy and technology. Mean total emissions are calculated based on the average emissions for each country or region. These emissions trajectories are then used for the allocation of the emissions to the power sector for each country. This method assigns carbon budgets on an 'industry fair-share' basis (see Box 3), allocating emissions to sectors according to cost-effectiveness while also considering political and social constraints. We believe this approach provides a more realistic allocation of budgets to sectors within each country as compared to other methodologies (e.g. an equal allocation-based approach), as it represents a more economically efficient distribution of budgets.

A sector budget for a country is then obtained by taking the percentage sector allocation from the country-level budget. The global sector budget is then calculated as the sum of all the country sector budgets.

It is possible to do a similar exercise for companies (or even investors), i.e. allocating a proportion of country-level carbon budget to companies (or investors). We have not undertaken this analysis in this paper and this is an area of future research.

Box 3: What are IAMs and what is 'industry fair-share'?

Integrated Assessment Models (IAMs) are a complex method of modelling a system by assimilating information from multiple disciplines. IAMs are mathematical computer models that model the behaviour of a system using explicit assumptions. The key strengths of IAMs is the ability to interact many factors simultaneously and to understand the consequences of changing the underlying modelling assumptions.

Initial assessments of the impact of decarbonisation on the power sector were undertaken using IAMs, which modelled the interaction of global energy, climate, and economic systems. One of these IAMs is "Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates" (AMPERE), which was a collaborative project across 22 institutions to assess mitigation pathways for medium and long-term climate targets.

'Industry fair-share' represents an economically efficient distribution of mitigation burdens across emitting sectors. Within AMPERE are nine energy-economy models that assess the effects of policy and technology on the feasibility and cost of the various warming scenarios. The percentage of the country-level carbon budget for the power sector was derived from all 2°C compliant AMPERE scenarios.

[23] Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., . . . Edenhofer, O. (2015). Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, 90, 8-23.

3. Analysis of Southeast Asia

This section applies Carbon Lock-in Curves (CLICs) to analyse the relative risk of fossil fuel power generation assets in Southeast Asia. We use a both global-level and country-level CLICs.

The global-level CLIC plots all current and planned power generating assets around the world providing an understanding of where Southeast Asian assets sit relative to other power stations around the world.

Country-level CLIC plots all current and planned power generating assets that are located in that country. This provides insight into how many assets are incompatible within a country-level carbon budget.

We also undertake a global-level and country-level CLIC analysis of the largest power generation companies in Southeast Asia.

This is not intended to be an exhaustive sensitivity analysis of every Southeast Asian fossil fuel power generation asset, but highlights what is possible and gives some indictive findings that can be interrogated further later on.

Global-level CLIC

Figure 3 presents a global-level CLIC with Southeast Asia assets shown.[24] This CLIC plots all current and planned power generating assets around the world. The width of each bar represents the committed emissions that are expected to occur over the remaining life of the unit.

In this CLIC, the power emitting assets within the Southeast Asian region are coloured orange and any other global power assets are brown. Each power unit in this CLIC is ordered by the plant efficiency (carbon intensity (kg/MWh), which is reported on the y-axis. The three vertical lines represent the global carbon budget that has been allocated to the global power sector. Power generating units that fall to the left of these budget lines are *compatible* with that budget, whereas assets that fall to the right of these budget lines are *incompatible* with the carbon budget allocation for that warming scenario and are likely to face a higher risk of stranding.

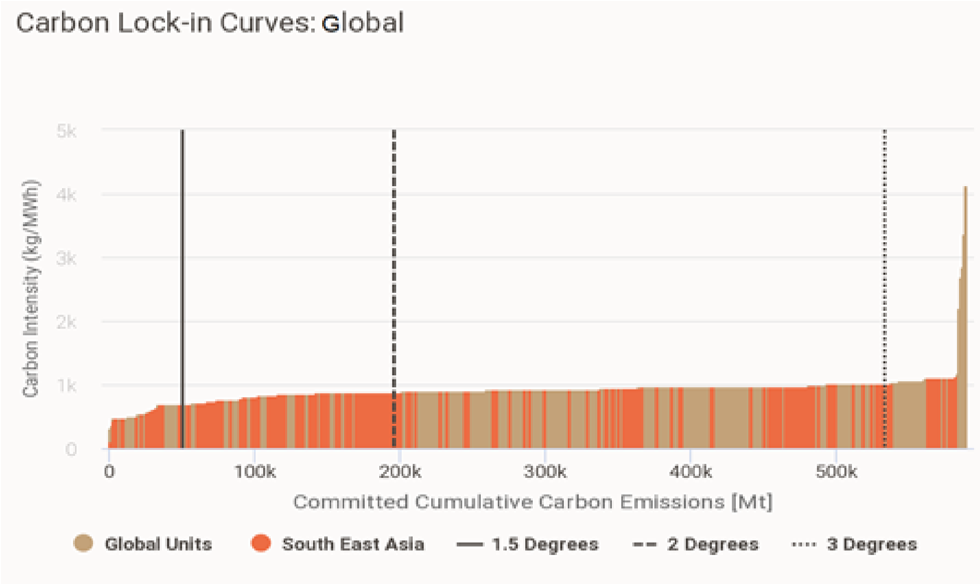
Not all units are easily visible on these global-level CLICs without the ability to zoom since over 90,000 individual assets are being plotted. As a result, assets with small CCCEs will not be discernible on this plot. To provide a better understanding of the stranding risk for power generating assets in the Southeast Asia region, Table 3 provides some statistics for the number of emitting assets and where they fall relative to the global budgets.

Table 3 reports the number of carbon emitting power units by country relative to the global carbon budgets. The majority of units (62.2%) in Southeast Asia are compatible with the 2°C budget but are incompatible with a 1.5°C global carbon budget.

[24] The Southeast Asian countries in this report include: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste and Vietnam.

Figure 3: Global-level Carbon Lock-in Curve

This figure plots a Global-level CLIC. All current and planned Southeast Asia power assets are in orange and other global power assets are in brown.



N.B. To improve rendering, assets with the same efficiency are aggregated and plotted as one. Therefore, each bar may represent the CCCEs of many individual assets. Using this rendering any bar with at least one Southeast Asian asset is coloured orange. Power generating assets are ordered by asset efficiency (carbon intensity (kg/MWh). The vertical lines represent the global emissions budget allocated to the global power sector for each warming scenario.

Table 3: Current and Planned Emitting Units Position Relative to the Global Budgets by Country

This table reports the emitting units position relative to the global budget for the countries in Southeast Asia. The number and percentage of units that are incompatible with each carbon budget are reported for each Southeast Asian country.

	Total Emitting Units			Units Incompatible with 1.5°C Budget	Units Incompatible with 1.5°C - 2°C Budget	Units Incompatible with 2°C - 3°C Budget
Country	Current	Planned	Total			
Brunei	55	7	62	88.7% (55)	45.2% (28)	0.0% (0)
Cambodia	155	13	168	94.6% (159)	10.1% (17)	1.8% (3)
Indonesia	2478	287	2765	89.0% (2460)	26.4% (730)	3.5% (97)
Laos	61	3	64	98.4% (63)	7.8% (5)	0.0% (0)
Malaysia	803	54	857	88.8% (761)	14.2% (122)	2.5% (21)
Myanmar	100	34	134	65.7% (88)	35.8% (48)	0.7% (1)
Philippines	1303	195	1498	83.3% (1248)	13.4% (200)	3.8% (57)
Singapore	149	5	154	81.2% (125)	33.8% (52)	7.8% (12)
Thailand	541	130	671	52.8% (354)	14.3% (96)	1.9% (13)
Timor-Leste	54	22	76	96.1% (73)	0.0% (0)	0.0% (0)
Vietnam	198	116	314	86.9% (273)	50.0% (157)	19.7% (62)
Total	5897	866	6763	83.7% (5659)	21.5% (1455)	3.9% (266)

Vietnam has one of the highest proportions of non-emitting power units (71.9%), also has the highest percentage of emitting units incompatible with the 2°C (50%) and the 3°C budgets (19.7%). The Philippines has the second largest total of emitting units and has one of the highest proportions of units that are compatible with the 2°C budget (86.7%). Thailand has the highest proportion of units (47.2%) that are compatible with the 1.5°C global carbon budget.

The CLICs presented in this report are all ranked by carbon intensity. However, this ordering method ignores other valid decarbonisation concerns including marginal costs, geographic equity, replacement costs, and biases against specific fuel-types. Furthermore, it should be noted that planned or under-construction plants will have lower carbon intensity, making these investments appear less risky. However, the planned and under-construction assets will also likely have the highest remaining expected committed emissions since their life expectancy is assumed to be 40 years.

To get around these concerns alternative ranking methods can also be applied. Currently the only alternative ordering approach we have programmed into our tool (see subsequent section) is by plant age. In future we will introduce the ability to order assets based on other methods, including: marginal cost, levelised cost of electricity, and a weighted index of several variables.

To provide greater insight into the risks within Southeast Asia a company-level analysis was also conducted based on global-level carbon budgets. Table 4 presents the number of emitting assets and where they fall relative to the global budgets for the ten largest power utilities (based on capacity) in Southeast Asia. These ten power utilities constitute approximately 20% of the units in the region.

According to our analysis, the majority of power utilities in Southeast Asia have between 20% and 45% by number of units and 20% and 82% by capacity incompatible with the 2°C global carbon budget. The power utility with the highest proportion of units that are compatible with the 2°C budget (91.9%) is Malaysia-based Sarawak Energy Bhd Group.

Table 4: Top 10 Power Utilities in Southeast Asia Relative to the Global Power Sector Carbon Budget

This table reports the current and planned emitting units position relative to the global budget for the ten largest power utilities in Southeast Asia. The number and percentage of units that are incompatible with each carbon budget are reported for each power utility. The largest utilities are determined on the total capacity (MW/hr) across all units owned by that provider. The providers are presented in order based on their total capacity.

	Emitting Units			Units Incompatible with 1.5°C Budget	Units Incompatible with 1.5°C - 2°C Budget	Units Incompatible with 2°C - 3°C Budget
Country	Current	Planned	Total			
EGAT	79	15	94	88.3% (83)	45.7% (43)	2.1% (2)
PT PLN Persero	503	69	572	89.3% (511)	29.2% (167)	5.4% (31)
PetroVietnam Power Corp	10	14	24	95.8% (23)	50.0% (12)	0.0% (0)
Electricity of Vietnam	6	11	17	70.6% (12)	35.3% (6)	11.8% (2)
Ministry of Electric Power (MM)	41	2	43	90.7% (39)	44.2% (19)	0.0% (0)
Tenaga Nasional Berhad	83	2	85	96.5% (82)	22.4% (19)	7.1% (6)
PT Indonesia Power	73	17	90	78.9% (71)	38.9% (35)	6.7% (6)
PT Pembangkitan Jawa-Bali	47	5	52	90.4% (47)	15.4% (8)	3.8% (2)
EVN Genco 3	27	3	30	100.0% (30)	53.3% (16)	43.3% (13)
Sarawak Energy Berhad Group	303	6	309	100.0% (309)	8.1% (25)	1.0% (3)
Total	1172	144	1316	91.7% (1207)	26.6% (350)	4.9% (65)

Country-level CLICs

A country-level CLIC plots all current and planned power generating assets that are located in a particular country. Country-level CLICs provide a useful way to assess stranding risk based on country-specific decarbonisation plans, such as Nationally Determined Contributions (NDCs).

This section presents country-level CLICs for the three largest power utilities (Electricity Generating Authority Thailand, PT PLN Persero, and PetroVietnam Power Corp) in Southeast Asia. These CLICs are presented in Figures 4 to 6.
Figure 4 is a Thailand CLIC where Electricity Generating Authority Thailand (EGAT) power generating units are coloured orange and other Thai power assets are coloured brown. Similarly, Figure 5 is an Indonesian CLIC where PT PLN Persero assets are coloured orange and other Indonesian power assets are brown. Finally, Figure 6 presents the Vietnamese CLIC. The PetroVietnam Power Corp assets are coloured orange and other power assets are coloured brown. A summary of these CLICs with the number and proportion of units relative to the country-level budgets is reported in Table 5. Over 85% of power generating units for the three power utilities are incompatible with the 2°C country-level budgets.

For each of these country-level CLICs there is a higher proportion of assets incompatible with a given carbon budget relative to the global-level CLIC. The country carbon budget allocations we have used in this analysis are weighted more towards maintaining current emission ratios (i.e. largest emitters today receive the largest proportions) (see Section 2 for more details). As Thailand, Indonesia, and Vietnam have a small current emission ratio they receive a relatively small allocation of the global carbon budgets in the future, which results in a higher proportion of assets being incompatible with each country-level carbon budget for the power sector. The global-level CLICs analysis ignores country-level carbon budget allocations and so side-steps this issue.

Figure 4: Thailand Carbon Lock-in Curve for Electricity Generating Authority Thailand (EGAT)
This figure plots Thailand country-level Carbon Lock-in Curve (CLIC) for Electricity Generating Authority (EGAT). All current and planned EGAT power assets are coloured orange and other Thai power assets are coloured brown. The vertical lines represent the Thai budget allocated to the Thai power sector for each warming scenario.

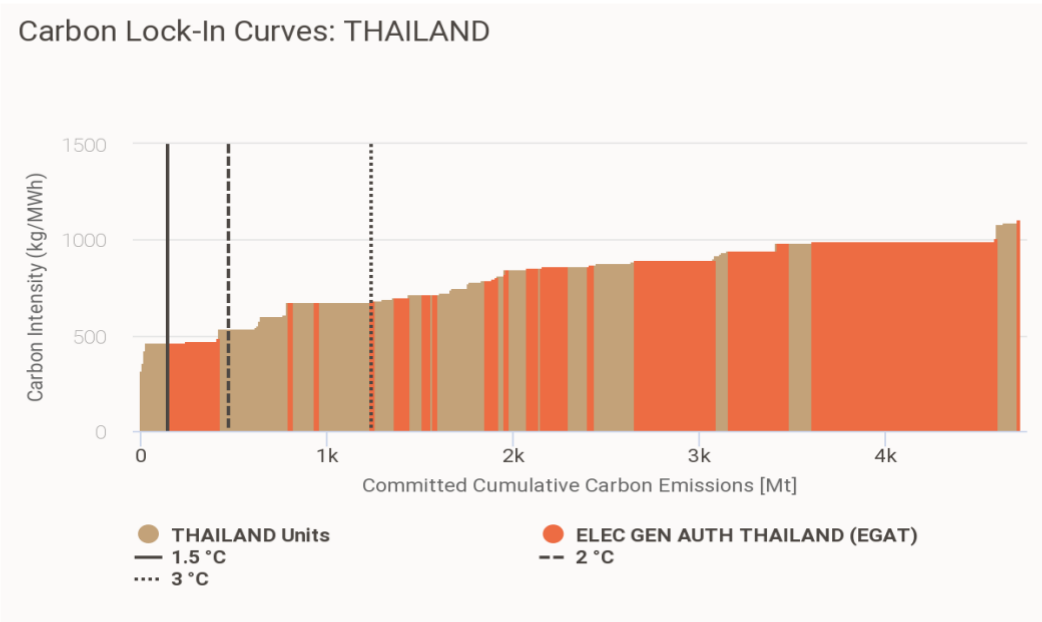


Figure 5: Indonesia Carbon Lock-in Curve for PT PLN Persero

This figure plots Indonesia country-level Carbon Lock-in Curve (CLIC) for PT PLN Persero. All current and planned PT PLN Persero power assets are coloured orange and other Indonesian power assets are coloured brown. The vertical lines represent the Indonesian budget allocated to the Indonesian power sector for each warming scenario.

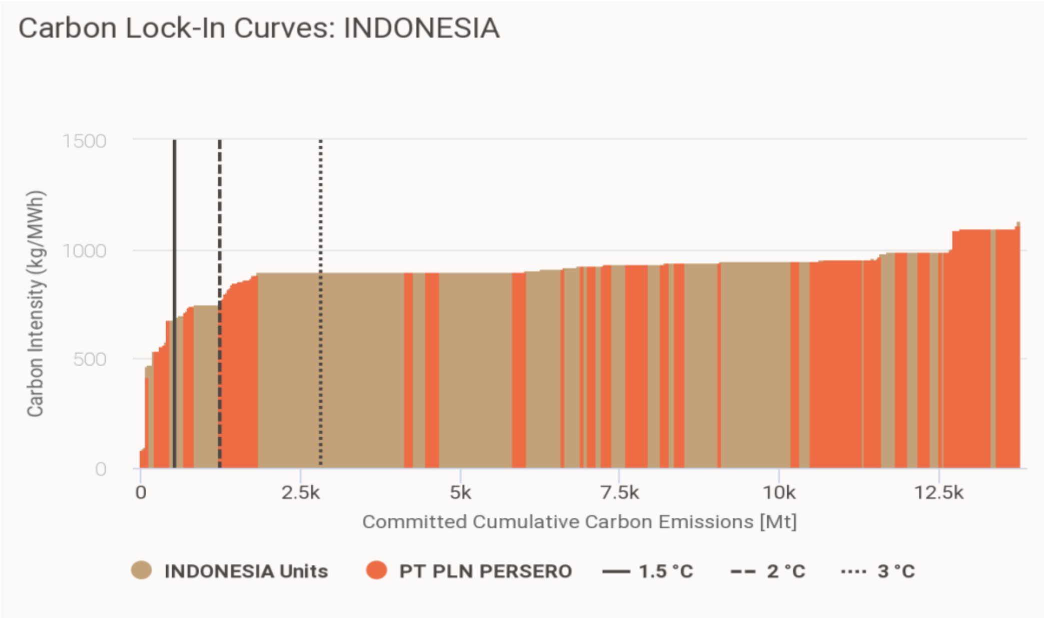


Figure 6: Vietnam Carbon Lock-in Curve for PetroVietnam Power Corp

This figure plots Vietnam country-level Carbon Lock-in Curve (CLIC) for PetroVietnam Power Corp. All current and planned EGAT power assets are coloured orange and other Vietnamese power assets are coloured brown. The vertical lines represent the Vietnamese budget allocated to the Vietnamese power sector for each warming scenario.

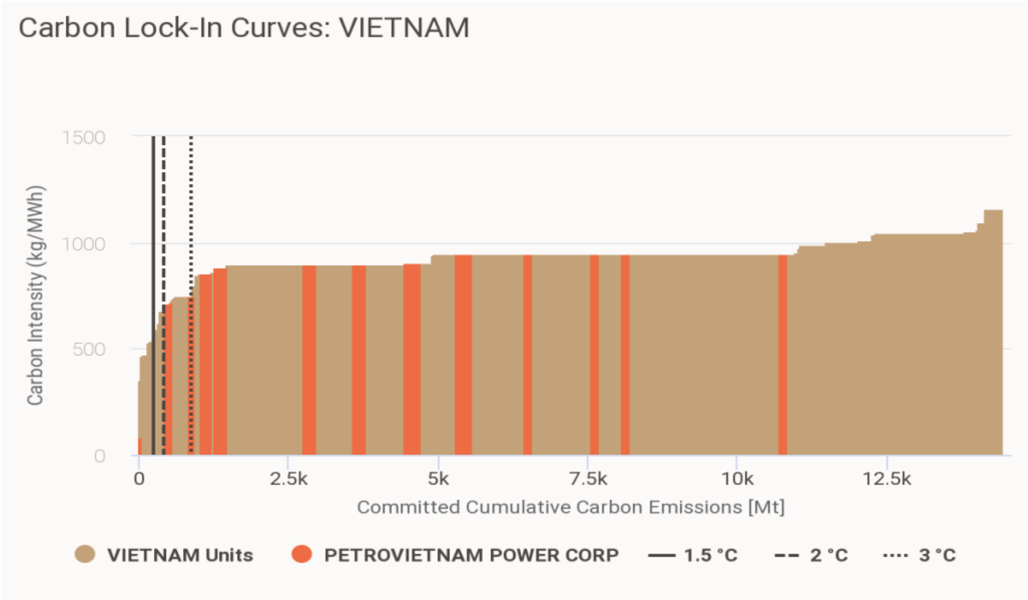


Table 5: Current and Planned Emitting Units Position Relative to the Country Budgets for the Three Largest Power Utilities in Southeast Asia

This table report the current and planned emitting units position relative to the country budget for the three largest power utilities in Southeast Asia. The number and percentage of units that are incompatible with each carbon budget are reported for each power utility.

Company	Emitting Units			Units Incompatible with 1.5°C Budget	Units Incompatible with 1.5°C - 2°C Budget	Units Incompatible with 2°C - 3°C Budget
	Current	Planned	Total			
Panel A: Electricity Generating Authority Thailand (EGAT) Units Relative to Thailand Budgets						
EGAT	79	15	94	98.9% (93)	90.4% (85)	90.4% (76)
Panel B: PT PLN Pesero Units Relative to Indonesia Budgets						
PT PLN Persero	503	69	572	89.3% (511)	87.8% (502)	22.6% (129)
Panel C: PetroVietnam Power Corp Units Relative to Vietnam Budgets						
PetroVietnam Power Corp	10	14	24	95.8% (23)	95.8% (23)	58.3% (14)

There are a several limitations to the CLIC analyses that should be noted. The cumulative committed carbon emissions calculations are based on historical rather than forward looking factors. As such, the CCCEs may not accurately reflect the future emissions from power generating assets. Certain factors are not available on a country basis (e.g. utilisation rates) so some of the calculations will likely over or under estimate the committed emissions. However, there is a significant amount of flexibility built into the production of CLICs, so users are able to modify any of these underlying assumptions. Finally, since the information on power assets are sourced from databases that are only periodically updated, there is a delay between when a planned asset or retirement of an asset is initially announced and when it is first accounted for in the CLICs. However, the use of remote sensing technologies affords a way to augment existing asset-level databases and provide more timely updates to changes in the operation of assets.[25]

[25] Caldecott, B., Kruitwagen, L., McCarten, M., Zhou, X., Lunsford, D., Marchand, O., . . . Bohn, N. (2018). Climate risk analysis from space: Remote sensing, machine learning, and the future of measuring climate-related risk.

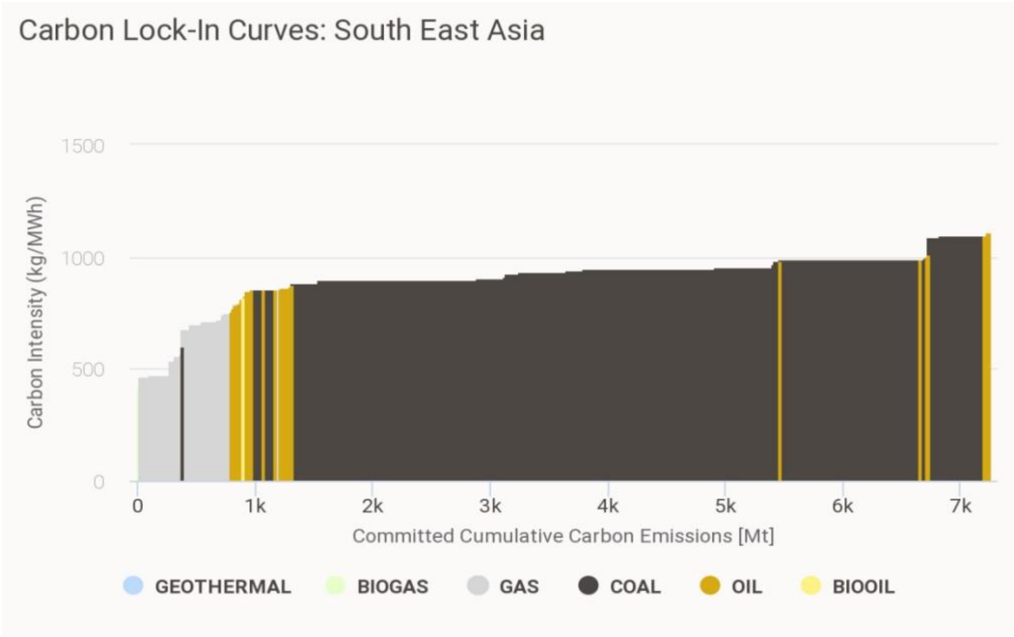
4. RIOT CLICs Module

The Risk Impact Opportunities Tool (RIOT) is an online platform developed by the Oxford Sustainable Finance Programme to provide analyses of environmental risks, impacts, and opportunities. The Carbon Lock-in Curves (CLICs) module is one of the tools that is available in RIOT. This provides an interactive environment with the flexibility to build CLICs across geographical areas and using different metrics.

The CLIC module enables users to calibrate the carbon budgets across three dimensions: (1) using the default allocated percentages on the weights used to initially calculate them, (2) customising the weights themselves, (3) manually positioning the warming threshold and overriding the weights completely, while maintaining the ability to set exactly the associated numerical values of the thresholds.

Among other interactive controls, users can also extract and save locally any generated and customised CLIC for further investigation/sharing/processing purposes. Portfolios are also user-profile based, therefore any calibration and filtering previously done to form a portfolio with executive structure will be stored and can be used in future analysis.

Figure 7: Carbon Lock-in Curve by Generation Type
This CLIC shows the types of generating technologies as allocated in Southeast Asia with a colour scheme which differentiates the type of technology used.



The main features of the CLICs module include the ability to:

- Change the ordering variable between carbon intensity, plant age (oldest to newest and newest to oldest), marginal cost, levelised cost of electricity (LCOE), weighted index (the last three to be implemented).
- Sort by size of committed emissions.
- View individual country-level CLICs.

- View country portfolio in global-level CLICs.
- View individual company CLICs (pending calculations/data for warming threshold adjustment).
- View company portfolio in country-level CLICs.
- View company portfolio in global-level CLICs.
- View any portfolio against global or any country-level CLICs.
- Toggle between generation technologies and portfolio assets.
- Use colour overlays to see both – i.e. technologies, and whether assets are in a selected portfolio or not.
- Click on individual assets on chart and get to unit/asset-level page.
- Export any generated CLICs as a picture file (e.g. jpg, png).
- Easily select/self-define any warming threshold to each 0.1 (vertical line), with defaults set at 1.5°C, 2°C, and 3°C. Users can also apply zero thresholds or thresholds already satisfied (for instance the 3°C) with corresponding display legend notes.
- Zoom in on parts of CLICs to see individual assets more clearly.
- Easily select/self-define any power sector carbon budget for global-level
- CLICs or any country or company CLICs, using five defaults (CAP, EPC, GDR, CPC, CER), and change the weightings applied to these budgets. Users can also define their own carbon budget for a country and globally for the sector. (All this can be done relatively easily either by directly setting the values for the thresholds, setting the weights indirectly affecting the thresholds, or by drag-and-drop action of the vertical lines which correspond to the warming thresholds. Any changes can be easily reset to the default values.)
- Click through to an individual generating units page, which includes detailed unit level information, values for all the risk hypotheses and a traffic-light rating for each of those to indicate whether they are at risk or not. The traffic-light rating is generated by comparing the individual risk metrics to the thresholds, which can either be a default value or be defined by the user, for each of the risk hypotheses.
- Show multiple companies on a CLIC, either against country or global scale and see them independently on the legend, to facilitate cross company comparisons.
- See from the company drop-down list which companies belong to the portfolio and which don't, so companies outside the portfolio, but located in the same country, can also be projected on the CLIC.
- Include/exclude planned infrastructure projects (assets).

5. Conclusion

Committed emissions are the cumulative carbon emissions that an asset is expected to emit over its remaining lifetime without substituting inputs or upgrading, retrofitting, refurbishing, or replacing the asset. This concept provides the ability to estimate future carbon 'lock-in' and when the current and planned stock of assets will be incompatible with carbon budgets.

Carbon Lock-in Curves (CLICs) create a way to order, optimise and visually represent portfolios of assets based on their committed emissions. This report presented an overview of how CLICs can be used to analyse the compatibility of power generating assets with different global and country-level carbon budgets by ordering assets according to carbon intensity.

A CLIC plots the CCCE for each asset ordered by a particular ranking method (e.g. plant efficiency, marginal cost, plant age). The width of each bar represents the CCCEs and the ordering variable is plotted on the y-axis. The carbon budgets are then plotted as a vertical line. Assets that are on the left of these budget lines are compatible with that carbon budget, whereas assets that fall to the right of these budget lines are in breach of the carbon budget allocation for that warming scenario.

This report uses CLICs to analyse the compatibility of power generating assets in Southeast Asia with global and country-level carbon budgets. Through our CLICs analysis for the Southeast Asian power sector we have found that:

- The vast majority (83.7%) of Southeast Asia's current and planned fossil fuel generation assets are incompatible with a Paris Agreement aligned carbon budget (1.5°C budget or 200 $GtCO_2$).
- 87.7% of Southeast Asia's current fossil fuel generation assets are incompatible with 1.5°C, 17.8% are incompatible with 2°C, and 2.3% with 3°C. 56.2% of Southeast Asia's planned fossil fuel generation assets are incompatible with 1.5°C, 46.5% are incompatible with 2°C, and 14.8% with 3°C. This highlights the scale of premature closures required to meet climate change objectives and the potential for significant asset stranding in the future.
- While many of the current and planned assets by capacity are coal (57.4%) and oil (7.8%), a significant proportion of gas plants are planned or operating (31.2%) and many of these gas assets are incompatible with different carbon budgets: 64.6% in 1.5°C, 11.0% in 2°C, and 0.3% in 3°C. This highlights how new gas assets, which are often pushed as a route to meeting climate mitigation objectives, are not necessarily a solution.
- Vietnam has the largest fleet of the region's fossil fuel generation assets. 86.9% of Vietnam's current and planned fossil fuel generation assets are incompatible with 1.5°C, 50% are incompatible with 2°C, and 19.7% the 3°C. All of Vietnam's current and planned gas plants, which account for 15.9% of assets by generation capacity, are incompatible with 1.5°C.
- We analysed the ten largest power utilities in Southeast Asia by capacity (Electricity Generating Authority Thailand (EGAT), PT PLN Persero, PetroVietnam Power Corp, Electricity of Vietnam, Ministry of Electric Power (MM), Tenaga Nasional Berhad (TNB), PT Indonesia Power, PT Pembangkitan Jawa-Bali, EVN Genco 3, and Sarawak Energy Berhad Group) and found that on average 90.7% of their current and planned fossil fuel generation assets are incompatible with 1.5°C, 26.6% are incompatible with 2°C, and 4.9% the 3°C.

The current RIOT CLIC module allows users to generate global and country-level CLICs for any portfolio of assets or subset of assets. Users can also plot numerous portfolios simultaneously providing an opportunity for comparative analyses to be undertaken across portfolios. Furthermore, it is also possible to zoom in on the curves to see where exactly units fall on the curve. The assumptions (e.g. budget assumptions, plant retirement ages) outlined in this report can also be adjusted by users to fit their own expectations. Forthcoming work on the CLIC module includes allowing users to add hypothetical assets, which will provide investors and companies with the ability to assess the risk associated with planned projects and providing alternative ranking methods. Planned future analyses include: adding other carbon-intensive sectors (e.g. steel and cement), incorporating national determined contributions (NDCs), investigating the impact of different transition scenarios on the value of outstanding loans, and assessing other stock-flow pollution problems (e.g. air quality and water quality).

Overall, the CLIC is an incredibly versatile tool with the flexibility to assess the risk associated with any portfolio of assets. The level of flexibility and the insight provided by CLICs present policymakers, financial institutions, governments, regulators, and civil society at large with an improved ability to make key decisions to ensure compatibility with the carbon budgets associated with different climate pathways.

Oxford Sustainable Finance Programme
Smith School of Enterprise and the Environment
University of Oxford
South Parks Road
Oxford, OX1 3QY
United Kingdom

E enquiries@smithschool.ox.ac.uk
T +44 (0)1865 614942
F +44 (0)1865 614960
www.smithschool.ox.ac.uk/research/stranded-assets/