National Bureau of Economic Research

1050 Massachusetts Avenue
Cambridge, MA 02138
United States

10th September 2026

Cover Letter

Workshop on Development Economics and Networks for Early-Career Researchers

Dear Workshop Organisers,

With this letter, I apply to the Workshop on Development Economics and Networks for Early-Career Researchers organised by NBER.

Attached you will find my personal statement motivating my application, my CV (including a list of all current and completed PhD courses), and the working paper to present at the workshop.

The referee for the application is Prof Rainer Kattel, University College London: r.kattel@ucl.ac.uk
University College London, 11 Montague street, London, WC1B 5BP, United Kingdom.

Thank you for considering my application, and I look forward to meeting you in Cambridge, MA.

Sincerely,

Dr Giovanni Tagliani

University College London

Institute for Innovation and Public Purpose

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Website: https://giovannitagliani.github.io

Personal Statement - NBER Workshop on Development Economics and Networks

I am an economist working at the intersection of development, industrial, and environmental economics, with a keen interest in the economics of innovation. My academic journey includes a BSc in Economics (Uni. of Bologna), an MPhil in Development Studies (Uni. of Cambridge), an MSc in Economics with a curriculum in green economy (Uni. of Ferrara), and two PhDs: the first (Uni. of Ferrara & Uni. of Parma) linking circularity in input use to economic development in the Thai bioeconomy; the second, which I complete in November 2026 at the UCL Institute for Innovation and Public Purpose, on the repurposing of capabilities in national oil companies. I am currently a Research Fellow at UCL, working with Prof Cecilia Rikap on digital industrial policy and the political economy of artificial intelligence.

What first got me interested in economics was its ability to provide nuanced answers to questions of national development:

Which emerging sectors should a developing country invest in?
How do productive capabilities travel between firms, sectors, and countries?
Which industrial and innovation policies make that diffusion work for people and planet?

Networks are useful tools to answer them. In my research, I try to see technologies, firms, sectors, and institutions as nodes in evolving structures: I build co-classification networks from patent data, product spaces from trade data, and citation networks, using tools such as economic complexity measures, centrality analysis, and automated text analysis. In my current postdoctoral work I have applied the same approach to a corpus of over 20,000 publications on AI regulation, mapping which actors and institutions shape the framings that reach policy. My training in these methods comes from the Oxford Summer School in Economic Networks, the UNU-MERIT course on Economic Fitness and Complexity, and a Winter School in Complexity Science.

The working paper I would bring to the workshop, *"Crossing the river by feeling the stones: Green Technological Transformation in National Oil Companies"*, is an empirical network paper on a development question. Fifty-one of the world's sixty-eight national oil companies are in middle-income countries, where they usually are the largest firm and the deepest pool of technological capabilities in the economy. Their transformation in the context of climate change is a structural change question. I build technology and product spaces for Thailand from patent and trade data, recovering firm-level portfolios through a new entity-linking procedure, and locate the Thai NOC within them. The firm patents in codes where the country holds no comparative advantage, bridging the basic technologies Thailand is strong in to the advanced biochemistry it is not. Fifty interviews helped me to understand why this is not the related diversification that complexity tools prescribe: the firm targeted distant, high-value activities first, then worked back through the network to find the stepping stones.

My motivation for attending is, first, methodological. My use of networks has grown out of innovation studies and economic complexity rather than out of the econometrics of network data. The networks I work with are themselves estimated, from patent co-classification and trade co-occurrence, and my claims about distance, bridging and diffusion depend on that construction. Sampling, measurement error, and inference when units are not independent are problems I meet in my own data. A day of lectures from the researchers who have set that frontier, and the chance to have this paper read by them and by fellow participants, would considerably improve my empirical work.

The second reason is the community. I have worked between academia and policy institutions (e.g. the Natural Resource Governance Institute, Brazil's Ministry of Management and Innovation, and Johns Hopkins' Net Zero Industrial Policy Lab), and the most useful criticism I have received has always come from small settings of the kind this workshop proposes. As I bring my PhD to a close, broadening my connections with the development economics community is my priority, and I would be glad to contribute with an industrial and innovation policy perspective to the exchange.

Dr Giovanni Tagliani,
University College London

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EDUCATION

UNIVERSITY COLLEGE LONDON October 2023 – November 2026

PhD in Economics, curriculum in Economic Policy and Political Economy

Thesis title: "Drilling for Sustainability: Repurposing Capabilities in National Oil Companies towards Sustainability Transitions in the Age of Climate Change", Supervisors Prof Rainer Kattel and Prof Antonio Andreoni

PhD Courses: Longitudinal Data Analysis, MATLAB, Applied Regression Analysis, Mendeley, IDEAs Workshop (Teaching with Digital Tools), Scripting Stata Graphs.

UNIVERSITY OF FERRARA & UNIVERSITY OF PARMA September 2020 – April 2024

PhD in Economics, curriculum in Economics and Management of Innovation and Sustainability

Thesis Title "Economic Development through Circularity: A Theory of Residuals in Production and the Case of the Thai Bioeconomy Sector", Supervisor Prof Susanna Mancinelli

PhD Courses: Instrumental Variables, Mixed Methods, Theories of Structural Dynamics, Game Theory, Research Methods, History of Italian Industry, Big Data Uses for Economic Analysis with Applications to Patents, Data Search, Advanced IT Course, Entrepreneurship and Innovation, Intellectual Property and Patents, Behavioural Economics on Local versus Global Public Goods, Qualitative Interviews, RCTs, Scientifical & Technical Writing, Thematic Analysis, Bibliometric Methods and Automated Text Mining for Systematic Literature Reviews.

UNIVERSITY OF FERRARA September 2019 – September 2021

MSc in Economics (1st Class Honours), curriculum in green economy and sustainability

Thesis Title "Paradigms, Trends and Perspectives on the Ecological Transition: The Role of Eco-Innovation and Green Finance", Supervisor Prof Susanna Mancinelli

Methods Courses: Statistics for Economics and Business, Applied Econometrics.

UNIVERSITY OF CAMBRIDGE September 2018 – July 2019

MPhil in Development Studies

Dissertation Title "State-owned Enterprises: The case of IRI and Historical Comparisons", Supervisor Prof Ha-Joon Chang

UNIVERSITY OF BOLOGNA September 2015 – July 2018

BSc in Economics (1st Class Honours)

Dissertation Title "The Japanese "In-House" Banking System: The Speculative Bubble Years, 1986 to 1991", Supervisor Prof Giuseppe Lusignani

Methods Courses: Maths, Maths Applied to Economics, Mathematical Models, Statistics, Applied Econometrics.

PROFESSIONAL EXPERIENCE

UNIVERSITY COLLEGE LONDON

Research Fellow November 2025 – present

Working as a Postdoctoral Researcher with Prof Cecilia Rikap. Project "AI for whom and for what?". First author of a paper that focuses on Digital Industrial Policy and AI Regulation. This paper includes a bibliometric analysis of over 20k publications on AI regulation (centrality, citations, and BERTopic analysis) to identify key regulation framings and networks of actors and institutions. It also explores the content of the EU AI Act through an amendment tracking exercise over the 7 versions of the Act. The research unveils the extent and ways in which Big Tech controls AI regulation framings through social sciences research on AI, and how the framings that they promote are integrated onto policy. The research also provides a critique of the EU regulatory approach to AI and argues for the adoption of an industrial policy approach. The research has already been presented at Digital Futures "Climate-Aligned AI" (KTH Royal Institute of Technology) and at the Society Advancement Socio-Economics (SASE).

JOHNS HOPKINS UNIVERSITY

Consultant October 2025 – present

Consultant for JHU's Net Zero Industrial Policy Lab. Developing the research strategy, leading and managing a team of four people in a project on alignment between climate policy and industrial strategy for countries with state-owned oil and gas companies. The research includes a mixed-methods approach: comparative advantage is calculated based on trade data and tracked onto industrial strategy and firm capabilities, and interviews with energy ministries and company executives help inform the analysis.

NATURAL RESOURCE GOVERNANCE INSTITUTE

Energy Sector Consultant July 2024 – August 2025

Building quantitative analysis for internal and external use of oil and gas firms and energy ministries, with particular focus on production and reserves forecasts, fiscal, political and energy security risks for oil- and gas-dependent nations, and on financial and operational risks from climate change in National Oil Companies (NOCs). Researching and writing an article of the experience of DONG-Orsted in the transition from oil&gas to offshore wind. Heading the drafting of sixteen factsheets and company profiles of NOCs comprehensive of qualitative and quantitative analyses. Writing a report covering policy-oriented research on the governance,

political economy, and technological transition of NOCs. Providing country teams with reviewing, consultancy, and research advice on reports, articles, and policy initiatives. Completed a project on the coordination of SOEs in Mexico between the NOC-Pemex, the energy SOE-CFE, and the new lithium mining SOE LitioMx with the goals of furthering industrial strategy and the green transition.

UNIVERSITY COLLEGE LONDON

Policy Researcher February 2024 – January 2025

Building policy-oriented research on State-Owned Enterprises in a collaborative project together with the Brazilian Ministry of Management and Innovation in Public Services of Brazil (Ministério da Gestão e da Inovação em Serviços Públicos - MGI) with the objective of aligning firm operations and practices in major SOEs, such as Petrobras and BNDES, with the overarching government vision in the Climate Plan and industrial strategy (Nova Industria Brasil), while maintaining profitability to abide by the state's fiscal constraints. Liaised and interviewed SOE executives and high-level government officials across Ministries and the Presidency.

CHULALONGKORN UNIVERSITY

Researcher October 2021 – December 2022

Working for the NRCT's (National Research Council of Thailand) research projects 93/64 and 111/65 on "Development Strategies in the Ecological Transition: Structural Trajectories in Green Economy Sectors".

UNIVERSITY COLLEGE LONDON

Research Assistant November 2020 – June 2021

Assisting Prof. Andreoni in the research and presentation for the "High-Level Workshop on the Just Transition", UCL IIPP (Institute for Innovation and Public Purpose)

AWARE

Research Collaborator November 2020 – June 2021

Collaborating with the Think-Tank AWARE on their research on Eco-innovation Policies in France

TEACHING EXPERIENCE

UNIVERSITY COLLEGE LONDON & LONDON SCHOOL OF ECONOMICS AND POLITICAL SCIENCE

Teaching Certifications and Training Courses July 2023 – present

Obtained the Advance Higher Education Fellowship: "Associate Fellow".
Successfully completed UCL's teaching training, and over 10 courses related to different aspects of teaching: Rubrics and Assessment, ARENA Gateway, EDI-Equality Diversity Inclusion, Unconscious Bias, Safety, Digital Tools and "IDEAs" teaching ["Inspirations for Digital Engagement Activities"], Preparing AHE Application and Professional Standards Framework, LSE training course on short modules, and UCL's module design method "ABC Learning Design", "Generative AI: developing your learning practice".

LONDON SCHOOL OF ECONOMICS AND POLITICAL SCIENCE

Class Teacher July 2026 – August 2026

Class Teacher for the course "Industrial Policy: Leading the Green and Digital Transitions" at the LSE. Design class material, organise classes, teach, marking, student mentorship.

UNIVERSITY COLLEGE LONDON

Post-Graduate Teaching Assistant September 2025 – December 2025

Post-Graduate Teaching Assistant for the MPA (Master of Public Administration) - Autumn term module in Economics of Innovation. The module "Economics of Innovation and Public Purpose" is headed by Prof Cecilia Rikap.

LONDON SCHOOL OF ECONOMICS AND POLITICAL SCIENCE

Class Teacher June 2025 – July 2025

Class Teacher (54 teaching hours) for the course "Industrial Policy: Leading the Green and Digital Transitions" at the LSE. Design class material, organise classes, teach, marking, student mentorship.

UNIVERSITY COLLEGE LONDON

Graduate Thesis Supervisor April 2025 – September 2025

Main supervisor for a Master Thesis for the MPA (Master of Public Administration) program at the Institute for Innovation and Public Purpose, University College London. Marker for two master theses.

UNIVERSITY COLLEGE LONDON

Post-Graduate Teaching Assistant September 2024 – December 2024

Post-Graduate Teaching Assistant for the MPA (Master of Public Administration) - Autumn term module in Economics of Innovation. The module "Economics of Innovation and Public Purpose" is headed by Prof Cecilia Rikap. The PGTA position also assists in the seminars and other teaching duties other UCL lecturers involved in the module, including Prof Mariana Mazzucato and Prof Carlota Perez.

UNIVERSITY COLLEGE LONDON

Post-Graduate Teaching Assistant January 2024 – April 2024

Assist Prof. Josh Ryan-Collins in the UCL module "Rethinking Capitalism", an Economics course with a mixed cohort of students which introduces the subject and grand economic challenges to public policy students from a range of different economics perspectives (including Neoclassical, post-Keynesian, ecological, evolutionary, weberian and other institutional economics approaches).

UNIVERSITY OF FERRARA

Subject Expert and Teaching Assistant September 2022 – July 2023

Subject Expert (Cultore della Materia) and TA in "Behavioural Economics for the Environment" (TA to Prof. Mancinelli).

RETHINKING ECONOMICS & CSEP

Co-convenor and Invited Lecturer 2019 – 2020

"Paper 0" by the Cambridge Society for Economic Pluralism (CSEP), invited lectures by RE Italia

GRANTS, SCHOLARSHIPS, AWARDS

ECR Teaching Excellence Award (Honorable Mention), The Bartlett - UCL, ~150 USD (Teaching Excellence)	2026
"Class Teacher Award" for "Teaching Excellence", London School of Economics (LSE), ~300 USD (Teaching Excellence)	2025
"Innovation and Knowledge" Award, Italian Cultural Association-Embassy of Italy, ~5k USD (Academic Excellence)	2025
Institute for New Economic Thinking-YSI, G20 Grant, ~1k USD (Young Scholars Initiative for the G20)	2024
University College London, The Bartlett, External Training Fund, ~1.3k USD (Research Skills)	2024
Ministry of University and Research of Italy, Full PhD Scholarship, ~55k USD (Academic Excellence)	2020-2023
University of Ferrara, International Mobility Grant, ~2.5k USD (Academic Excellence)	2022
Cambridge Trust, University of Cambridge, European Scholarship, ~13k USD (Academic Excellence)	2018-2019
Chamber of Commerce, Ferrara, Francesco Viviani Award (Educational Excellence)	2014

CONFERENCES AND SEMINARS *(Paper presentations, Invited speeches, Research training)*

BCS - The Chartered Institute for IT, Measuring IT Sovereignty (Invited speaker)	2026
SASE Annual Conference, Society for the Advancement of Socio-Economics, France (Paper presentation)	2026
Government Ownership for Sustainability and Strategic Autonomy, Utrecht University, Netherlands (Paper presentation)	2026
Digital Futures, Climate-Aligned AI, KTH, Sweden (Workshop)	2026
Geography of Innovation, University of Pavia, Italy (Workshop)	2026
Complexity Science (Winter School)	2026
Association of International Energy Negotiators, National Oil Company Conference, UK (Invited speaker)	2025
Oxford Economic Networks (Summer School)	2025
EU-SPRI, Dortmund (Paper presentation)	2025
United Nations University-MERIT, Economic Fitness & Complexity Course, Maastricht, Netherlands (Training)	2024
Annual Conference - PA Capabilities for Digital & Sustainable Transition, London UK (Organising Committee Member)	2024
Patent Data – PNRR program – SEEDS Centre, University of Ferrara, Italy (Summer school)	2024
Young Scholars Initiative INET - Festival of Economics, Turin (Paper presentation)	2024
SASE Annual Conference, Society for the Advancement of Socio-Economics, Brazil (Paper presentation)	2023
IIPPE Annual Conference, International Initiative for Promoting Political Economy, Italy (Paper presentation)	2022
Universitat de Barcelona, School of Economics "Ecological and Feminist Macroeconomics", Spain (Summer school)	2021
SASE Annual Conference, Society for the Advancement of Socio-Economics (Paper presentation)	2021
United Nations Conference on Trade and Development,"Globalization and Development Strategies" (Summer school)	2020
PKES, Post-Keynesian Economics Society, UK (Summer school)	2019
UCL, UCL IIPP workshop,"Rethinking the State in the 21st Century", UK (Master thesis presentation)	2019

PUBLICATIONS

Academic Peer-Reviewed Publications

- Tagliani, G. (2025). Increasing returns through circularity: A theory of production residuals for sustainable circular transitions. *Structural Change and Economic Dynamics*, *75*, 913–925. https://doi.org/10.1016/j.strueco.2025.10.018
- Tagliani, G. (2021). Entrepreneurship in State-Owned Enterprises . An International Comparative Analysis of IRI, Temasek and ÖIAG. *L'Industria (Review of Industrial Economics and Policy)*, (1), 149–174. https://doi.org/10.1430/99917

Working Papers

- Tagliani, G., Kozlowski, D., Rikap, C., (expected submission to *Research Policy* in September 2026). *AI Nets: Mapping Big Tech control of the AI regulation narratives*. *[presented at the 2026 SASE Conference, Bordeaux, France].*
- Tagliani, G. (2025). Drilling for Sustainability: Dynamic Capabilities in National Oil Companies. UCL Institute for Innovation and Public Purpose, Working Paper Series (IIPP WP 2025-17). ISSN 2635-0122 Available at: https://www.ucl.ac.uk/bartlett/publications/2025/sep/drilling-sustainabilitydynamic-capabilities-national-oil-companies
- Tagliani, G. (2025) Crossing the river by feeling the stones: Green Technological Transformation in National Oil Companies. Available at SSRN: https://ssrn.com/abstract=5133426 or http://dx.doi.org/10.2139/ssrn.5133426 [*under advanced stages of peer-review for the Journal of Environmental Innovation and Societal Transitions*]
- Tagliani, G. (2025). State Oil Regimes in Transition: The Political Economy of NOCs in the Age of Climate Change. *SSRN Electronic Journal*. http://dx.doi.org/10.2139/ssrn.5393202 [*Under submission for special issue in the Journal of Economic Policy Reform*]
- Mazzucato, M., Teixeira, F., & Tagliani, G. (2024). A mission-oriented framework for the coordination of State-Owned Enterprises in Brazil. *UCL Institute for Innovation and Public Purpose*, *IIPP WP 2024-18*. https://www.ucl.ac.uk/bartlett/public-purpose/wp2024-18

Policy-oriented publications

- Furnaro, A., Tagliani, G., Heller, P., González Espinosa, A. C., George-Ikoli, T., Ballesteros, F., & Woodroffe, N. (2026). *National oil company transformation: Strategic choices for an uncertain energy future*. Natural Resource Governance Institute.
- Barberis, F. L., Bez, C., Bigi, D., Castellani, A., Collodoro, C., Cresti, L., Genovese, E., Rocca, E. L., Leonardi, E., Musu, F., Negro, B., Risi, G., Sala, G., Seri, C., & Tagliani, G. (2026). Un lavoro per il clima. *Feltrinelli*. https://fondazionefeltrinelli.it/scopri/un-lavoro-per-il-clima/
- Tagliani, G., Furnaro, A., Manley, D., & Romero, C. (2025). DONG to Ørsted: Seven insights to transform national oil companies. *Natural Resource Governance Institute*. https://resourcegovernance.org/publications/dong-orsted-seven-insights-transform-national-oil-companies
- Mazzucato, M. & Tagliani, G. (2024). Economic Shortsightedness Is Jeopardizing Italy's G7 Ambitions, *Project Syndicate*. https://www.project-syndicate.org/commentary/italy-g7-presidency-marred-by-lack-of-forward-looking-industrial-policy-by-mariana-mazzucato-and-giovanni-tagliani-2024-06
- Tagliani, G. (2024). Long in the making: Policy insights from the Thai bioeconomy sector. Policy Brief. *UCL Institute for Innovation and Public Purpose*, Policy Brief No.29. https://www.ucl.ac.uk/bartlett/public-purpose/publications/2024/mar/29/policy-insights-thai-bioeconomy-sector
- Co-author of the conference proceedings (2020) "Territorialising the food system. A proposal for the restoration of lifecycle value within social boundaries", Conference "Transformative Economies: From Circular economy to Green New Deal", *Feltrinelli Foundation*.
- "Climate neutrality, just transition and SOEs" (2020) *Feltrinelli Foundation*.
- "Why Cassa depositi e prestiti is so important for Italy" (2020), *Kritica Economica*, https://www.kriticaeconomica.com/perche-cassa-depositi-e-prestiti-e-cosi-importante-per-litalia-cdp/

SERVICE

Affiliations

Life Member, Clare Hall, University of Cambridge; Rethinking Economics; PKES - Post-Keynesian Economics Society; SASE - Society for the Advancement of Socio-Economics; INET - Institute for New Economic Thinking - Member of YSI's Economics of Innovation, Development, States&Markets, Complexity Economics Working Groups; ISA - International Studies Association; Life Member, Cambridge Union, University of Cambridge, Member of the Complex Systems Society.

Research roles

- Member of CIRIEC International's Scientific Commission for Public Services & Public Enterprise. (CIRIEC - International Centre of Research and Information on the Public, Social and Cooperative Economy - www.ciriec.uliege.be)
- Organiser of the YSI Development Working Group
- Member of "Climate Jobs" research group

Reviewer roles

- Annals of Public and Cooperative Economics (Wiley-Blackwell)
- L'Industria - Review of Industrial Economics and Policy (Il Mulino)
- EU Commission – OECD "CONCORDi2025" 10th European Conference on Corporate R&D and Innovation – Reviewer of submissions for the topic of "Innovation Policy"
- Energy Research & Social Science (Elsevier)

Editor roles

Co-Editor of the Annals of Public and Cooperative Economics (Wiley-Blackwell)

REFERENCES

Rainer Kattel
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Vassilis Monastiriotis
Professor in Political Economy, London School of Economics and Political Science
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LANGUAGE PROFICIENCY	IT SKILLS (Software & Coding)
English (C1 - IELTS 8), French (B2 – DELF), Thai (B1 – Chulalongkorn University, THAI 4), Spanish (B1), Japanese (A2 – JLPT N5), Portuguese (A2), Italian (Native speaker)	Econometrics, text analysis, network analysis, economic complexity (R, STATA, MATLAB, GRETL, NVivo, Office, VOsviewer, Python, PatSeer)

Title

"Crossing the river by feeling the stones: Green Technological Transformation in National Oil Companies"

Abstract

Despite holding most oil reserves and producing most fossil fuels, the role of National Oil Companies in climate change and their stranded capabilities have been overlooked by the literature. This paper fills this gap by investigating how NOCs can leverage their capabilities to develop viable green technological transformation avenues. The study relies on the concepts of niche experimentation and incumbent reorientation from the sustainability transitions literature, such concepts are used to address limitations in dynamic capabilities and economic complexity approaches. Given NOCs' economic size and central position for the reproduction of their national socio-technical systems, NOCs' green technological transformation is framed as a process of incumbent reorientation. Related and unrelated diversification are located within incumbent reorientation, and the concept of niche experimentation is unpacked to reveal its key processes of multidimensional learning and network building. Niche experimentation is then used to explain the emergence of dynamic capabilities in NOCs. Dynamic capabilities, especially sensing, is shown to enable the unrelated diversification underpinning green technological transformation. The paper relies on novel data on NOC patents and fifty semi-structured interviews. The case study of Thailand's NOC in biotech highlights complexity-informed diversification and niche experimentation as mechanisms for green technological transformation, offering concrete policy recommendations for NOCs.

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Keywords

Sustainability Transitions; Oil; Niche Experimentation; Biotech; Complexity; Incumbent Reorientation;

JEL Codes

L32 L65 O33 Q35 Q55

Highlights

- Incumbent reorientation in oil sector: NOCs as major polluters and innovators.
- Thai NOC biotech case reveals niche experimentation for dynamic capabilities.
- Multidimensional learning and network building by major oil&gas incumbents.
- New complexity tools used to analyse NOCs' green tech transformations.

Declaration of competing interest

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

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgements

The author would like to express his sincere gratitude to Professor Kattel and Professor Andreoni for their insights and comments on an earlier draft of this paper. The author wishes to thank Prof Rikap, Myriam Nobre, Iacopo Gronchi, Josh Entsminger, and the participants at UCL IIPP's internal seminar for their comments. The author would like to thank the patent data expert group at the University of Ferrara, the complexity team at UNUMERIT and Oxford, and would like to extend a special acknowledgment to Dr Caldarola for his insights on complexity methods. The author also thanks the anonymous reviewers and the editor for the invaluable input and guidance received.

1. Introduction

National Oil Companies (or "NOCs") hold direct responsibility for around 9-12% of global CO2 emissions (IEA, 2023; Manley et al., 2019; Sachs et al., 2017; US EPA, 2020)[1]. In addition, 63% of historical CO2 and methane emissions can be traced back to just 90 oil and gas companies, almost two-thirds of these are NOCs (Ekwurzel et al., 2017; Heede, 2014; Mahdavi et al., 2022). NOCs are the largest or among the largest companies in their countries. They play essential roles in government revenues and employment provision, as well as having significant technological capabilities. NOCs also hold most of oil&gas reserves, however, around half of deepwater resources must not be developed if the world is to achieve a low CO2 energy system (McGlade & Ekins, 2014), with the risk of creating not just major stranded assets and even stranded nations, but also *stranded technological capabilities* (Herzog-Hawelka & Gupta, 2023; Manley et al., 2017; Semieniuk et al., 2022). While research has been carried out on international oil companies and the oil sector (Kenner & Heede, 2021; Tillotson et al., 2023), the sustainability transitions literature has not given the same level of scrutiny to NOCs, particularly regarding how these major fossil fuel incumbents can reorient their capabilities to spur broader sustainability transitions and green technologies.

This research investigates how NOCs can leverage their technological capabilities to develop viable green technological transformations. Given that 51 out of 68 NOCs are based in middle-income countries, the paper integrates sustainability transitions (ST) literature and the resource-capability view of the firm with structural change insights from economic complexity (Andreoni et al., 2016; Penrose, 1959; Piening, 2013). What emerges is that no single literature alone, whether based on ST, dynamic capabilities or complexity, explains NOC transformations in middle-income countries.

This study contributes to the ST literature by embedding dynamic capabilities development within the ST concept of niche experimentation, particularly through the key processes of multidimensional learning and network building involved in niche experimentation, which explain the emergence of these capabilities, especially sensing capabilities. The paper also contributes to the ST literature by addressing the empirical gap in the study of NOCs as major fossil fuel incumbents, with relevant implications for research on incumbent reorientation and niche experimentation led by incumbents.

This paper's case study focuses on Thailand's NOC 'PTT', and examines the reorientation of this oil&gas incumbent towards biochemistry and, more recently, biopharmaceuticals. Among NOCs, PTT represents an outlier illustrative case in which inputs and productive activities not related to fossil fuels have entered the core business of the firm. The company has an immense impact on the national economy with revenues equivalent to around a fifth of GDP, and the lowest oil supply chain emissions per barrel

[1] Author's calculation based on data that reports four-fifths of CO2 emissions coming from fossil fuels (US EPA, 2020), 15-20% of emissions from fossil fuels due to oil&gas production (IEA, 2023; Sachs et al., 2017), and 73% of production being carried out by NOCs (Manley et al., 2019).

of oil in the developing world (second overall after Norway's NOC; Fossil Fuel Registry, 2024; PTT, 2024; *World Bank Open Data*, 2023). Among the 21 largest NOCs, PTT has the most comprehensive green transformation strategy (Furnaro & Manley, 2023), covering carbon emissions in fossil fuels and new green activities. This includes downstream development, divestment of high-risk assets, clean energy initiatives, and decarbonising scope 1 and 2 emissions. Additionally, PTT is one of the few NOCs pursuing unrelated diversification (Furnaro & Manley, 2023). No academic case study has yet examined its green technological transformation from oil and gas extraction to advanced biochemistry.

Because of NOCs' unique economic, political, technological and environmental relevance, their green transformation inevitably affects national socio-technical regimes in middle-income countries. Achieving broader sustainability transitions adds another layer to structural change in these countries, which is the combination of industrialisation with the greening of the economic system (Rodrik, 2014; UNCTAD, 2021)[2]. By studying NOCs' incumbent role in technological learning, network building, and scaling of niche innovations in the bio-circular-green economy (Bocken et al., 2018; Colesante & D'Adamo, 2021; D'Amato & Korhonen, 2021), this paper aims to contribute to addressing this policy challenge.

While NOCs' green technological transformations involve multiple factors, including organisational change, the paper adopts the technological lens as its focus. This is achieved through a mixed methods approach of statistical analysis of patent data and an illustrative case study, following validated methods (Granstrand et al., 1997). The paper utilises patent data analysis to evaluate NOC technological capabilities that can promote broader sustainability transitions (Köhler et al., 2019), while the case study, which includes fifty semi-structured interviews, has a fundamental role in understanding patent evolution and key processes involved in niche experimentation (such as multidimensional learning and network building) that lead to dynamic capabilities development.

The next section articulates the theoretical framework and gaps addressed by the paper. The third section provides a description of the methods employed. The fourth section contains the empirical analysis. The conclusion recapitulates the results and argues for the utilisation of the theoretical constructs and data analysis tools developed in the paper, underscoring its original contributions to the literature, in addition to providing policy recommendations.

2. Challenges faced by National Oil Companies in Green Technological Transformations

[2] A process akin to the one described as "developmental environmentalism" in Thurbon et al. (2023).

Despite their economic and environmental weight, NOC transformations have received relatively little attention in grey literature and even less so in the academic one. This paper identifies the distinctive challenges associated with the repurposing of NOCs technological capabilities towards green productions. One such challenge is that NOCs need to identify opportunities for transformation, which requires dynamic capabilities (DC). However, the dynamic capabilities literature often relies on a tautology whereby a firm has DC if it is successful (Kattel, 2022), without addressing how DC are developed in the first place. Another gap lies in the ST literature, which has relatively overlooked NOCs despite their indisputable central role in the fossil fuel economy as primary producers and major polluters, with relevant implications for research on incumbent reorientation and the variety of actors in niche experimentation. This paper also examines how key processes involved in niche experimentation, such as multidimensional learning, network building and scaling, unfold when such experimentation is led by incumbents. These gaps and the theoretical framework adopted are articulated in greater detail in the following subsections: subsection 2.1 introduces the ST literature framing, subsection 2.2 focuses on the link between structural change, dynamic capabilities and key processes in niche experimentation, and subsection 2.3 on incumbent reorientation, diversification and relatedness.

2.1 Sustainability Transitions literature on reorienting oil&gas incumbents through niches

The ST literature offers an invaluable guiding framework when analysing the reorientation of major oil&gas incumbents like NOCs. This paper employs two key ST concepts: niche experimentation and incumbent reorientation.

The Multi-Level Perspective (MLP) of the ST literature sees transitions along the levels of external landscape development, socio-technical regimes, and *niches*. Socio-technical regimes are usually structured at the national level and represent the institutions of the existing systems leading to path dependence and incremental change, whereas niches are protected spaces, usually at the organisation level, where radical innovations take place (Köhler et al., 2019, p. 4). Niche experimentation is often developed by new entrants or relative outsiders, in partial opposition to regime incumbency (Köhler et al., 2019). Recent ST literature has put into question this framing, because of the variety of incumbents (Kungl, 2025; Turnheim & Sovacool, 2020; van Mossel et al., 2018), and through evidence of incumbents playing an enabling role in innovation resulting from niche experimentation (Ampe et al., 2021). Furthermore, a more nuanced distinction between incumbent socio-technical regimes (for which pressure due to innovation from niche experimentation may constitute a cause of decline; Köhler et al., 2019, p. 6) and specific incumbent actors (for which engagement in niche experimentation may constitute a deliberate and calculated business strategy; Chizaryfard & Karakaya, 2022; Kungl, 2025; Mori & Zhang, 2024) could also help recompose the debate.

Niche experimentation involves several processes, key ones include building networks and coalitions (Hess, 2014; Wesche et al., 2024), social, network and reflective learning (Costa et al., 2022; Flood & Romm, 1996; Holmqvist, 2003; Tosey et al., 2012), technological learning (Goyal & Howlett, 2020), resource mobilisation and legitimation (Avelino & Rotmans, 2009; Fuenfschilling, 2019; Geels & Verhees, 2011), and scaling and practice diffusion (Augenstein et al., 2020; Ruggiero et al., 2018). Because of their unique size in their respective oil&gas-producing countries (Tagliani, 2025a), NOCs are major incumbents holding a central position for the reproduction of their national socio-technical system (Kungl, 2025, p. 10). Given their overwhelming role in oil and gas production, NOCs are also among the main incumbents of the fossil fuel economy. NOCs play indispensable duties in the provision of human capital, engineering expertise, energy, infrastructure, government revenues due to state ownership, and political consent (Losman, 2010; Marcel, 2006). NOCs' nodal centrality enables them to lead key processes involved in niche experimentation such as resource mobilisation and legitimation, and network building with researchers, policymakers and other firms. The creation of new interdependencies and the pooling of resources and knowledge are essential elements of network building and resource mobilisation processes (Avelino & Rotmans, 2009; Costa et al., 2022), and can also lead to transformative learning (Beers et al., 2016). NOC literature has downplayed NOCs' role in technological learning and development, focusing instead on financial performance and governance (Manley et al., 2019; Victor, 2007). Despite NOCs' central position and potentialities for niche experimentation, there are limited attempts at interpreting NOC transformations through this ST lens, especially in relation to specific key processes involved niche experimentation. This paper aims to address this gap through the study of PTT's green technological transformation and patenting activity, including co-patenting in external engagements, which often results from network building. The case study also contributes to our understanding of the mechanisms that make sequences of projects coalesce into niche experimentation (Schot & Geels, 2008). The case of Thailand's NOC sheds a light on key processes involved in niche experimentation led by major oil&gas incumbents, with a focus on multidimensional (social-network-technological) learning and on key steps in network building and scaling.

NOCs escape the strict category of "firm" in niche experimentation. While the kind of niche experimentation explored in this paper is still a multi-actor, socio-technical, and politically-embedded concept in line with ST literature, NOCs cannot be treated simply as the firm actor within niche experimentation. NOCs are also key government entities, major research entities, in addition to firms with unmatched economic impact. In this sense, the paper promotes an understanding of actor categorisations that takes into account the unique reality of NOCs as government-research-firm actors and as pillars of many developing countries' economies. By analysing NOCs' green technological transformations by way of niche experimentation, this paper explores a multi-actor yet NOC-led process in which the firm-level dimension has inherent impacts for the national

socio-technical regime given the outsized role of NOCs in national economies, and thus directly contributes to broader sustainability transitions. Similarly, the paper's findings will have relevance for both NOCs and their government-owners.

The ST literature has made substantial advances in the study of niche experimentation by regime incumbents (Altunay et al., 2021; Saleh et al., 2025), including in upstream industry (Chizaryfard & Karakaya, 2022; Mori & Zhang, 2024). Andersen & Gulbrandsen (2020) study insights from petroleum diversification including the dual role of oil&gas incumbents in the form of suppliers that also cater to ST. Geels (2024) further systematises this idea by promoting a new research agenda on *incumbent reorientation*. Niche innovations are a central mechanism of technological transitions (Geels, 2002; Hölscher et al., 2023), including for incumbent reorientation. Magnusson & Werner, (2023) show that incumbents follow innovating and competing behaviours, which partially escape the commonly held view of incumbents as change-resistant actors. The ST literature has studied the support of incumbents towards cleaner technologies in power generation (Bergek et al., 2013) and CCS (Raven et al., 2016), and their reorientation through niches (Hess, 2013; Penna & Geels, 2015). This paper builds on these contributions and develops this research agenda by exploring how NOCs—the main oil&gas incumbents, predominantly located in developing countries—can achieve a green technological transformation by linking dynamic capabilities in incumbents and key processes involved in niche experimentation. The paper aims to fill this gap on the incumbent reorientation of NOCs by researching NOC-led niche experimentation in developing countries through the case of PTT, a rare instance of NOC incumbent reorientation through niche experimentation.

2.2 Structural Change, Dynamic Capabilities and Multidimensional Learning

Given relatively limited academic contributions, policy-oriented literature has shaped the recent debate on NOC transformations. Strambo et al. (2023) show that four Latin American NOCs have embarked on limited diversification away from fossil fuels, with ongoing commitment to expanding oil and gas production. Further policy-oriented literature focuses on NOCs' impact on climate change and explores their business exposure to energy transitions (Manley et al., 2023; Manley & Heller, 2021; NRGI, 2021). Strambo et al. (2023) and the IEA (2020, 2023) argue that new capabilities need to be developed to take advantage of low-carbon businesses, however, this aspect is not analysed further. Fethi and Rahuma (2020) have analysed eco-innovation's effect on CO2 emissions in a selection of oil companies, albeit without inquiring which specific technological capabilities are held.

What is missing is an understanding of the capabilities needed for green technological transformations, and of the implications of such transformations for structural change in developing countries, especially middle-income economies, since

they host seven out of the ten most polluting NOCs (Griffin, 2017; NRGI, 2019; Tagliani, 2025a; World Bank, 2023).

A core dimension of structural change is technological change. Middle-income countries face strong technological competition from high-income ones (Sumner, 2018). The gradual build-up of technological capabilities to competitively make more complex products is a key ingredient of structural change (Diodato et al., 2022), and the surpassing of a certain degree of economic complexity is the first goalpost indicating whether countries will be able to graduate from the middle-income group (Hartmann et al., 2021). Economic complexity theory has also developed applied tools to measure and map complexity, such as technological and product spaces (Hausmann & Hidalgo, 2011, 2013; Hidalgo et al., 2007).

Countries are more likely to enter industries whose productions are closer to their current technological capabilities—*related diversification*—which is the pathway favoured by prevailing policy recommendations based on economic complexity (Pinheiro, 2025). Vice versa, an entry into productions that are further away from a country's technological capabilities is defined as unrelated diversification. New literature on the subject has convincingly shown that unrelated diversification is needed, particularly for countries in the process of catch-up (Pinheiro, 2025), hence its relevance for NOCs in middle-income countries. At the level of regions, a similar argument has been made by Boschma et al. (2017), combining transition studies and complexity theory. Incumbents have also shown a stronger ability to reorient by entering emerging fields than previously thought (Apajalahti et al., 2018).

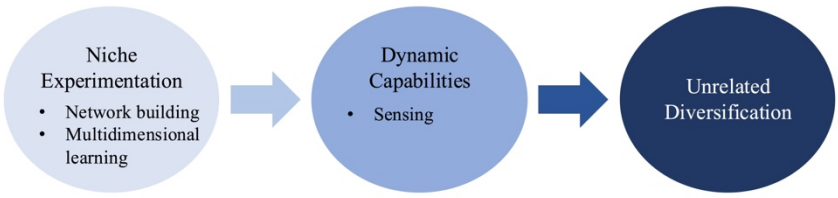
However, economic complexity approaches have a bias towards related diversification and do not indicate which dynamic capabilities firms need for unrelated diversification. Conversely, the DC literature often relies on the tautology whereby a firm has DC if it is successful (Kattel, 2022), without addressing how DC are developed in the first place. This paper uses the ST concept of niche experimentation to explain how DC emerge, and how DC can enable the pursuit of unrelated diversification (figure 1). Especially relevant for unrelated diversification is *sensing,* the DC to scan, filter and accumulate information about the opportunity environment in order to achieve the "identification, development, codevelopment and assessment of technological opportunities" (Kump et al., 2019; Teece, 2007, 2014).

While niche experimentation involves several key processes, this papers focuses on ones that underpin DC development and NOC green technological transformations: social-network learning, network building, technological learning, and scaling. Network and social learning are processes essential to the identification codevelopment of opportunities in the technological space. Social learning is the interactive process through which diverse stakeholders co-produce new shared knowledge (Beers et al., 2016; Ingram et al., 2015), while network learning can be viewed along two dimensions (Costa et al., 2022): *learning-in* takes place between actors within a socio-technical system, whereas *learning-by* refers to learning by the regime as a whole, often expanding the network,

including to other countries. Network building is indispensable for enabling learning between different actors by creating relationships among them, while social and network learning enable joint actions by different stakeholders (Costa et al., 2022), which is critical for scaling. Technological learning and capabilities will be achieved once the network of actors is established and has engaged in other learning dimensions (social and network), with such actors being able to effectively engage with and understand a technology, including its characteristics, production processes, and use (Goyal & Howlett, 2020; Kemp et al., 1998).

This paper argues that dynamic capabilities development can be embedded within the ST concept of niche experimentation, specifically its key processes of network building and multidimensional (social-network-technological) learning. NOCs are especially well-placed to engage in network building given their nodal centrality in the economy. In a successful NOC-led niche experimentation, NOCs will have to enable social and network learning with other actors (such as other public agencies, research centres and universities) and leverage co-produced knowledge for technological learning, including in external engagement (a form of *learning-by,* expanding the network to other countries). Social and network learning sustain the scanning, filtering and accumulation of information about the opportunity environment, while technological learning specifically enables the "identification, development, codevelopment and assessment of technological opportunities" (Teece, 2014), known as "sensing capabilities". Network building and multidimensional learning, as key processes within niche experimentation, lead to sensing capabilities development. Sensing capabilities enable firms to choose technologies and partners for a successful technological transfer. Once such transfer has happened, NOCs will be able to transform towards unrelated productions and pursue the scaling and commercialisation of knowledge produced in niches.

Figure 1: "Linking Niche Experimentation and Unrelated Diversification Through Dynamic Capabilities"



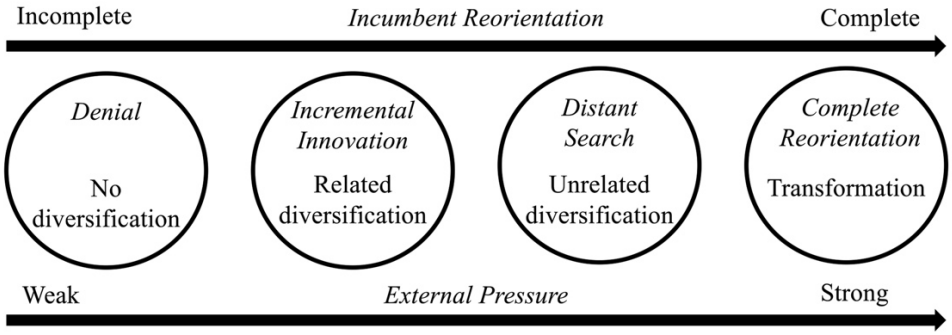
Source: Author's.

2.3 NOC Transformation Avenues: Reorientation, Diversification and Relatedness

Diversification is a crucial intermediate step within the overall process of incumbent reorientation in the ST literature (Geels, 2024, p. 13). Incumbent reorientation is often a strategic response to external pressures, which can include climate change and resource depletion (Ertelt & Kask, 2024; Halttunen et al., 2023). Halttunen et al. (2023) have

shown the pressures towards diversification endured by oil companies. Diversification intervenes in different degrees along the four stages of incumbent firms' responses to transition processes (Geels, 2014; Steen & Weaver, 2017). The first stage of denial is likely to be followed by incremental innovation (Steen & Weaver, 2017), which underpins related diversification. However, a third stage whereby "incumbents initiate [a] more distant search" can follow if pressures gain enough strength (Steen & Weaver, 2017, p. 1073), leading to an unrelated diversification which necessitates sensing capabilities enabling such distant search. A fourth and final stage is achieved when the core business is transformed (figure 2).

Figure 2: "Diversification process within the Four Stages of Incumbent Reorientation"



Source: Author's.

Diversification requires technological capabilities to competitively make more complex products. This accumulation of capabilities most often involves diversifying from a sub-sector to a related higher-value one on which the firm has enough information and where routines, competencies and learning can be more easily applied[3].

Relatedness and technological capabilities can be measured through patents, rendering it a critical indicator of successful diversification efforts (Granstrand et al., 1997). Large firms tend to patent in nearby technological systems (Breschi et al., 2003), and those with extensive patenting tend to fill *technological gaps* between their existing patents (Breschi et al., 2003). Furthermore, countries are more likely to enter industries that are closer to their current activities and capabilities (Diodato et al., 2022), especially for green productions (Ekins, 2021; Mealy & Teytelboym, 2017). As large patentees, with economy-wide dimensions, NOCs aiming for green transformations see their inclination to explore related productions strongly reinforced.

Although that is the case in general, Chatterjee & Wernerfelt (1991) have shown that, unlike knowledge-based and physical resources, internal financial resources are associated with more unrelated diversification, and NOCs, because of the nature of resource rents, make greater use of internal financing. Therefore, we can expect NOCs with abundant internal financing to include unrelated diversification in their strategy

[3] An institutional bounded rationality (Simon, 1957, 1962).

(Pinheiro et al., 2022). While climate change is likely to entail a long-term unrelated diversification away from fossil fuels for many NOCs (IEA, 2020; Peszko & et al, 2020), unrelated diversification remains extremely complex and potentially value-destroying (Wiersema & Beck, 2017). This risk could be mitigated by adopting a long-term strategy of successive steps of related diversification progressively moving the NOC's core business away from oil and gas until the green transformation is achieved or, in Deng Xiaoping's approach, *crossing the river by feeling the stones*.

Despite its widespread use, the exact nature of relatedness remains elusive. Up to this point, relatedness has been used in the sense of proximity, however, the literature has also linked the term to commonality, or complementarity (Breschi et al., 2000, 2003). Moreover, an understanding of relatedness valid for all firms discounts firm experience and the firm's relative perception of relatedness. Relatedness is not just a factual spatial position in system-wide analysis, but is also "purposively shaped by firms" in their efforts to diversify (Breschi et al., 2003, p. 85). The more the firm perceives a technology as unrelated according to its own experience, the slower and harder the development of technological capabilities (Tordo et al., 2011). Despite the importance of the firm's perception of relatedness in the development of technological capabilities, complexity tools of technological and product space are at the macro-level, based on national trade and patenting data with only indirect meso-sectoral implications (Yamada et al., 2024), discounting the firm dimension. This paper aims to address this by highlighting the NOC's position within product and technological spaces. The paper lays the ground for an extended complexity framework where related innovation recommendations based on static analysis can be studied and applied at the micro-firm dimension, unveiling how micro-level changes feed back into diversification patterns at the macro-national level. NOCs, as the largest firm in their countries, offer privileged access to study this relationship given that their micro-firm diversification strongly affects the macro-national scale.

Not all experience leads to technological capabilities. Experience in *related*, yet different, technological sub-systems and in different combinations (for instance, acquisitions of varying size or geography) are particularly effective in contributing to technological capabilities accumulation (Brown & Eisenhardt, 1997; Teece et al., 1997)[4]. NOCs must weigh the benefits of related diversification against the potential pitfalls of carbon lock-in, such as in diversification where competition for inputs entails exploration and production expansion.

Technological transformation strategies away from oil&gas can be categorised according to their dominant direction into vertical and horizontal strategies, with vertical strategies delineating a focus on upstream or downstream technologies. Horizontal integration strategies leverage economies of scale and partnerships (whose benefits are acknowledged in the NOC literature; Tordo et al., 2011). Vertical integration based on

[4] In addition to space parameters, firm experience is most likely to lead to the accumulation of technological capabilities when it is *paced* over time (Laaksonen & Peltoniemi, 2018; Zollo & Winter, 2002).

forward and backward technology linkages requires technological capabilities. Pursuing either path presents considerable obstacles for middle-income countries—the horizontal avenue is hindered by weaknesses in the national production ecosystems, while the vertical one demands substantial capabilities.

Given the fragility of the national ecosystem, the external dimension assumes greater weight in horizontal strategies, along with its associated risk of falling into traps in lower value-added positions within foreign-dominated GVCs. While firms may engage external actors, technological capabilities are absent if the firm is unable to directly understand, use and interface with the technology at any stage without the intermediation of external actors. External engagements may be necessary for technological transfer, however, without internal capabilities, these relationships can lead to value extraction by the external actor instead of promoting domestic emancipation and development. External engagements by middle-income countries do not necessarily lead to technological transfer as the evidence from FDI demonstrates (Narula & Driffield, 2012), and can either entrench extractive patterns of developmental and technological lock-ins or achieve developmental outcomes. Consequently, external engagement of major vertically-integrated firms in middle-income countries, such as NOCs, are indispensable, as well as sensing capabilities that can guide the NOC in the selection of external actors and opportunities.

In terms of specific transformation avenues, we can distinguish upstream-related capabilities (e.g. in Exploration&Production) and downstream-related capabilities (largely in transformation and petrochemicals; Ashrafkhanov et al., 2024). The integration of offshore wind with the upstream oil&gas technological system has been explored from a technical, legal, and economic point of view, with widespread applications (Årdal, 2011; Herrera Anchustegui & Tscherning, 2024; Mota et al., 2022; US DoE, 2017)[5]. However, the competitive space in renewables is narrow, with established global giants in wind and solar. In hydrogen[6], where the competitive space is wider, costs and infrastructure prevent this technology from being a substitute for fossil fuels.

Grey literature related to NOCs adopts an upstream-renewable energy emphasis (Manley & Heller, 2021; Strambo et al., 2023) while focusing on Latin American NOCs (Ramírez-Cendrero & Paz, 2017; Singh, 2024; Strambo et al., 2023), neglecting other regions and downstream-derived capabilities. Particularly overlooked are those capabilities developed in petrochemicals that have been successfully applied to second-generation biofuels (Queiroz Pinto et al., 2016), and biochemistry at large, by Asian NOCs in China and Thailand (Wianwiwat & Asafu-Adjaye, 2013). In this regard, the ST

[5] Ørsted, formerly DONG, was the Danish NOC whose early investments in renewables made the company an off-shore wind energy giant (Algers & Kattel, 2021; Tagliani et al., 2025; Voldsgaard et al., 2022).

[6] Given its creation as a by-product in some oil and gas processes, hydrogen has also been painted with great promise as an energy transition alternative, despite relatively limited accomplishments by NOCs (IEA, 2020).

literature represents a growing body of work that has given ample space to bioeconomy-based approaches (Allain et al., 2022), including on the part of incumbents. For instance, Bauer (2018) positions biorefining as a key technology shaping bioeconomy-based narratives by incumbents. However, empirical contributions within the ST literature differ on whether bioeconomy-based transitions favours incumbents or not. Kuckertz et al. (2020) state that bioeconomy-based innovation is unlikely to championed by incumbents, whereas Holmgren et al. (2022) find that incumbents in forestry were strengthened by bioeconomy-related innovations.

Middle-income countries can leverage their downstream technological capabilities in the bioeconomy for development. This sector can also involve energy generation through biofuels (Bell et al., 2011; Sampaio & Bonacelli, 2018), however, its most promising avenues are in new materials and biopharmaceuticals. While biofuels might not directly contribute to the overcoming of the middle-income trap (other than alleviating balance of payments constraints in oil-importing countries), they could be a suitable strategy for the transformation of NOCs since they open new technology platforms for other high-value-added productions.

3. Research Design and Methods

The research design follows best practices in social science and energy (Sovacool et al., 2018). The paper adopts a research design based on a complexity-informed patent data analysis (Appendix A) and a case study with semi-structured interviews (Appendix B). The case study explains PTT's role in Thailand's product and technological spaces based on complexity analysis. The interviews inform, validate and enrich the case of PTT's green technological transformation, playing a fundamental role in understanding patent evolution processes identified through quantitative analysis. To strengthen the paper's validity, alternative explanations are explored to ensure that observed trajectories are due to the identified factors.

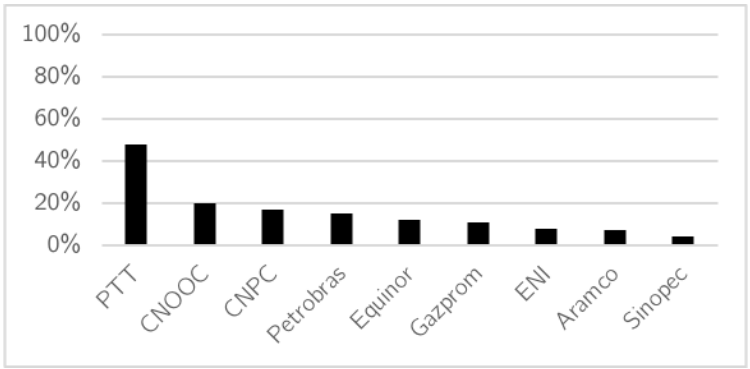
In addition to theoretical and empirical novelty, this study also introduces methodologically-novel elements. NOC patenting activity is severely under-researched, including the study of firm-related assignees. The patent data analysis developed by Granstrand et al. (1997) has been refined by fully embracing mixed methods, with the inclusion of a case study grounded in secondary literature, datasets, and primary data via semi-structured interviews. This mixed methods approach overcomes some of the limitations of purely quantitative ones (Sovacool et al., 2018) and enhances policy relevance. Patent data was collected through a time-intensive yet highly precise novel automated-manual entity-linking algorithm (described in Appendix A). The patent analysis has also been improved with insights from the economic complexity approach, including by contributing to the development of firm-level complexity methods with new firm-level data from PatSeer database, and by including qualitative analysis of patents.

Despite these novel research design improvements, the methods exhibit some limitations prompting further research avenues. Quantitative patent analysis has relatively limited explanatory power in recognising and interpreting uncodified knowledge. Such limitation is partially mitigated by the case study and its introduction of dynamic capabilities, but it is not fully overcome. The paper primarily focuses on detecting those NOCs' technological capabilities needed to develop viable avenues for a green technological transformation, which are well explained using patent data. However, some of the factors needed to activate capabilities, such as organisational change, while introduced in the case study, are not explored with an equivalent level of granularity, pointing towards the study of NOCs transformations along such further line of inquiry.

4. The Biotech-based Transformation of the Thai NOC

NOCs hold over 300'000 patents, including over 20'000 in climate change adaptation and mitigation technologies (Author's calculation from PatSeer, 2024). Patents do not directly represent a knowledge-creation mechanism, instead, they constitute the phase of appropriation and assetisation of co-created knowledge (Rikap, 2023). However, even in this phase, NOCs display variations in the proportion of patents that are developed internally (exclusively assigned to the firm) versus those that are developed through external engagement (co-assigned to the firm and an external entity). In particular, PTT has a disproportionately high percentage of patents co-assigned to entities which at the time of application were placed within the corporate innovation system but not strictly within the main subsidiaries of the NOC, such as joint ventures or external acquisitions (figure 3). Among such co-assignees, NatureWorks represents 44% of co-assigned parents (since 2012 a PTT joint venture with Cargill) and Myriant 17% (a firm acquired by PTT in 2011, whose internalisation process culminated in its 2018 rebranding as PTTGC Innovation America).

Figure 3: "Proportion of patents developed in external engagements among major NOCs"



Source: Author's elaboration, PatSeer dataset.

Among NOCs that consistently patent high-quality inventions, PTT stands out. While most other innovative NOCs are from cash-rich Gulf countries or China[7], PTT is a mid-sized oil&gas producer based in a mid-sized middle-income country, with costs for crude oil production above the average and relatively moderate gas reserves (NRGI, 2025). The Thai firm has the lowest oil supply chain emissions per barrel of oil in the developing world, second overall after Norway's NOC (Fossil Fuel Registry, 2024). Among the 21 largest NOCs, PTT stands out for having the most comprehensive green transition strategies (Furnaro & Manley, 2023), including downstream development, divestment of high-risk assets, clean energy initiatives, and decarbonising scope 1 and 2 emissions. Additionally, PTT is one of the few NOCs also pursuing unrelated diversification (Furnaro & Manley, 2023). As a result of successful external engagement in technological development, it is now a major producer of high value-added biodegradable bio-based bioplastics. Despite Thailand receiving some attention in the literature (Bandaogo, 2020; Doner, 2009; Wharton, 2017), the role of its biotech sector and the value-adding transformation of its NOC have been neglected.

4.1 Technological and Production Capabilities in Thailand

In the past twenty years, Thailand has substantially increased its investment in technological capabilities, R&D and STI skills:

Table 1: "R&D expenditure and employment in Thailand"

R&D expenditure	National: from 0.25% of GDP in 2006 to 1% in 2017 Private/Firm: from around 0.3 in 2006 to 3.7 billion USD in 2017
R&D employment	National: from 73,498 in 2006 to 216,737 employees in 2017 Public: +106% from 2006 to 2017 Private/Firm: +614% from 2006 to 2017
R&D expenditure in chemistry	Private/Firm: +638% between 2010 and 2017, reaching around 286 million USD

Source: Author's, data from NXPO (2019), currency in USD (2017 value).

Thailand has the highest number of industrial robots in the developing world after China (Andreoni & Anzolin, 2019), and in 2022 it had the fifth highest Global Innovation Index among 36 surveyed middle-income countries (WIPO, 2022).

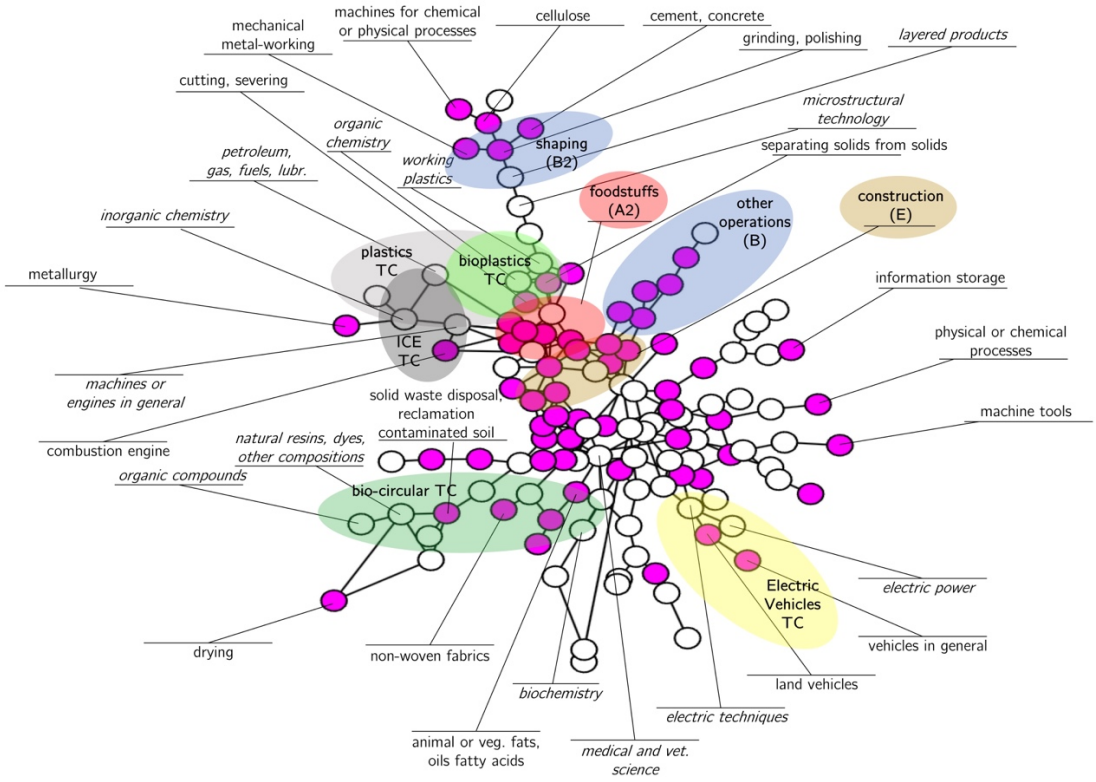
Thailand has built strong foundations in biochemistry throughout the value chain. The country is the second-largest exporter of sugar after Brazil (US Department of Agriculture, 2024). Sugar is the key input in the Thai bioplastic value chain[8], its

[7] The top-five biggest patentees are Sinopec, Aramco, ENI, CNPC, CNOOC (PatSeer, 2024).

[8] Thailand is the world's third-largest producer and the number one exporter of tapioca (FAO, 2023; OEC, 2023). The country has advanced research, patents, prototypes, and commercial production of tapioca-based biomaterials (Executive Business Association Agricultural Commodity, interview, 25 March 2022) such as

production is highly regulated by the Office of the Cane and Sugar Board (OSCB) to avoid extreme fluctuations in price and quantity, grow yields, and balance sugar destined to food with other uses (OCSB, 2024). A key reason for establishing a bioplastic industrial plant in Thailand is the "stability and productiveness of the sugar industry" (Director Bioplastic Company, interview, 22 March 2023)[9]. Thailand has increased R&D employment and expenditure downstream, in chemicals, above the economy-wide growth (NXPO, 2019). PTT is the largest chemical company in Thailand by far and has focused its growth efforts on sustainable businesses.

Figure 4: "Technological Space of Thailand"



Source: Author's elaboration, data from PatSeer dataset.
Note: Specific technological clusters (TC) are highlighted. The distance between dots reflects the relatedness between two technological codes, and purple dots indicate a Comparative Advantage (CA).

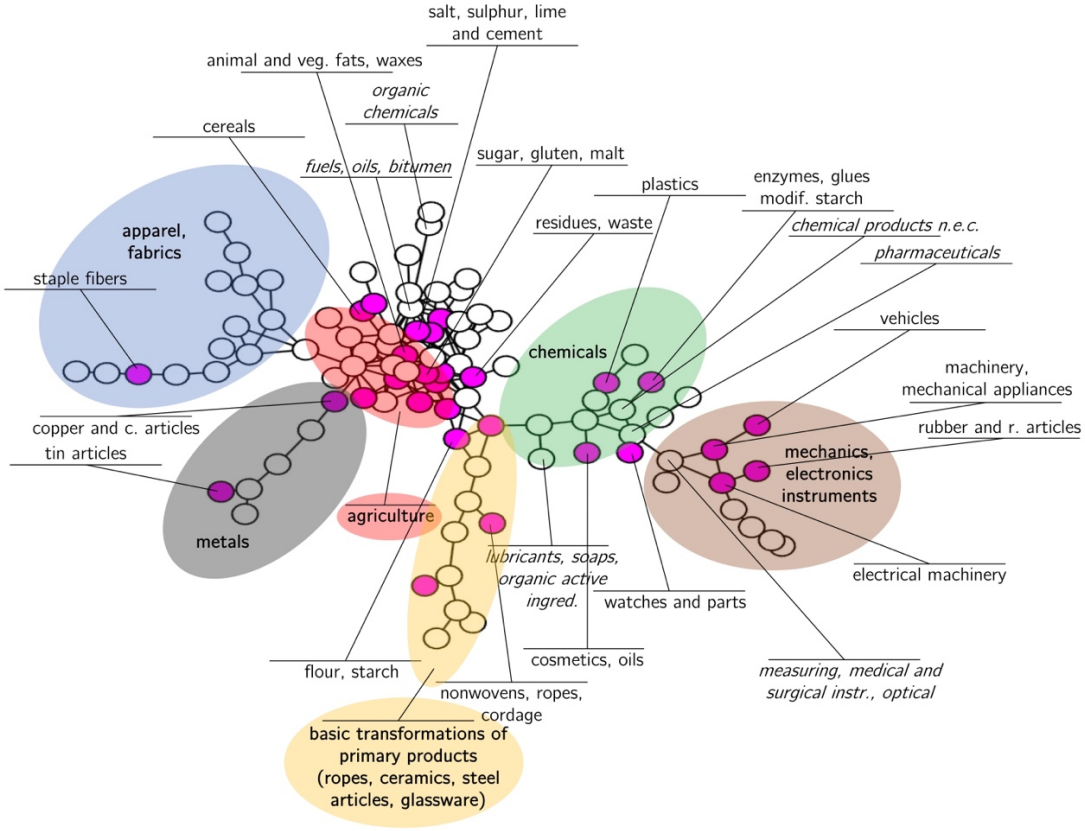
Thailand's technological space (figure 4) reveals the country's positioning and challenges in technological development. Thailand has strengths in foundational technological areas for the bioeconomy, in physical or chemical processes, machines for such processes, cellulose, and circular technologies in solid waste disposal and reclamation of contaminated soil. Patent code B01 (physical or chemical processes) is one of the three

tapioca-based thermoplastic starch (TPS), however, these tapioca-based alternatives have not yet reached the scale of sugar-based bioplastics.

[9] Which is also a result of Thailand's defiance of the world trade regime (Danvivathana, 2010)

most common codes in biofuel-related patents, and code B09 (solid waste disposal, reclamation of contaminated soil) is central to the country's Bio-Circular-Green policy which jointly targets the bioeconomy, circularity, and the climate transition (Tagliani, 2024). While Thailand does not yet command a comparative advantage (CA) in other advanced biotech-specific technological areas at the country level (such as organic chemistry and compounds, working plastics, biochemistry, and medical and veterinary science), the country is surprisingly close to biotech, given the short distance between CA dots and biotech technological codes.

Figure 5: "Product Space of Thailand"



Source: Author's elaboration, data from UN Comtrade dataset.

Thailand's product space (figure 5) demonstrates the CA of the country in agriculture, in addition to chemistry, mechanics, electronics and other instruments. The product space broadly matches the country's technological space, reinforcing the validity of both complexity analyses[10]. The CA in technological codes "vehicles in general" and "land vehicles" are matched by Thailand's role as a major car producer and assembler, shown in the product space by the CA in "vehicles" products. While this sector is mostly

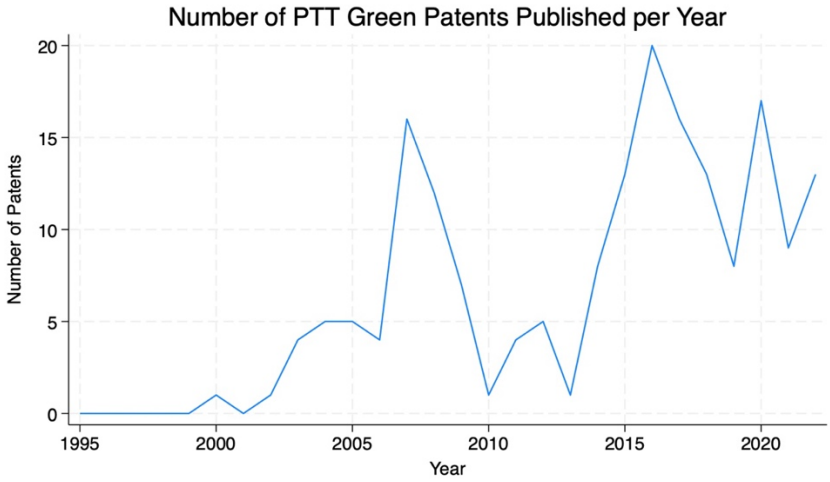
[10] For instance, the CA in patent codes in information storage is matched by a CA in products in electrical machinery, which accounts for Thailand's position as the world's top producer of hard disks (The Nation, 2024).

dominated by foreign firms (Busser, 2008; Lee et al., 2021), the same is not true for Thailand's advanced chemistry and biochemistry, which sees PTT at the forefront of technological innovation and production, leveraging Thailand's CA in agricultural inputs and chemistry (including, specifically, plastics and enzymes) to produce high value-added bioproducts.

4.2 A Blueprint for the Green Technological Transformation of NOCs: The case of PTT

PTT represents 7.2% of Thailand's R&D with only 0.08% of its total employment (2021 data)[11]. PTT has developed 2170 patents including 195 green patents, with an increasing yearly rate (figure 6), and has concentrated its overall innovation efforts in patent codes critical to advanced biochemistry and biopharma (table 2).

Figure 6: "Number of PTT Green Patents Published per Year"



Source: Author's elaboration, Y02-coded patents, data from PatSeer dataset.

Table 2: "Most common 20 patent codes among PTT patents"

PTT Patent codes	**Number of Patents**	**Share of PTT patents**
C08: ORGANIC MACROMOLECULAR COMPOUNDS	705	32.4%
C12: BIOCHEMISTRY	540	24.8%
C07: ORGANIC CHEMISTRY	500	23.0%
B01: PHYSICAL OR CHEMICAL PROCESSES	288	13.2%
C09: NATURAL RESINS, DYES, OTHER COMPOSITIONS	178	8.2%

[11] This means that the share of PTT's R&D out of national R&D is almost 100 times higher than the share of PTT's employment out of national employment. Latest available data from PTT's 2021 Annual Report (PTT R&D expenditure and employment; PTT, 2022), Bank of Thailand (exchange rates; Bank of Thailand, 2025), World Bank (National R&D expenditure; *World Bank Open Data*, 2023), and ILO (National employment; ILO, 2024).

C10: PETROLEUM, GAS, FUELS, LUBRICANTS	67	3.1%
B29: WORKING PLASTICS	58	2.7%
C01: INORGANIC CHEMISTRY	57	2.6%
A61: MEDICAL OR VETERINARY SCIENCE	55	2.5%
D21: CELLULOSE	41	1.9%
B32: LAYERED PRODUCTS	39	1.8%
D01: NATURAL OR ARTIFICIAL FIBRES	39	1.8%
E21: DRILLING, MINING	31	1.4%
F28: HEAT EXCHANGE	27	1.2%
F16: ENGINEERING ELEMENTS, FUNCTIONING OF MACHINES, THERMAL INSULATION	21	1.0%
C13: SUGAR INDUSTRY	19	0.9%
G01: MEASURING	19	0.9%
A01: AGRICULTURE, FORESTRY, FARMING	18	0.8%
B08: CLEANING	16	0.7%
H01: BASIC ELECTRIC ELEMENTS	16	0.7%

Source: Author's elaboration, data from PatSeer dataset.

PTT's frontier role is confirmed by its patenting activity which is concentrated in critical biotech areas, specifically, in organic compounds-C08 (with 32% of PTT patents having such code), biochemistry-C12 (25%), and organic chemistry-C07 (23%). These patent classes are the top 3 patent classes out of PTT's patent codes[12]. Physical or Chemical Processes (B01) is the fourth most common PTT patent class with 288 patents, representing around 13% of PTT patents. B01 is, together with C12 and C10, the most common code for biofuels. C10 (petroleum, gas, fuels, lubricants) is the 6th most common patent code among PTT patents with 67 patents.

Despite the lack of commercial biopharmaceutical products directly made by PTT as of late 2025, surprisingly, among the top ten patent codes there is already "medical or veterinary science" (A61), a class crucial for PTT's biopharmaceuticals business. With the acquisition of Lotus Pharmaceuticals (a large Taiwanese manufacturer) and the establishment of Innobic as the pharmaceutical arm of PTT (Bloomberg, 2023; PTT Website, 2021), the Thai NOC is currently entering the sector.

Expectedly, PTT still has some patenting activity in fossil fuel-related activity, for example, in E21-"drilling, mining" and in C10-"petroleum, gas, fuels, lubricants" (the latter, however, also heavily recalled in biofuel-related patents).

4.2.1 PTT's external engagement

PTT has built its current technological capabilities in advanced biotechnologies by way of external engagement. Three PTT subsidiaries emerged from such process (table 3): PTTGC Innovation America, PTTMCC Biochem, and NatureWorks.

[12] In the study by Squicciarini et al. (2013, p. 50), biotechnologies, pharmaceuticals and macromolecular chemistry emerge as the technological fields with the highest originality.

Table 3: "External engagements by PTT"

Time	Name	Relevance	Outcome
January 2011	Myriant (later, PTTGC Innovation America)	PTTGC (PTT's chemicals subsidiary) acquired Myriant, a biotech developer and manufacturer of bio-based chemicals with established experience in critical technological sub-fields for advanced biochemistry. Myriant is the third-largest entity among PTT-linked patent holders. Examples among its 176 patents include: • Succinic acid production from renewable feedstock using genetically modified microbial biocatalysts (filed in 2010) • Integrated biorefinery operations (2012) • Genetically altered escherichia coli bacteria to produce succinic acid, fumaric acid, malic acid, and 1,4-butanediol (2010) • Organic acids from xylose-rich hydrolyzate by bacterial fermentation (2011). These were critical technologies for the production of advanced renewable biochemicals and for PTT's plans of establishing high value-added bioplastic production in Thailand. Many such patent applications were not yet submitted or public at the time of Myriant's acquisition by PTT, indicating the presence of substantial sensing capabilities by the Thai firm that guided the acquisition (Teece et al., 1997; Weick, 2004).	Myriant Technologies was completely absorbed by PTT and rebranded into "PTTGC Innovation America" in 2018.
March 2011	PTTMCC Biochem	PTT established a joint venture with Mitsubishi Chemical, known as PTTMCC Biochem. The company's headquarters and production plants are in Thailand. In 2012, the company was able to trademark a novel biomaterial with desirable food-contact and flexibility properties: BioPBS (Bio-Polybutylene Succinate). The biodegradable and compostable polymer mainly relies on bio-based succinic acid through a process of fermentation that uses biomass as feedstock. BioPBS precisely relies on those molecules and technologies in which Myriant had advanced expertise, such as 1,4-butanediol and succinic acid.	In 2017, the first large-scale production of high-value-added bioplastics in Thailand and the first BioPBS plant in the world entered its commercial operations with PTTMCC producing BioPBS at an initial capacity of 20'000 metric tonnes/year.
October 2011	NatureWorks	PTTGC acquired 50% of NatureWorks for 150 million USD (PTTGC & Stock Exchange Thailand, 2012). The company is a world-leading producer of biopolymers, particularly polylactic acid (PLA). PLA is durable, recyclable, and has a high-value-added as signalled by its several medical applications (DeStefano et al., 2020; Luchian-Lupu et al., 2020) and market price, up to 200 times higher when compared to raw Thai sugar (Top	As of late 2025, NatureWorks is set to start commercial production in its PLA plant in the province of Nakhon Sawan. High-value-added products from the plant's PLA will include advanced

		Executive Bioproduct Association, interview, 17 March 2022). NatureWorks has finished construction of a PLA plant in Thailand with an initial capacity of 75'000 metric tonnes/year. The plant is the first integrated biorefinery plant, from upstream sugarcane production (sourced within 50km of the site) to downstream PLA production, instead of relying on pre-processed lactic acid (Director Bioplastic Company, interview, 13 January 2023; NatureWorks, 2023; Top Executive Major Chemical Corporation, interview, 20 May 2022). Within the integrated plant, sugar is first transformed through engineered bacterial fermentation into lactic acid (a sophisticated process protected by industrial secrets and IP rights), then the lactic acid is polymerised, another technologically complex process that requires high expertise (Director Bioplastic Company, interview, 13 January 2023).	fibres, 3D printing, and durable goods for the automotive sector (Director Bioplastic Company, interview, 13 January 2023).

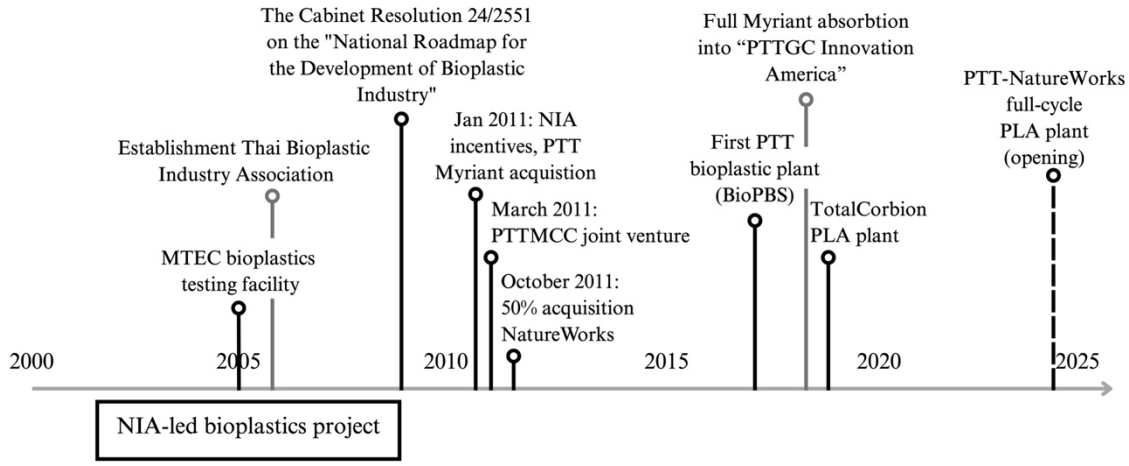
Source: Author's.

In 2016, Thailand had no bioplastic production at industrial scale, while in 2019 the country became the world's second-largest producer of PLA[13], with volumes driven by TotalCorbion's plant in Rayong province and due to improve further in 2026 following the put in operation of the NatureWorks plant (figure 7 provides a timeline of PTT's green technological transformation). In 2017, Thailand reached 23.6% of global PBS production capacity of PBS driven by PTT's BioPBS, and from 2019 to 2021 its bioplastic exports doubled both in terms of volume and value, positioning the country among the top producers globally after China and the US (EEC, 2020; PLASTAT, 2023; S&P Global, 2022; Statista, 2021; Tagliani, 2024), with an even greater market share in the sub-category of biodegradable and bio-based bioplastics (figure 8). PTT is at the forefront of bioplastic production and biomaterials research[14].

Figure 7: "A timeline of PTT's green technological transformation"

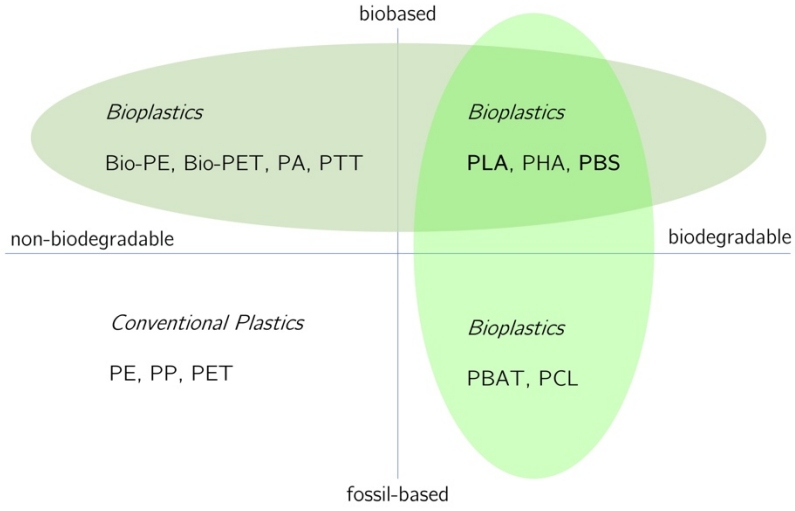
[13] With a production capacity of 75000 tonnes out of 290000 (European Bioplastics, 2022; Fortune Business Insights, 2021; Tagliani, 2024).

[14] Recent developments by PTT include bio-based Nylon 6,6 from agricultural waste and polymers based on captured CO2.



Source: Author's.

Figure 8: "Typologies of Bioplastics along biobased and biodegradability dimensions"



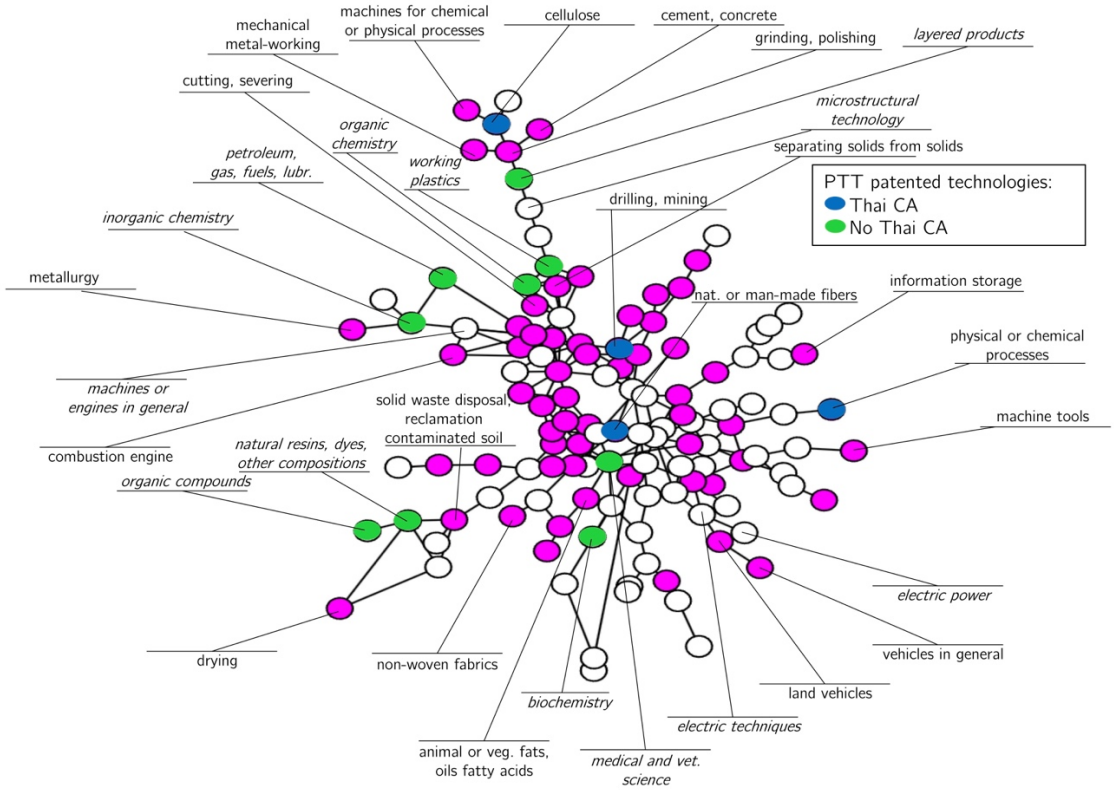
Source: Author's elaboration.

Effective technological transfer and internalisation of technological capabilities from external engagement is only possible if firms have the sensing capabilities (Teece et al., 1997) to identify the technological transformation pathway to pursue, and if they can rely on previous technological capabilities in related sub-systems (in the case of PTT in petrochemical and biofuel technologies). While PTT's incumbent reorientation aligns with the literature on oil&gas fostering green technologies (e.g. Norway's offshore wind; Mäkitie et al., 2018), there's also a point of divergence. In PTT's case, the contribution of oil&gas emerged not through direct advancement of targeted green technologies but via intermediary innovations enabling their adoption.

While biofuels are not high value-added productions, the experience of PTT with biofuel technologies, such as biorefinery or catalysts and enzymatic processes (particularly related to codes B01, C12 and C10), has been an essential stepping stone

towards the development of advanced biochemistry. PTT and Thai policy-makers saw "biofuels as a first step towards biochemicals in the biorefinery process" (Top Executive Energy&Chemistry Foundation, interview, 21 November 2022). This experience helped PTT to make sense, and "extract cues" (Helms Mills et al., 2010), in its external engagement. These technological stepping-stones by PTT are evidenced by the position of the Thai NOC when it is revealed within Thailand's technological space (figure 9).

Figure 9: "Technological Space of Thailand with PTT patenting activity highlighted"



Source: Author's elaboration, data from PatSeer dataset.
Note: Patent codes in which PTT holds at least 30 of its patents are highlighted in green and blue in the graph. These primary codes represent the top 13 patent codes out of 121 patent codes involved in PTT patenting activity.

External engagement does not always lead to developmental outcomes, on the contrary, it may also cause extractive patterns and technological lock-ins (Booth, 2007; Mahdavi, 2020; Narula & Driffield, 2012), so it is worth exploring what were the specific mechanisms of PTT's external engagement. While PTT has achieved full command of advanced biochemistry and biomaterial production in great part due to a process of external engagement with foreign partners leading to technological transfer, this engagement built on solid foundations of pre-existing technological and sensing capabilities (Teece et al., 1997). PTT's case supports the argument from the ST literature that incumbent firms can successfully integrate emerging technologies (Bergek et al., 2013).

4.2.2 Two mechanisms guiding external engagement: complexity and niche experimentation

PTT's successful external engagement is due to two interconnected mechanisms: the first based on a complexity-informed related diversification, the second on the development of dynamic capabilities through socio-technical niche experimentation. These also reflect the prevailing stages of incumbent reorientation (Geels, 2014), in which incremental innovation (as in the related diversification towards biofuels) precedes more distant searches leading to unrelated diversification (Steen & Weaver, 2017).

At a surface glance, PTT seems to have broadly followed the standard complexity recommendation of related diversification. Its most common 13 patent codes are no more than one network point away from another PTT common code, except for "mining, drilling" and for "physical or chemical processes", indicating a moderate acceptance of perceived unrelatedness in how PTT engages in innovative activity. PTT's patenting activity and innovative products are in partial defiance of CA as they are in codes on which Thailand does not have technological CA, albeit not too far from PTT's own network points. In many cases, PTT acts as a bridge between advanced technological areas and basic technologies in which Thailand already has a CA. PTT is precisely engaging in a diversification in related yet different subsystems, which is needed to accumulate new technological capabilities (Eisenhardt & Martin, 2000, p. 1115; Teece et al., 1997).

On a deeper look, the evidence partially contradicts prevailing complexity literature recommending related diversification. This necessitates going beyond the unproductive debate between related diversification (justified through static complexity analysis) and unrelated diversification (advocated by structural change literature). The evidence indicates that PTT has achieved a complexity-informed yet unrelated diversification, the firm has been *crossing the river by feeling the stones*. Its green technological transformation has been towards initially unrelated subsystems, however, it has leveraged intermediate related technological steps in line with Geels' (2014) stage-based approach for reorientation (Steen & Weaver, 2017). In this sense, this paper points towards a solution for resolving the limitations of economic complexity tools based simply on relatedness. The case study also reverses the focus of the transformation: PTT's focus has been on strong dynamic change, first directly targeting non-near high-value-added bioproductions, then determining which technological areas would need to be developed, and, finally, identifying the specific stepping stones to get there based on complexity-informed technological relatedness. This exercise entails the employment of sensing capabilities (Ambrosini & Bowman, 2009; Teece, 2021), beyond complexity theory and pre-existing technological capabilities.

4.2.3 Development of PTT's sensing capabilities: niche experimentation

Having already identified crucial technological capabilities by PTT in green transition technologies (for instance, in biofuels and biorefining), the paper now seeks to explain the emergence of those sensing capabilities that informed the dynamic trajectory and enabled external engagement. To sense technological opportunities and *feel* the stones to cross the river of technological upgrading, PTT employed a mechanism based on socio-technical niche experimentation (Geels, 2002, p. 1257, 2022), instrumental to its external engagement. PTT engaged in socio-technical experimentation in many endeavours, such as the EEC[15] or the collaboration with NSTDA-BIOTEC[16]. However, the project initiated in 2002 by Thailand's National Innovation Agency (NIA) on bioplastics stands out for its socio-technical relevance, its directionality and multiple actors (Haddad et al., 2022), its focus on building sensing capabilities, and its specific role in the development of PTT's bioplastic business (Top Executive Major Chemical Corporation, interview, 20 May 2022).

These socio-technical experimentation projects were multi-actor (involving NSTDA, NIA, TotalCorbion, OCSB, Chulalongkorn University and others). Indeed, the collaboration with such a numerous and diverse set of actors is part of the network building process involved in niche experimentation. The Deputy Secretary-General of a Public Agency (emphasis added, interview, 9 March 2022) stated that the success of the experimentation processes in bioplastics was due to Thailand's natural endowment, but also to "good innovation, ***learning*** and R&D capacity" and to the "ability to ***build*** international partnerships and ***networks***", reflecting the two key processes of technological learning and network building involved in niche experimentation.

PTT led the push towards experimentation, even directly assisting other Thai firms that wanted to experiment with bioplastic: "PTTGC presented and helped update our machines to work with bioplastics. PTTGC also helped in getting the new materials, in

[15] The Eastern Economic Corridor (EEC), initially established in the 1980s as the Eastern Seaboard Development Programme, is a special development zone where numerous initiatives of regulatory sandboxing and technological experimentation have been introduced since its inception. The EEC Office implements specific regulatory flexibility and financial incentives, for instance in terms of visa & immigration, plant approval and industrial zoning (with the Industrial Estate Authority of Thailand), skilling and education initiatives (such as the Thai Austrian Technical College), financial and regulatory incentives graded based on technological sophistication, other tax and foreign currency incentives (in addition to national ones, which are instead established by Thailand's Board of Investment), among others. Technological experimentation programs have been introduced in numerous EEC industrial zones and innovation hubs such as Map Ta Phut (where much of PTT's chemical production takes place) and EECi.

[16] NSTDA is Thailand's National Science and Technology Development Agency. The agency has set up over 200 skilling and re-skilling initiatives (NSTDA, 2019), technological upgrading programs (including for the green transition, for example within the Innovation Technology Assistance Program), and socio-technical experimentation (such as the prototyping, testing, and policy interaction spaces at the Thailand Science Park in collaboration with public universities, major firms, including PTT, research institutes, and government departments). First established in 1983 as the National Center for Genetic Engineering and Biotechnology, NSTDA-BIOTEC is now one of five NSTDA research centres and its biotechnology branch, overseeing all initiatives related to the sector (NSTDA-BIOTEC, 2022).

improving productions, and in understanding the benefits of bioplastics. PTTGC also helped the company in finding new customers and improving acceptance" (CEO Medium-Sized Biotech Company, interview, 26 April 2022). Instead, public agencies "played a supporting role in building facilities and the network" (Managing Director Major Biotech Company, interview, 15 December 2022).

However, PTT was not simply a firm actor, it was also a government actor involved in the roadmap execution and bio-circular-green policy advocacy, a research actor that developed and acquired bioeconomy-related technology, in addition to being the largest firm sitting on policy committees and the main business advisor on how such bioeconomy policies had to be managed and adjusted (Executive Director Research Public Organisation, interview, 16 March 2022; Tagliani, 2025; Top Executive Major Chemical Corporation, interview, 20 May 2022; Top Executive Research Public Agency, interview, 15 November 2022). Therefore, changes in Thailand's socio-technical regime came as a direct result of PTT's central role and firm-level green technological transformation, albeit in a multi-actor framework.

The bioplastic project was first established by the NIA as the granting agency[17], in collaboration with the National Research Council of Thailand, Chulalongkorn University (Thailand's highest-ranked university), starch producers, and led by PTT (Full Professor Chemistry Major University, interview, 4 October 2022; Cabinet Resolution 24/2551, 2008). The explicit goal of this multi-actor socio-technical experimentation project was to establish a new government roadmap leading to Thai commercial production of bioplastics, hence its political embeddedness. The project was chaired by a team of three people with a budget of around 45 million USD over five years between 2003 and 2008. The focus was on production and technology, rather than sustainability concerns (Full Professor Chemistry Major University, interview, 4 October 2022). The roadmap prioritised building capabilities, in line with theory on niche socio-technical experimentation (Hölscher et al., 2023; Schot & Geels, 2008). The socio-technical nature was embedded not just in the institutions involved, but also in the four project areas (Full Professor Chemistry Major University, interview, 4 October 2022):

Table 4: "Project areas in the NIA bioplastic niche experimentation project"

Project area name	**Niche experimentation**
Upstream	• Inputs • Bio-feedstock • Experimentation on cassava, starches, and sugar solutions
Technological transfer from abroad	• Sensing opportunities • Turnkey technologies • Repurposing of available technologies among thai technological capabilities

[17] Until 2003 known as the Innovation Development Fund.

Domestic technological development	• Academic research • Internal firm R&D • Industry collaboration
Government policy and regulation	• Scouting policy solutions abroad

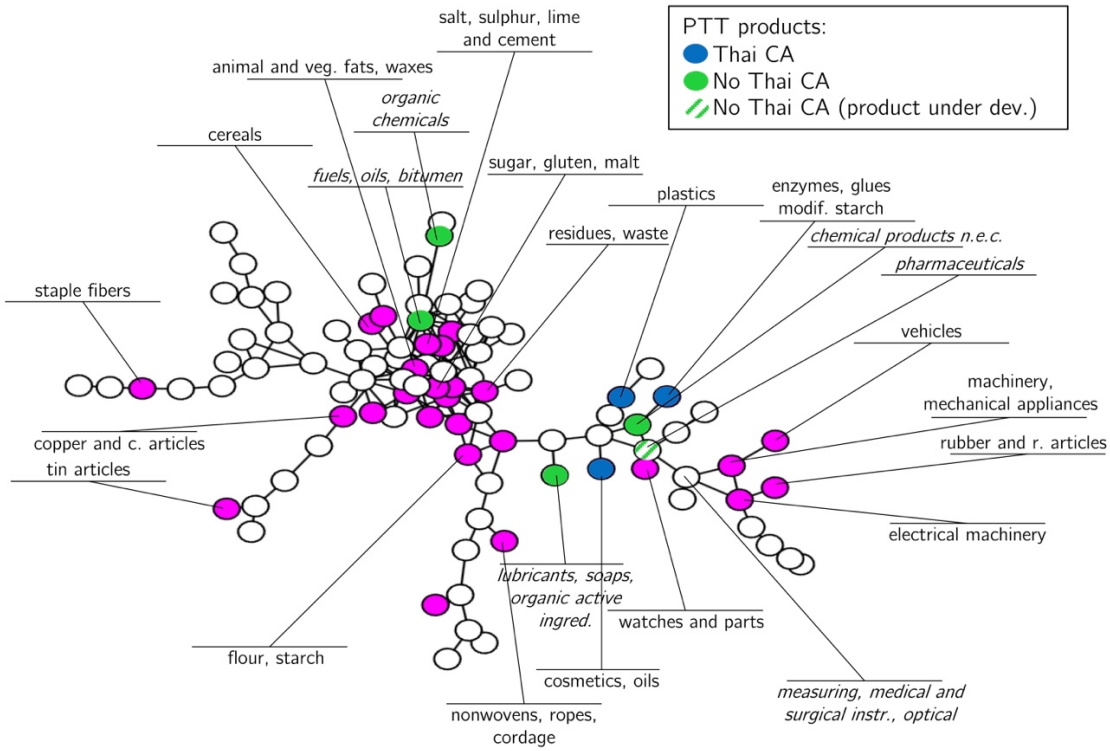
Source: Author's, Full Professor Chemistry Major University, interview (4 October 2022).

In terms of niche socio-experimentation, the project surveyed policies and regulations adopted in the countries with the most advanced bioeconomy sector at the time (Germany, Netherlands, and EU regulation), made in-person visits to these countries, and scouted interesting policy solutions, experimenting their re-elaboration in the Thai context (Top Executive Research Public Agency, interview, 15 November 2022). In terms of niche technical-experimentation, the project team studied bioplastic solutions in Germany and the US, focusing on PLA models, PBS, and PBS-A (Full Professor Chemistry Major University, interview, 4 October 2022), leveraging both public and firm laboratories in Thailand. The Cabinet Resolution 24/2551 on the "National Roadmap for the Development of Bioplastic Industry" (2008) highlights the NIA's role in negotiations between Thai firms and leading foreign bioplastic companies, including, specifically, NatureWorks. Socio-technical niche experimentation within the project directly resulted in successful external engagement, with a top executive in a key public agency stating that it was this "development project on bioplastics led by a Chulalongkorn University research team which later led to agreements with industry led by PTT, these engagements with large companies [PTT and foreign companies] for large-scale production of bioplastics [were] still led by NIA following the development project" (Top Executive Research Public Agency, interview, 15 November 2022).

In 2005, the National Metal and Materials Technology Center (MTEC) developed an additional bioplastics testing facility. In 2006, the Thai Bioplastic Industry Association was formed (a network-building exercise which now includes four PTT subsidiaries: PTTMCC, IRPC, NatureWorks, and PTTGC), with the support of the NIA and Chulalongkorn University Petrochemical College (Cabinet Resolution 24/2551, 2008). The NIA also organised two international exhibitions on bioplastics in 2006 and 2008[18], and supported new bioplastic plants with 300 million THB in incentives in 2011 (Bangkok Post, 2011). That same year PTT moved forward with its three major external engagements with Myriant, NatureWorks, and PTTMCC. Thailand now has a CA not just in plastics, but also in enzymes, with PTT producing chemical products (general category), organic active ingredients, and organic chemicals, and recently entering biopharmaceuticals. Figure 10 shows Thailand's product space with PTT productions highlighted in blue and green.

Figure 10: "Product Space of Thailand with PTT productions highlighted"

[18] InnoBioPlast in 2006 and EcoInnovaAsia in 2008.



Source: Author's elaboration, data from UN Comtrade dataset.

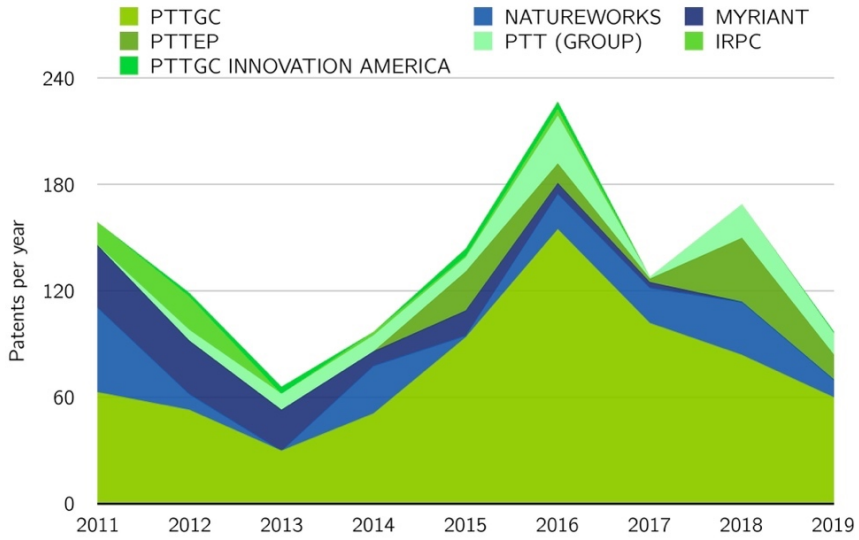
Alternative explanations for PTT's external engagement that led to the incumbent's reorientation towards advanced biochemistry include financial capacity and more traditional FDI-related technological transfer. However, while financial means were likely a precondition of that external engagement by the NOC, the condition of abundant internal financial capacity is far from unique to PTT since most NOCs are cash-rich organisations given their rentier, and often monopolistic, positions. Furthermore, the external engagement by PTT does not follow the typical process of FDI as it was PTT that searched through its sensing capabilities (Weick, 1995) for these investments abroad, not the reverse. Furthermore, while some countries require joint ventures for FDI, PTT also engaged in full acquisitions (in the case of Myriant) which escape FDI-related explanations and practice. The NOC's transformation path was intentionally built though niche experimentation (Kemp et al., 2001), even in a context of strong technological path dependency.

4.2.4 Internalisation of technological capabilities

PTT's green patenting has two phases of growth (figure 6), shifting performance over its innovation journey (Van de Ven, 1999, p. 41). During the period of niche experimentation in biochemicals, from 2002 to 2010 (with a first peak in 2007), PTT increased its green patenting activity by leveraging its internal capabilities, typical of a large vertically-integrated petrochemical firm (with a role played by public intermediaries, such as

Chulalongkorn University and the NIA; Andreoni, 2018), without external engagement abroad. This initial phase of niche experimentation included multidimensional learning and network building, and laid the ground for those sensing capabilities needed for the following phase of external engagement (Schot & Geels, 2011). The second growth period happened post-2015 (with a peak in 2016), as PTT already internalised technological capabilities from the external engagement. This is confirmed by the fact that growth was primarily driven by green patents filed by PTTGC, demonstrating that technological capabilities had been transferred. Industrial-scale production began shortly after, in 2017.

Figure 11: "Patents filed per year for each of the main PTT entities"



Source: Author's elaboration, data from PatSeer dataset.
Note: Internal PTT entities in shades of green, External Engagements (NatureWorks and Myriant) in shades of blue. From the bottom: PTTGC, NatureWorks, Myriant, PTTEP, PTT (Group), IRPC, PTTGC Innovation America.

The weighted average invention age is 20 years for NatureWorks and 10 years for Myriant, whereas it is only 7 years for PTT excluding external engagements[19], signalling the recency of internal green technological development. The patenting pattern of the main PTT entities (figure 11) shows that the company has progressively shifted from reliance on external engagements towards internal technological development, proving the successful development of technological capabilities and the NOC's green technological transformation.

5. Conclusion

[19] Data from PatSeer dataset.

NOCs make up almost two-thirds of the 90 oil and gas companies responsible for 63% of historical carbon dioxide and methane emissions (Ekwurzel et al., 2017; Heede, 2014; Mahdavi et al., 2022). Crucially, NOCs hold most of oil&gas reserves, however, around half of deepwater resources must not be developed if the world is to achieve a low CO2 energy system (McGlade & Ekins, 2014), with the risk of creating stranded assets, stranded nations, and *stranded technological capabilities* (Herzog-Hawelka & Gupta, 2023; Manley et al., 2017; Semieniuk et al., 2022).

NOCs possess 300'000 patents and 20'000 green patents[20]. Their technological transformations possess a high potential for structural change towards frontier higher value-added green productions, a particularly desirable quality for the over fifty middle-income countries with NOCs which are struggling to compete on current technologies with high-income economies.

This study contributes to the literature on sustainability transitions, which has so far relatively overlooked NOCs despite their central role in the fossil fuel economy (figure 12, arrow from case study and DC literature to ST). The filling of this empirical gap meant broadening the concept of firm actor to include NOCs as government-firm-research entities, and contributing to the emerging literature on incumbent reorientation by linking reorientation stages with diversification and relatedness. The paper shows how unrelated diversification underpinned by sensing capabilities is enabled by the key processes of multidimensional learning and network building involved in niche experimentation (Kungl, 2025; Magnusson & Werner, 2023; Saleh et al., 2025). The case study also fills the empirical gap on the mechanisms that make sequences of projects coalesce into niche experimentation (Schot & Geels, 2008), and provides additional evidence to the finding of Holmgren et al. (2022) that incumbents are strengthened in bioeconomy-based transitions. The paper makes a contribution *from* the ST literature as well, namely explaining the emergence of dynamic capabilities through niche experimentation (arrow from ST to DC literature), delineating the role of specific key processes within it.

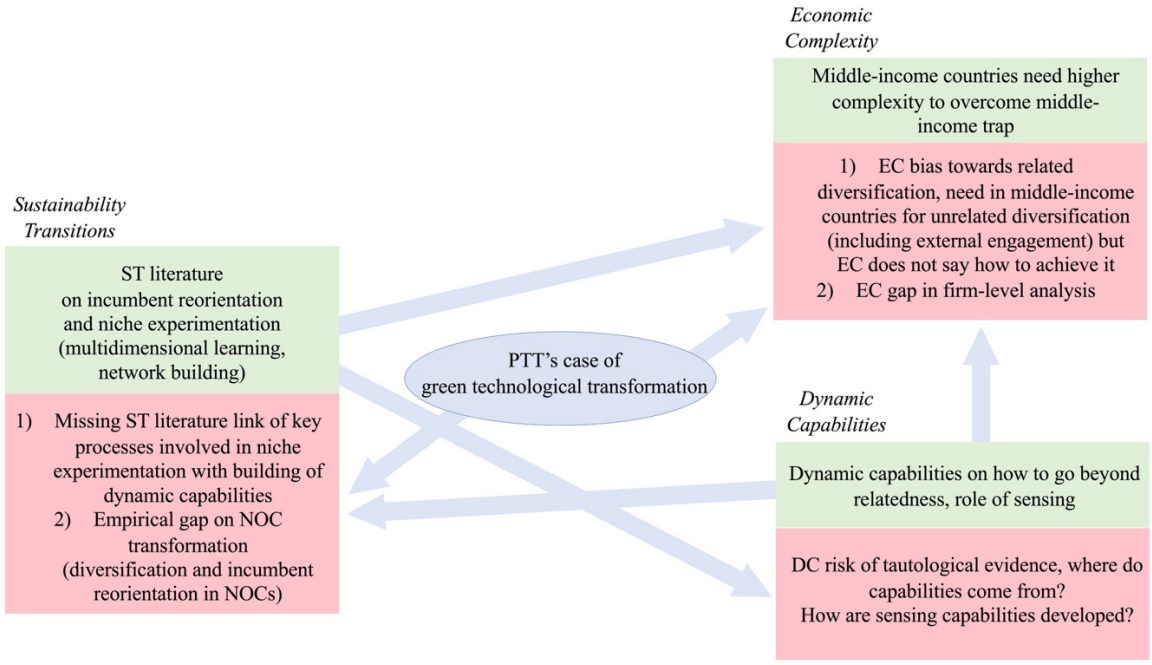
The ST literature, together with the capabilities approach, contributes to addressing the limitations of economic complexity (arrows towards economic complexity), especially in middle-income countries where firms' external engagement and unrelated diversification are essential for structural change but missing in the macro-level analysis of economic complexity. Sensing capabilities developed through niche experimentation enable unrelated diversification through successful external engagements. Furthermore, the empirical analysis of the NOCs' positioning within the technological space addresses the complexity gap in firm-level analysis.

Only by complementing each other, the three frameworks can explain PTT's green technological transformation. By combining the three frameworks, the paper describes in detail the preconditions and the two mechanisms through which PTT has successfully managed its external engagements leading to the transfer of technological capabilities and

[20] Author's calculations, data from PatSeer.

high-value-added bioproductions. One mechanism is complexity-informed related diversification and the other is unrelated diversification guided by sensing capabilities developed by way of niche experimentation. The incumbent reorientation of these major oil&gas firms can be achieved by combining these two mechanisms.

Figure 12: "Theoretical and empirical contributions of the paper"



Source: Author's elaboration.
Note: The theoretical strengths of each stream of the literature are in green, the gaps in each stream are in red, and paper's contributions are in light blue. For instance, this paper uses (arrow in blue) the ST literature on niche experimentation (a theoretical strength, in green) to explain the development of sensing capabilities (a gap in the DC literature, in red).

The paper's finding reinforces the stage-based approach to incumbent reorientation (Geels, 2014, 2024; Steen & Weaver, 2017), which sees incremental innovation precede "distant search". By studying the connection between the two mechanisms, the research goes beyond existing literature and qualifies the stage of incremental innovation (underpinning complexity-informed related diversification, in the case of PTT, towards biofuels) as a potential stepping-stone towards the stage of distant search (underpinning unrelated diversification in advanced biochemistry), subject to the development of sensing capabilities by way of niche experimentation.

This study promotes a novel understanding of NOC transformations which goes beyond the prevailing focus on renewables, favouring more comprehensive data-driven complexity-informed solutions. It provides original data on NOC patenting and primary interview data, in addition to methodological contributions towards economic complexity tools (improving the micro-firm dimension and elaborating a novel manual-automated entity-linking algorithm for patent data). The research indicates the type of complexity-

informed diversification and sensing capabilities through which NOCs can concretise policy recommendations and effectively transform towards green technologies and products.

PTT's successful reorientation from a purely oil&gas firm to a diversified company operating in biochemistry shows potential for biopharmaceuticals. While Thailand does not yet command a CA in the trade or technological codes relevant to biopharmaceuticals at the country level, the novel firm-level complexity approach introduced in this paper demonstrates that PTT already has advanced knowledge in key codes, such as medical and veterinary science.

References

Algers, J., & Kattel, R. (2021). *Equinor and Ørsted: How industrial policy shaped the Scandinavian energy giants* (Policy Brief Series, Issue IIPP PB 14). UCL Institute for Innovation and Public Purpose.

Allain, S., Ruault, J.-F., Moraine, M., & Madelrieux, S. (2022). The 'bioeconomics vs bioeconomy' debate: Beyond criticism, advancing research fronts. *Environmental Innovation and Societal Transitions*, *42*, 58–73. https://doi.org/10.1016/j.eist.2021.11.004

Altunay, M., Bergek, A., & Palm, A. (2021). Solar business model adoption by energy incumbents: The importance of strategic fit. *Environmental Innovation and Societal Transitions*, *40*, 501–520. https://doi.org/10.1016/j.eist.2021.10.013

Ambrosini, V., & Bowman, C. (2009). What are dynamic capabilities and are they a useful construct in strategic management? [Article]. *International Journal of Management Reviews*, *11*(1), 29–49. https://doi.org/10.1111/j.1468-2370.2008.00251.x

Ampe, K., Paredis, E., Asveld, L., Osseweijer, P., & Block, T. (2021). Incumbents' enabling role in niche-innovation: Power dynamics in a wastewater project. *Environmental Innovation and Societal Transitions*, *39*, 73–85. https://doi.org/10.1016/j.eist.2021.03.004

Andersen, A. D., & Gulbrandsen, M. (2020). The innovation and industry dynamics of technology phase-out in sustainability transitions: Insights from diversifying petroleum technology suppliers in Norway. *Energy Research & Social Science*, *64*, 101447. https://doi.org/10.1016/j.erss.2020.101447

Andreoni, A. (2018). The architecture and dynamics of industrial ecosystems: Diversification and innovative industrial renewal in Emilia Romagna. *Cambridge Journal of Economics*, *42*(6), 1613–1642. https://doi.org/10.1093/cje/bey037

Andreoni, A., & Anzolin, G. (2019). A Revolution in the making? Challenges and Opportunities of Digital Production Technologies for developing countries. In *Inclusive and Sustainable Industrial Development Working Paper Series* (pp. 1–71). UNIDO.

Andreoni, A., Frattini, F., & Prodi, G. (2016). Structural cycles and industrial policy alignment: The private–public nexus in the Emilian Packaging Valley. *Cambridge Journal of Economics*, bew048. https://doi.org/10.1093/cje/bew048

Apajalahti, E.-L., Temmes, A., & Lempiälä, T. (2018). Incumbent organisations shaping emerging technological fields: Cases of solar photovoltaic and electric vehicle charging.

Technology Analysis & Strategic Management, *30*(1), 44–57. https://doi.org/10.1080/09537325.2017.1285397
Årdal, A. R. (2011). Feasibility Studies on Integrating Offshore Wind Power with Oil Platforms [Master thesis, Institutt for elkraftteknikk]. In *128*. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/257082
Ashrafkhanov, S., Benham, H., & Coffin, M. (2024). *PETROCHEMICAL IMBALANCE: Why chemicals are unlikely to prop up oil demand* [Analyst Report]. Carbon Tracker.
Augenstein, K., Bachmann, B., Egermann, M., Hermelingmeier, V., Hilger, A., Jaeger-Erben, M., Kessler, A., Lam, D. P. M., Palzkill, A., Suski, P., & von Wirth, T. (2020). From niche to mainstream: The dilemmas of scaling up sustainable alternatives. *GAIA - Ecological Perspectives for Science and Society*, *29*(3), 143–147. https://doi.org/10.14512/gaia.29.3.3
Avelino, F., & Rotmans, J. (2009). Power in Transition: An Interdisciplinary Framework to Study Power in Relation to Structural Change. *European Journal of Social Theory*, *12*(4), 543–569. https://doi.org/10.1177/1368431009349830
Bandaogo, M. S. (2020). Escaping the Middle-Income Trap: Long-Term Growth Scenarios for Thailand. In *World Bank* (pp. 1–23).
Bangkok Post. (2011, April 18). *NIA hopes to kickstart new industry with B300m*. https://www.bangkokpost.com/business/economics/232375/nia-hopes-to-kickstart-new-industry-with-b300m
Bank of Thailand. (2025). *Statistics*. https://www.bot.or.th/en/statistics.html
Bauer, F. (2018). Narratives of biorefinery innovation for the bioeconomy: Conflict, consensus or confusion? *Environmental Innovation and Societal Transitions*, *28*, 96–107. https://doi.org/10.1016/j.eist.2018.01.005
Beers, P. J., Mierlo, B. V., & Hoes, A.-C. (2016). Toward an Integrative Perspective on Social Learning in System Innovation Initiatives. *Ecology and Society*, *21*(1), art33. https://doi.org/10.5751/ES-08148-210133
Bell, D. R., Silalertruksa, T., Gheewala, S. H., & Kamens, R. (2011). The net cost of biofuels in Thailand-An economic analysis. *Energy Policy*, *39*(2), 834–843. https://doi.org/10.1016/j.enpol.2010.11.002
Bergek, A., Berggren, C., Magnusson, T., & Hobday, M. (2013). Technological discontinuities and the challenge for incumbent firms: Destruction, disruption or creative accumulation? *Research Policy*, *42*(6), 1210–1224. https://doi.org/10.1016/j.respol.2013.02.009
Bloomberg. (2023). *Bloomberg, Lotus Pharmaceutical Co Ltd*. https://www.bloomberg.com/quote/1795:TT
Bocken, N. M. P., Schuit, C. S. C., & Kraaijenhagen, C. (2018). Experimenting with a circular business model: Lessons from eight cases. *Environmental Innovation and Societal Transitions*, *28*, 79–95. https://doi.org/10.1016/j.eist.2018.02.001
Booth, A. (2007). Night watchman, extractive, or developmental states? Some evidence from late colonial south-east Asia. *The Economic History Review*, *60*(2), 241–266. https://doi.org/10.1111/j.1468-0289.2007.00377.x
Boschma, R., Coenen, L., Frenken, K., & Truffer, B. (2017). Towards a theory of regional diversification: Combining insights from Evolutionary Economic Geography and Transition Studies. *Regional Studies*, *51*(1), 31–45. https://doi.org/10.1080/00343404.2016.1258460

Breschi, S., Lissoni, F., & Malerba, F. (2003). Knowledge-relatedness in firm technological diversification. *Research Policy*, *32*(1), 69–87. https://doi.org/10.1016/S0048-7333(02)00004-5
Breschi, S., Malerba, F., & Orsenigo, L. (2000). Technological Regimes and Schumpeterian Patterns of Innovation. *The Economic Journal*, *110*(463), 388–410.
Brown, S. L., & Eisenhardt, K. M. (1997). The Art of Continuous Change: Linking Complexity Theory and Time-Paced Evolution in Relentlessly Shifting Organizations. *Administrative Science Quarterly*, *42*(1), 1–34. https://doi.org/10.2307/2393807
Busser, R. (2008). 'Detroit of the East'? Industrial upgrading, Japanese car producers and the development of the automotive industry in Thailand. *Asia Pacific Business Review*, *14*(1), 29–45. https://doi.org/10.1080/13602380701660962
CEO Medium-Sized Biotech Company. (2022, April 26). *Interview Thailand 7* [Personal communication].
Chatterjee, S., & Wernerfelt, B. (1991). The link between resources and type of diversification: Theory and evidence. *Strategic Management Journal*, *12*(1), 33–48. https://doi.org/10.1002/smj.4250120104
Chizaryfard, A., & Karakaya, E. (2022). The value chain dilemma of navigating sustainability transitions: A case study of an upstream incumbent company. *Environmental Innovation and Societal Transitions*, *45*, 114–131. https://doi.org/10.1016/j.eist.2022.10.002
Colesante, A., & D'Adamo, I. (2021). The circular economy and bioeconomy in the fashion sector: Emergence of a "sustainability bias". *Journal of Cleaner Production*, *329*(129774). https://doi.org/10.1016/j.jclepro.2021.129774
Costa, I., Bui, S., De Schutter, O., & Dedeurwaerdere, T. (2022). A network perspective to niche-regime interactions and learning at the regime level. *Environmental Innovation and Societal Transitions*, *43*, 62–79. https://doi.org/10.1016/j.eist.2022.03.001
D'Amato, D., & Korhonen, J. (2021). Integrating the green economy, circular economy and bioeconomy in a strategic sustainability framework. *Ecological Economics*, *188*, 107143. https://doi.org/10.1016/j.ecolecon.2021.107143
Danvivathana, P. (2010). Thailand's experience in the WTO dispute settlement system: Challenging the EC sugar regime. In G. C. Shaffer & R. Meléndez-Ortiz (Eds), *Dispute Settlement at the WTO* (1st edn, pp. 210–229). Cambridge University Press. https://doi.org/10.1017/CBO9780511663192.007
Deputy Secretary-General Public Agency. (2022, March 9). *Interview Thailand 2* [Personal communication].
DeStefano, V., Khan, S., & Tabada, A. (2020). Applications of PLA in modern medicine. *Engineered Regeneration*, *1*, 76–87. https://doi.org/10.1016/j.engreg.2020.08.002
Diodato, D., Hausmann, R., & Schetter, U. (2022). A Simple Theory of Economic Development at the Extensive Industry Margin. *Harvard University - CID Working Paper*, *416*. https://doi.org/10.2139/ssrn.4233395
Director Bioplastic Company. (2023, January 13). *Interview Thailand 37* [Personal communication].
Director Bioplastic Company. (2023, March 22). *Interview Thailand 39* [Personal communication].
Doner, R. (2009). *The Politics of Uneven Development: Thailand's Economic Growth in Comparative Perspective*. Cambridge University Press.

EEC. (2020). *Biofuel and Biochemical*. EEC. https://www.eeco.or.th/en
Eisenhardt, K. M., & Martin, J. A. (2000). Dynamic capabilities: What are they? *Strategic Management Journal*, *21*(10–11), 1105–1121. https://doi.org/10.1002/1097-0266(200010/11)21:10/11%253C1105::AID-SMJ133%253E3.0.CO;2-E
Ekins, P. (2021). The costs and benefits of environmental sustainability. *Sustainability Science*.
Ekwurzel, B., Boneham, J., Dalton, M. W., Heede, R., Mera, R. J., Allen, M. R., & Frumhoff, P. C. (2017). The rise in global atmospheric CO2, surface temperature, and sea level from emissions traced to major carbon producers. *Climatic Change*, *144*(4), 579–590. https://doi.org/10.1007/s10584-017-1978-0
Ertelt, S.-M., & Kask, J. (2024). Home field advantage: Examining incumbency reorientation dynamics in low-carbon transitions. *Environmental Innovation and Societal Transitions*, *50*, 100802. https://doi.org/10.1016/j.eist.2023.100802
European Bioplastics. (2022). *BIOPLASTICS MARKET DEVELOPMENT UPDATE 2022*. European Bioplastics.
Executive Director Research Public Organisation. (2022, March 16). *Interview Thailand 3* [Personal communication].
FAO. (2023). *Cassava production, 1961 to 2022. Our World in Data.* [Data set]. https://ourworldindata.org/grapher/cassava-production?tab=table
Flood, R. L., & Romm, N. R. A. (1996). Plurality revisited: Diversity management and triple loop learning. *Systems Practice*, *9*(6), 587–603. https://doi.org/10.1007/BF02169215
Fortune Business Insights. (2021). *Polylactic Acid Market Size, Share & COVID-19 Impact Analysis*. https://www.fortunebusinessinsights.com/polylactic-acid-pla-market-103429
Fossil Fuel Registry. (2024). *Fossil Fuel Registry* [Data set]. https://fossilfuelregistry.org/
Fuenfschilling, L. (2019). *Chapter 12: An institutional perspective on sustainability transitions*. https://www.elgaronline.com/edcollchap/edcoll/9781788112567/9781788112567.00020.xml
Full Professor Chemistry Major University. (2022, October 4). *Interview Thailand 17* [Personal communication].
Furnaro, A., & Manley, D. (2023). *Facing the Future What National Oil Companies Say About the Energy Transition*. National Resource Governance Institute.
Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Research Policy*, *31*(8–9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8
Geels, F. W. (2014). Reconceptualising the co-evolution of firms-in-industries and their environments: Developing an inter-disciplinary Triple Embeddedness Framework. *Research Policy*, *43*(2), 261–277. https://doi.org/10.1016/j.respol.2013.10.006
Geels, F. W. (2022). Causality and explanation in socio-technical transitions research: Mobilising epistemological insights from the wider social sciences. *Research Policy*, *51*(6), 104537. https://doi.org/10.1016/j.respol.2022.104537
Geels, F. W. (2024). *The Multi-Level Perspective on Sustainability Transitions: Background, overview, and current research topics*. https://doi.org/10.33774/coe-2024-c15gb

Geels, F. W., & Verhees, B. (2011). Cultural legitimacy and framing struggles in innovation journeys: A cultural-performative perspective and a case study of Dutch nuclear energy (1945–1986). *Technological Forecasting and Social Change*, *78*(6), 910–930. https://doi.org/10.1016/j.techfore.2010.12.004
Goyal, N., & Howlett, M. (2020). Who learns what in sustainability transitions? *Environmental Innovation and Societal Transitions*, *34*, 311–321. https://doi.org/10.1016/j.eist.2019.09.002
Granstrand, O., Patel, P., & Pavitt, K. (1997). Multi-Technology Corporations: Why They Have "Distributed" Rather Than "Distinctive Core" Competencies. *California Management Review*, *39*(4), 8–25. https://doi.org/10.2307/41165908
Griffin, D. P. (2017). *CDP Carbon Majors Report 2017*. CDP & Climate Accountability Institute.
Haddad, C. R., Nakić, V., Bergek, A., & Hellsmark, H. (2022). Transformative innovation policy: A systematic review. *Environmental Innovation and Societal Transitions*, *43*, 14–40. https://doi.org/10.1016/j.eist.2022.03.002
Halttunen, K., Slade, R., & Staffell, I. (2023). Diversify or die: Strategy options for oil majors in the sustainable energy transition. *Energy Research & Social Science*, *104*, 103253. https://doi.org/10.1016/j.erss.2023.103253
Hartmann, D., Zagato, L., Gala, P., & Pinheiro, F. L. (2021). Why did some countries catch-up, while others got stuck in the middle? Stages of productive sophistication and smart industrial policies. *Structural Change and Economic Dynamics*, *58*, 1–13. https://doi.org/10.1016/j.strueco.2021.04.007
Hausmann, R., & Hidalgo, C. A. (2011). The network structure of economic output. *Journal of Economic Growth*, *16*(4), 309–342. https://doi.org/10.1007/s10887-011-9071-4
Hausmann, Ricardo., & Hidalgo, C. A. (2013). *The atlas of economic complexity: Mapping paths to prosperity / edited by Ricardo Hausmann and César A. Hidalgo.* (Updated edition.). The MIT Press.
Heede, R. (2014). Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854–2010. *Climatic Change*, *122*(1–2), 229–241. https://doi.org/10.1007/s10584-013-0986-y
Helms Mills, J., Thurlow, A., & Mills, A. J. (2010). Making sense of sensemaking: The critical sensemaking approach. *Qualitative Research in Organizations and Management: An International Journal*, *5*(2), 182–195. https://doi.org/10.1108/17465641011068857
Herrera Anchustegui, I., & Tscherning, R. (2024). Offshore oil and gas infrastructure electrification and offshore wind: A legal exploration. *The Journal of World Energy Law & Business*, *17*(1), 35–53. https://doi.org/10.1093/jwelb/jwad035
Herzog-Hawelka, J., & Gupta, J. (2023). The role of (multi)national oil and gas companies in leaving fossil fuels underground: A systematic literature review. *Energy Research & Social Science*, *103*, 103194. https://doi.org/10.1016/j.erss.2023.103194
Hess, D. J. (2013). Industrial fields and countervailing power: The transformation of distributed solar energy in the United States. *Global Environmental Change*, *23*(5), 847–855. https://doi.org/10.1016/j.gloenvcha.2013.01.002
Hess, D. J. (2014). Sustainability transitions: A political coalition perspective. *Research Policy*, *43*(2), 278–283. https://doi.org/10.1016/j.respol.2013.10.008

Hidalgo, C. A., Klinger, B., Barabási, A.-L., & Hausmann, R. (2007). The Product Space Conditions the Development of Nations. *Science*, *317*(5837), 482–487. https://doi.org/10.1126/science.1144581
Holmgren, S., Giurca, A., Johansson, J., Kanarp, C. S., Stenius, T., & Fischer, K. (2022). Whose transformation is this? Unpacking the 'apparatus of capture' in Sweden's bioeconomy. *Environmental Innovation and Societal Transitions*, *42*, 44–57. https://doi.org/10.1016/j.eist.2021.11.005
Holmqvist, M. (2003). A dynamic model of intra- and interorganizational learning. *Organization Studies*, *24*(1), 95–123. https://doi.org/10.1177/0170840603024001684
Hölscher, K., Wittmayer, J. M., Olfert, A., Hirschnitz-Garbers, M., Walther, J., & Schiller, G. (2023). Creating actionable knowledge one step at a time: An analytical framework for tracing systems and agency in niche innovation pathways. *Environmental Innovation and Societal Transitions*, *46*, 100682. https://doi.org/10.1016/j.eist.2022.11.007
IEA. (2020). *The Oil and Gas Industry in Energy Transitions*. International Energy Agency.
IEA. (2023a). *Emissions from Oil and Gas Operations in Net Zero Transitions: A World Energy Outlook Special Report on the Oil and Gas Industry and COP28*. OECD. https://doi.org/10.1787/317cbf59-en
IEA. (2023b). *The Oil and Gas Industry in Net Zero Transitions*.
ILO. (2024). *Data and statistics | International Labour Organization*. https://www.ilo.org/data-and-statistics
Ingram, J., Maye, D., Kirwan, J., Curry, N., & Kubinakova, K. (2015). Interactions between Niche and Regime: An Analysis of Learning and Innovation Networks for Sustainable Agriculture across Europe. *The Journal of Agricultural Education and Extension*, *21*(1), 55–71. https://doi.org/10.1080/1389224X.2014.991114
Kattel, R. (2022). *Dynamic capabilities of the public sector: Towards a new synthesis*. UCL - IIPP.
Kemp, R., Rip, A., & Schot, J. (2001). Constructing transition paths through the management of niches. In *Path dependence and creation* (pp. 269–299). Psychology Press.
Kemp, R., Schot, J., & Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis & Strategic Management*, *10*(2), 175–198. https://doi.org/10.1080/09537329808524310
Kenner, D., & Heede, R. (2021). White knights, or horsemen of the apocalypse? Prospects for Big Oil to align emissions with a 1.5 °C pathway. *Energy Research & Social Science*, *79*, 102049. https://doi.org/10.1016/j.erss.2021.102049
Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M. S., … Wells, P. (2019). An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions*, *31*, 1–32. https://doi.org/10.1016/j.eist.2019.01.004
Kuckertz, A., Berger, E. S. C., & Brändle, L. (2020). Entrepreneurship and the sustainable bioeconomy transformation. *Environmental Innovation and Societal Transitions*, *37*, 332–344. https://doi.org/10.1016/j.eist.2020.10.003

Kump, B., Engelmann, A., Kessler, A., & Schweiger, C. (2019). Toward a dynamic capabilities scale: Measuring organizational sensing, seizing, and transforming capacities. *Industrial and Corporate Change*, *28*(5), 1149–1172. https://doi.org/10.1093/icc/dty054
Kungl, G. (2025). Incumbent firms in sustainability transitions – Different conceptions, heterogeneous roles and ideal types. *Environmental Innovation and Societal Transitions*, *57*, 101010. https://doi.org/10.1016/j.eist.2025.101010
Laaksonen, O., & Peltoniemi, M. (2018). The Essence of Dynamic Capabilities and their Measurement. *International Journal of Management Reviews*, *20*(2), 184–205. https://doi.org/10.1111/ijmr.12122
Lee, K., Qu, D., & Mao, Z. (2021). Global Value Chains, Industrial Policy, and Industrial Upgrading: Automotive Sectors in Malaysia, Thailand, and China in Comparison with Korea. *European Journal of Development Research*.
Losman, D. L. (2010). The Rentier State And National Oil Companies: An Economic And Political Perspective. *The Middle East Journal*, *64*(3), 427–445. https://doi.org/10.3751/64.3.15
Luchian-Lupu, A.-M., Zaharescu, T., Lungulescu, E.-M., Râpă, M., & Iovu, H. (2020). Availability of PLA/SIS blends for packaging and medical applications. *Radiation Physics and Chemistry*, *172*, 108696. https://doi.org/10.1016/j.radphyschem.2020.108696
Magnusson, T., & Werner, V. (2023). Conceptualisations of incumbent firms in sustainability transitions: Insights from organisation theory and a systematic literature review. *Business Strategy and the Environment*, *32*(2), 903–919. https://doi.org/10.1002/bse.3081
Mahdavi, P. (2020). *Power grab: Political survival through extractive resource nationalization*. University Press.
Mahdavi, P., Green, J., Hadden, J., & Hale, T. (2022). Using Earnings Calls to Understand the Political Behavior of Major Polluters. *Global Environmental Politics*, *22*(1), 159–174. https://doi.org/10.1162/glep_a_00641
Mäkitie, T., Andersen, A. D., Hanson, J., Normann, H. E., & Thune, T. M. (2018). Established sectors expediting clean technology industries? The Norwegian oil and gas sector's influence on offshore wind power. *Journal of Cleaner Production*, *177*, 813–823. https://doi.org/10.1016/j.jclepro.2017.12.209
Managing Director Major Biotech Company. (2022, December 15). *Interview Thailand 30* [Personal communication].
Manley, D., Cust, J. F., & Cecchinato, G. (2017). Stranded Nations? The Climate Policy Implications for Fossil Fuel-Rich Developing Countries. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3264765
Manley, D., Furnaro, A., & Heller, P. R. P. (2023). *Riskier Bets, Smaller Pockets: How National Oil Companies Are Spending Public Money Amid The Energy Transition*. National Resource Governance Institute.
Manley, D., & Heller, P. R. P. (2021). *Risky Bet—National Oil Companies in the Energy Transition*. NRGI.
Manley, D., Mihalyi, D., & Heller, P. R. P. (2019). Hidden Giants: It's time for more transparency in the management and governance of national oil companies. *Finance & Development*.

Marcel, V. (with Mitchell, J. V.). (2006). *Oil Titans: National Oil Companies in the Middle East* (1st edn, p. x). Brookings Institution Press and Chatham House.
McGlade, C., & Ekins, P. (2014). Un-burnable oil: An examination of oil resource utilisation in a decarbonised energy system. *Energy Policy*, *64*, 102–112. https://doi.org/10.1016/j.enpol.2013.09.042
Mealy, P., & Teytelboym, A. (2017). *Economic Complexity and the Green Economy*. https://ssrn.com/abstract=3111644
Mori, A., & Zhang, K. (2024). Networked sustainable business model innovation and sustainable energy transitions: A case study of incumbent Chinese manufacturers in 2010–2022. *Environmental Innovation and Societal Transitions*, *53*, 100911. https://doi.org/10.1016/j.eist.2024.100911
Mota, D. dos S., Alves, E. F., Sanchez-Acevedo, S., Svendsen, H. G., & Tedeschi, E. (2022, October 13). *Offshore Wind Farms and Isolated Oil and Gas Platforms: Perspectives and Possibilities*. ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering. https://doi.org/10.1115/OMAE2022-80645
Narula, R., & Driffield, N. (2012). Does FDI Cause Development? The Ambiguity of the Evidence and Why it Matters. *The European Journal of Development Research*, *24*(1), 1–7. https://doi.org/10.1057/ejdr.2011.51
National Roadmap for the Development of Bioplastic Industry, Cabinet Resolution 24/2551 (2008).
NatureWorks. (2023). *NatureWorks Announces Next Phase of Construction on New Fully Integrated Ingeo™ PLA Biopolymer Manufacturing Facility in Thailand*. https://www.natureworksllc.com/about-natureworks/news/press-releases/2023/2023-10-18-natureworks-announces-next-phase-of-construction-thailand
NRGI. (2019). *The National Oil Company Database*. National Resource Governance Institute.
NRGI. (2021). *National Oil Companies and Climate Change: Economic Challenges and Potential Responses*. Natural Resource Governance Institute. http://resourcegovernance.org/articles/national-oil-companies-and-climate-change-economic-challenges-and-potential-responses
NRGI. (2025). *National Oil Company Profiles*. National Resource Governance Institute. https://resourcegovernance.org/national-oil-companies-profiles
NSTDA. (2019). *NSTDA Annual Report 2019*.
NSTDA-BIOTEC. (2022). *NSTDA-BIOTEC website*. https://www.biotec.or.th/home/en/biotec-home-2021-en/
NXPO. (2019). *Thai STI Indicators 2019*. Office of National Higher Education Science Research and Innovation Policy Council. https://www.nxpo.or.th/th/en/report/4322/
OCSB. (2024). *Office of the Cane and Sugar Board*. https://catalog.ocsb.go.th/about
OEC. (2023). *Observatory of Economic Complexity* [Data set].
PatSeer. (2024). *PatSeer Software and Database* [Data set]. www.patseer.com
Penna, C. C. R., & Geels, F. W. (2015). Climate change and the slow reorientation of the American car industry (1979–2012): An application and extension of the Dialectic Issue LifeCycle (DILC) model. *Research Policy*, *44*(5), 1029–1048. https://doi.org/10.1016/j.respol.2014.11.010
Penrose, E. (1959). *The Theory of the Growth of the Firm*. Basil Blackwell.
Peszko, G., & et al. (2020). *Diversification and Cooperation in a Decarbonizing World*. World Bank Group.

Piening, E. P. (2013). Dynamic Capabilities in Public Organizations: A literature review and research agenda. *Public Management Review*, *15*(2), 209–245. https://doi.org/10.1080/14719037.2012.708358
Pinheiro, C. (2025). Relatedness and economic complexity as tools for industrial policy: Insights and limitations. *Structural Change and Economic Dynamics*, S0954349X24001486. https://doi.org/10.1016/j.strueco.2024.09.019
Pinheiro, F. L., Hartmann, D., Boschma, R., & Hidalgo, C. A. (2022). The time and frequency of unrelated diversification. *Research Policy*, *51*(8), 104323. https://doi.org/10.1016/j.respol.2021.104323
PLASTAT. (2023). *PLASTAT, Database by PITH (Plastic Institute of Thailand)* [Data set]. http://www.plastats.com/about.php
PTT. (2022). *PTT Annual Report 2021*.
PTT. (2024). *PTT Annual Report*.
PTT Website. (2021, April 17). *Innobic (Asia) Invests in LOTUS Pharmaceutical to Expand Its Pharmaceutical Portfolio Overseas*. https://www.pttplc.com/en/Media/News/Content-25580.aspx
PTTGC, & Stock Exchange Thailand. (2012, June 1). *Notification on the Investment in NatureWorks LLC*. https://www.pttgcgroup.com/en/investor-relations/newsroom/set-announcements/17322/notification-on-the-investment-in-natureworks-llc
Queiroz Pinto, H., Fagundes de Almeida, E., Bomtempo, J. V., Iootty, M., & Goulart Bicalho, R. (2016). *Economia da energia: Fundamentos econômicos, evolução histórica e organização industrial*. Elsevier.
Ramírez-Cendrero, J. M., & Paz, M. J. (2017). Oil fiscal regimes and national oil companies: A comparison between Pemex and Petrobras. *Energy Policy*, *101*, 473–483. https://doi.org/10.1016/j.enpol.2016.11.009
Raven, R., Kern, F., Verhees, B., & Smith, A. (2016). Niche construction and empowerment through socio-political work. A meta-analysis of six low-carbon technology cases. *Environmental Innovation and Societal Transitions*, *18*, 164–180. https://doi.org/10.1016/j.eist.2015.02.002
Rikap, C. (2023). Intellectual monopolies as a new pattern of innovation and technological regime. *Industrial and Corporate Change*, dtad077. https://doi.org/10.1093/icc/dtad077
Rodrik, D. (2014). Green industrial policy. *Oxford Review of Economic Policy*, *30*(3), 469–491. https://doi.org/10.1093/oxrep/gru025
Ruggiero, S., Martiskainen, M., & Onkila, T. (2018). Understanding the scaling-up of community energy niches through strategic niche management theory: Insights from Finland. *Journal of Cleaner Production*, *170*, 581–590. https://doi.org/10.1016/j.jclepro.2017.09.144
Sachs, L. E., Maennling, N., & Toledano, P. (2017). *How Oil and Gas Companies Can Help Meet the Global Goals on Energy and Climate Change*. Columbia Law School. https://scholarship.law.columbia.edu/sustainable_investment_staffpubs/35
Saleh, R., Vidican Auktor, G., & Brem, A. (2025). Incumbency and sustainability transitions: A systematic review and typology of strategies. *Energy Research & Social Science*, *122*, 104000. https://doi.org/10.1016/j.erss.2025.104000
Sampaio, R. M., & Bonacelli, M. B. M. (2018). Biodiesel in Brazil: Agricultural R&D at Petrobras Biocombustível. *Journal of Technology Management & Innovation*, *13*(1), 66–74. https://doi.org/10.4067/S0718-27242018000100066

Schot, J., & Geels, F. W. (2008). Strategic niche management and sustainable innovation journeys: Theory, findings, research agenda, and policy. *Technology Analysis & Strategic Management*, *20*(5), 537–554. https://doi.org/10.1080/09537320802292651
Schot, J., & Geels, F. W. (2011). Strategic niche management and sustainable innovation journeys: Theory, findings, research agenda, and policy. In *The Dynamics of Sustainable Innovation Journeys*. Routledge.
Semieniuk, G., Holden, P. B., Mercure, J., Salas, P., Pollitt, H., Jobson, K., Vercoulen, P., Chewpreecha, U., & Edwards, N. R. (2022). Stranded fossil-fuel assets translate to major losses for investors in advanced economies. *Nature - Climate Change*. https://doi.org/10.1038/s41558-022-01356-y%0AStranded
Simon, H. A. (1957). *Administrative Behavior: A Study of Decision-Making Processes in Administrative Organization*. Macmillan.
Simon, H. A. (1962). The Architecture of Complexity. *Proceedings Ofthe American Philosophical Society*, *106*(6), 467–482.
Singh, J. T. N. (2024). *Business of the State: Why State Ownership Matters for Resource Governance*. Oxford University Press.
Sovacool, B. K., Axsen, J., & Sorrell, S. (2018). Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. *Energy Research & Social Science*, *45*, 12–42. https://doi.org/10.1016/j.erss.2018.07.007
S&P Global. (2022). *Global Trade Atlas (IHS Markit)*.
Squicciarini, M., Dernis, H., & Criscuolo, C. (2013). *Measuring Patent Quality: Indicators of Technological and Economic Value* (OECD Science No. 03; Technology and Industry Working Papers). OECD Publishing. http://dx.doi.org/10.1787/5k4522wkw1r8-en
Statista. (2021). *Statista, Distribution of the production capacities of bioplastics worldwide*. https://www.statista.com/statistics/678775/production-capacity-distribution-of-bioplastics-worldwide-by-material/
Steen, M., & Weaver, T. (2017). Incumbents' diversification and cross-sectorial energy industry dynamics. *Research Policy*, *46*(6), 1071–1086. https://doi.org/10.1016/j.respol.2017.04.001
Strambo, C., Calles Almeida, P., & Arond, E. (2023). *Energy transition ambitions of four national oil and gas companies in South America*. Stockholm Environment Institute. https://doi.org/10.51414/sei2023.059
Sumner, A. (2018). Development and Distribution: Structural Change in South East Asia. In *Development and Distribution: Structural Change in South East Asia*. Oxford University Press. https://doi.org/10.1093/oso/9780198792369.001.0001
Tagliani, G. (2024). Long in the Making: Policy insights from the Thai bioeconomy sector. *Policy Brief UCL Institute for Innovation and Public Purpose*, *29*. https://www.ucl.ac.uk/bartlett/public-purpose/publications/2024/mar/long-making-policy-insights-thai-bioeconomy-sector
Tagliani, G. (2025a). Drilling for Sustainability: Dynamic Capabilities in National Oil Companies. *IIPP Working Paper*, *WP 2025—17*. https://www.ucl.ac.uk/bartlett/publications/2025/sep/drilling-sustainability-dynamic-capabilities-national-oil-companies
Tagliani, G. (2025b). State Oil Regimes in Transition: The Political Economy of NOCs in the Age of Climate Change. *SSRN Electronic Journal*.

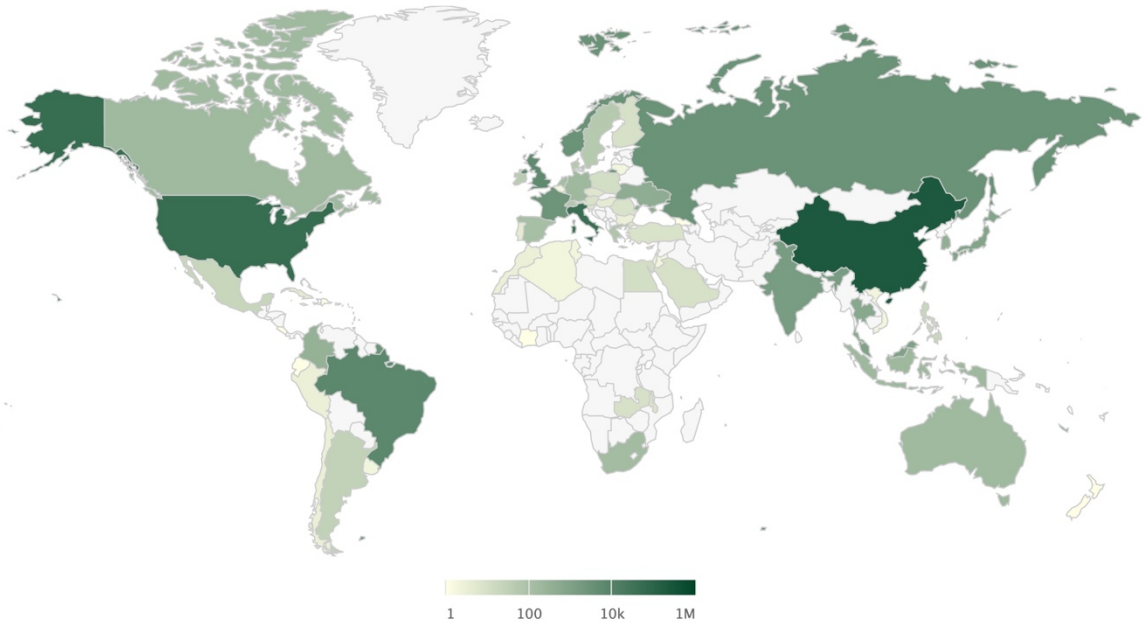
Tagliani, G., Furnaro, A., Manley, D., & Romero, C. (2025). *DONG to Ørsted: Seven insights to transform national oil companies*. Natural Resource Governance Institute.
Teece, D. J. (2007). Explicating dynamic capabilities: The nature and microfoundations of (sustainable) enterprise performance [Article]. *Strategic Management Journal*, *28*(13), 1319–1350. https://doi.org/10.1002/smj.640
Teece, D. J. (2014). The Foundations of Enterprise Performance: Dynamic and Ordinary Capabilities in an (Economic) Theory of Firms. *Academy of Management Perspectives*, *28*(4), 328–352. https://doi.org/10.5465/amp.2013.0116
Teece, D. J. (2021). Evolutionary Economics, Routines, and Dynamic Capabilities. In R. R. Nelson, K. Dopfer, & A. Pyka (Eds), *The Handbook of Evolutionary Economics* (Draft Version). Routledge.
Teece, D. J., Pisano, G., & Shuen, A. M. Y. (1997). Dynamic Capabilities and Strategic Management. *Strategic Management Journal*, *18*(7), 509–533.
The Nation. (2024, June 11). *Growth expected for Thailand's HDD industry*. Nationthailand. https://www.nationthailand.com/business/tech/40038717
Thurbon, E., Kim, S., Mathews, J. A., & Tan, H. (2023). *Developmental environmentalism: State ambition and creative destruction in East Asia's green energy transition / Elizabeth Thurbon, Sung-Young Kim, John A. Mathews, Hao Tan.* Oxford University Press. https://doi.org/10.1093/oso/9780192897794.001.0001
Tillotson, P., Slade, R., Staffell, I., & Halttunen, K. (2023). Deactivating climate activism? The seven strategies oil and gas majors use to counter rising shareholder action. *Energy Research & Social Science*, *103*, 103190. https://doi.org/10.1016/j.erss.2023.103190
Top Executive Bioproduct Association. (2022, March 17). *Interview Thailand 4* [Personal communication].
Top Executive Energy&Chemistry Foundation. (2022, November 21). *Interview Thailand 25* [Personal communication].
Top Executive Major Chemical Corporation. (2022, May 20). *Interview Thailand 8* [Personal communication].
Top Executive Research Public Agency. (2022, November 15). *Interview Thailand 23* [Personal communication].
Tordo, S., Tracy, B. S., & Arfaa, N. (2011). *National Oil Companies and Value Creation*. The World Bank. https://doi.org/10.1596/978-0-8213-8831-0
Tosey, P., Visser, M., & Saunders, M. N. (2012). The origins and conceptualizations of 'triple-loop' learning: A critical review. *Management Learning*, *43*(3), 291–307. https://doi.org/10.1177/1350507611426239
Turnheim, B., & Sovacool, B. K. (2020). Forever stuck in old ways? Pluralising incumbencies in sustainability transitions. *Environmental Innovation and Societal Transitions*, *35*, 180–184. https://doi.org/10.1016/j.eist.2019.10.012
UNCTAD. (2021, October 28). *Green industrial policies key for developing countries to adapt to climate change*. https://unctad.org/news/green-industrial-policies-key-developing-countries-adapt-climate-change
United States Environmental Protection Agency. (2020). *Global Greenhouse Gas Emissions Data* [Data set]. United States Environmental Protection Agency.
US Department of Agriculture. (2024). *Sugar: World Markets and Trade* [Data set]. https://fas.usda.gov/data/production/commodity/0612000

US DoE. (2017). *A Renewable Future for the Oil and Gas Industry*. Energy.Gov. https://www.energy.gov/eere/wind/articles/renewable-future-oil-and-gas-industry
Van de Ven, A. H. (1999). *The innovation journey*. Oxford University Press.
van Mossel, A., van Rijnsoever, F. J., & Hekkert, M. P. (2018). Navigators through the storm: A review of organization theories and the behavior of incumbent firms during transitions. *Environmental Innovation and Societal Transitions*, *26*, 44–63. https://doi.org/10.1016/j.eist.2017.07.001
Vice-President Business Association Agricultural Commodity. (2022, March 25). *Interview Thailand 6* [Personal communication].
Victor, N. M. (2007). On Measuring the Performance of National Oil Companies (NOCs). *Stanford University*, *Program on Energy and Sustainable Development*(Working Paper #64).
Voldsgaard, A., Mazzucato, M., & Conway, R. (2022). *From Competition State to Green Entrepreneurial State: New challenges for Denmark* (SAMFUNDSØKONOMEN, pp. 7–21).
Weick, K. E. (1995). *Sensemaking in Organizations*. SAGE.
Weick, K. E. (2004). FROM SENSEMAKING IN ORGANIZATIONS. In F. Dobbin (Ed.), *The New Economic Sociology*. Princeton University Press.
Wesche, J., Löhr, M., & Hess, D. J. (2024). *Only changing policy? The role of coalitions in sustainability transitions*. Cambridge Open Engage. https://doi.org/10.33774/coe-2024-tdwdx-v2
Wharton. (2017). *Can Thailand Escape the Middle-income Trap ?* (pp. 1–6). Wharton School of the University of Pennsylvania. https://knowledge.wharton.upenn.edu/article/can-thailand-escape-middle-income-trap/
Wianwiwat, S., & Asafu-Adjaye, J. (2013). Is there a role for biofuels in promoting energy self sufficiency and security? A CGE analysis of biofuel policy in Thailand. *Energy Policy*, *55*, 543–555. https://doi.org/10.1016/j.enpol.2012.12.054
Wiersema, M. F., & Beck, J. B. (2017). Corporate or Product Diversification. In *Oxford Research Encyclopedia of Business and Management*. https://doi.org/10.1093/acrefore/9780190224851.013.14
WIPO. (2022). *Global innovation index 2022*. World Intellectual Property Organization. https://doi.org/10.34667/TIND.46596
World Bank. (2023). *World Bank* [Data set]. https://data.worldbank.org/
World Bank Open Data. (2023). World Bank Open Data. https://data.worldbank.org
Yamada, E., Balland, P.-A., Kawakami, T., & Nemoto, J. (2024). The structure and dynamics of the auto parts industry: Product space and complexity perspectives. *Structural Change and Economic Dynamics*, S0954349X24001589. https://doi.org/10.1016/j.strueco.2024.11.004
Zollo, M., & Winter, S. G. (2002). Deliberate learning and the evolution of dynamic capabilities. *Organization Science*, *13*(3), 339–351.

Appendix A – Patent Data and Economic Complexity Methods

Patent data can be used to identify and position technological systems, and assess potential green transition avenues (Haščič & Migotto, 2015; OECD, 2015). Patent data on NOCs was collected over the course of 18 months and elaborated with rigour. Only the best quality patent data was selected by accessing the large PatSeer dataset. PatSeer is a proprietary dataset that collects patent data from all major patent offices worldwide (EPO, USPTO, CNIPA, WIPO, JPO) and over 108 patent offices and authorities worldwide. Patent data by NOCs, including PTT, has been collected across the whole dataset, as some NOCs choose major patent offices as priority countries in which to patent (especially in cases of triadic patent families). Some NOC subsidiaries are also based abroad and patent in their foreign host country. For these reasons, NOC patents go far beyond their national boundaries and are not limited to the main patent offices.

Figure 1-A: "Priority country for NOC patents"



Source: Author's from PatSeer dataset.

A major obstacle in the analysis has been the identification of all entities related to each NOC, particularly for those that adopt other scripts in addition to Latin. Ignoring this

constraint (for example by excluding non-Latin script or limiting the analysis to EPO, USPTO, CNIPA, WIPO, JPO) would provide grossly inaccurate numbers in the case of NOCs (for example, over a half of PTT's patents have Thai script). To address this, a novel entity-linking was developed.

One of the most challenging technical obstacles of dealing with patent data is data collection itself. Compared to country-level patent data, collecting data about firms increases the obstacles in terms of location and name disambiguation. Unlike countries, firms can be located across the globe through subsidiaries and international patent applications, both at national patent offices of foreign countries and at supranational offices (such as the European Patent Office, which since 2023 has seen the entry into force of the Unitary Patent process[21], or the World Intellectual Property Organization, to which applications can be made pursuant the pathway set out by the Patent Cooperation Treaty). Moreover, firms display an incredibly vast range of applicant names through which they apply, including all parent companies, subsidiaries and joint ventures, but also numerous misspellings, uses of non-Latin script and co-patenting instances. The process of name disambiguation "consists in assigning a unique identifier to n>1 records containing information on the same entity" (Pezzoni et al., 2014). The process of finding and verifying the association between an entity, in all its locations and names, and its patents is known as the "entity-linking" process.

The literature has developed a vast array of sophisticated algorithms for the entity-linking process, with evident trade-offs between time-consumption and accuracy. Location has been dealt with both indirectly, by assessing entities, and directly, with sophisticated techniques which include co-location based on satellite data from available addresses (de Rassenfosse et al., 2019). However, applications sometimes lack location information or provide generic, sometimes inaccurate, ones. The address is occasionally absent, city names are often part of road addresses causing confusion for the algorithm, and non-Latin script is not taken into consideration, thereby limiting its accuracy for those countries where the most common language is based on non-Latin script. Name

[21] The Unitary Patent or, more precisely, the "European patent with unitary effect" is achieved with a process through which applicants to national offices of countries which are part of the Unified Patent Court Agreement, all of which are European countries, can request their patent to have unitary effects across member countries, replacing the need for validation of the patent in each individual country concerned.

disambiguation has also proved to be particularly complex for large corporations, for which a multiplication of world-wide subsidiaries requires either manual time-consuming name finding and verification processes, or automated process, albeit with several limitations, particularly in terms of misspellings and reach of firm subsidiaries.

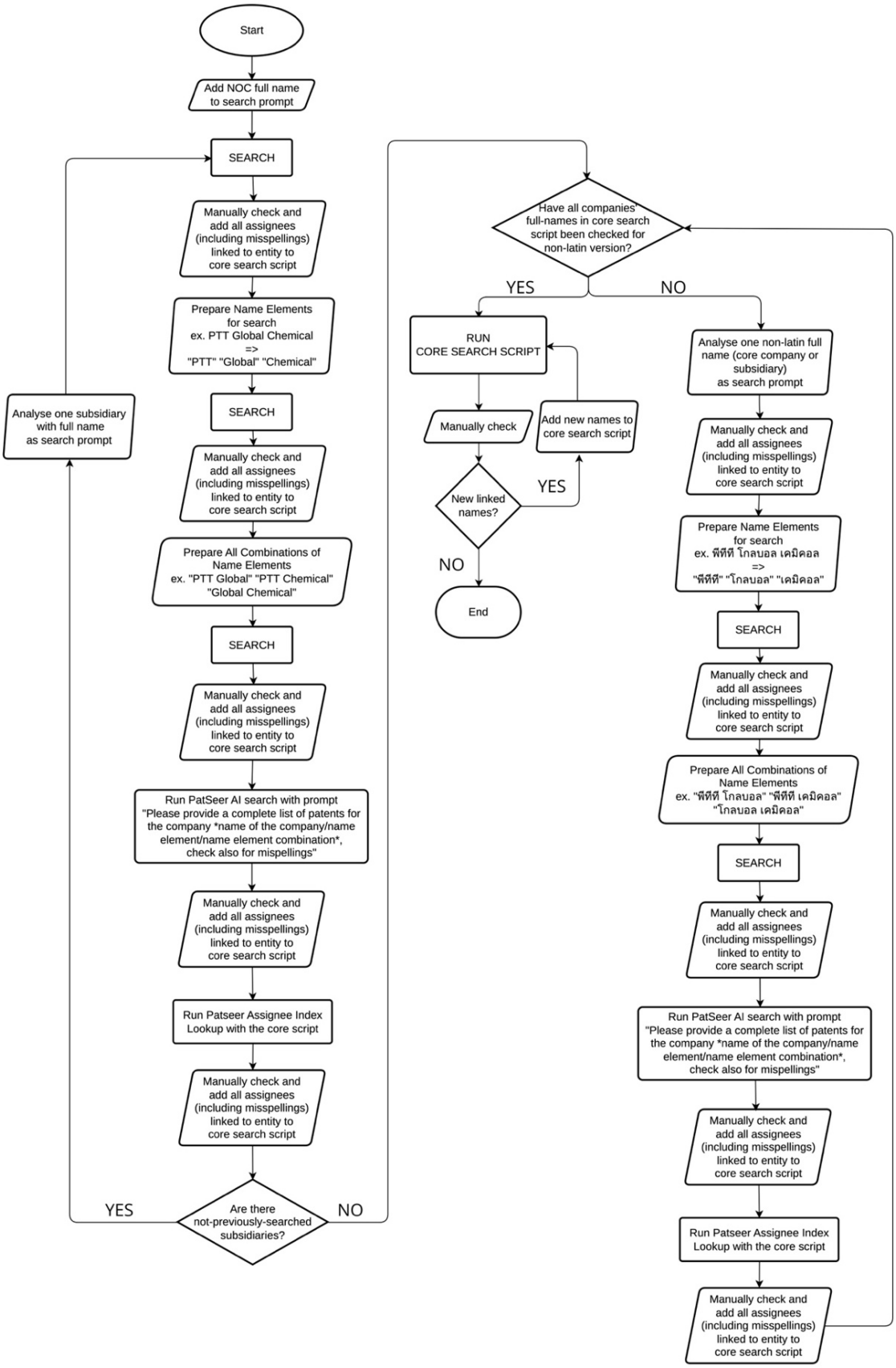
The algorithm adopted in this paper goes beyond entity-linking methods present in the literature (de Rassenfosse et al., 2019; Pellegrino et al., 2023; Pezzoni et al., 2014; Smalheiser & Torvik, 2009) and combines manual and automated techniques, prioritising accuracy, eliminating false positives through a final verification, and minimising false negatives by virtue of six time-intensive controls. The algorithm starts with the most common full name of the company, in our case a NOC, thereby imposing a lax condition and limiting instances of false negatives. The largest available array of names of parent companies and subsidiaries was collected on official websites, annual reports, PatSeer's built-in company tree for assignees[22], and on Eikon Refinitiv[23], a second control for reducing false negatives. Starting from the main company name, the algorithm runs the search on PatSeer, all manually verified entity names are added to the "core search script" (a list of entity names that includes only verified names perfectly corresponding to the patent applicant). Each name is then de-composed and all single components and combination of components go through similar search and verification processes, a third control for reducing false negatives. If new verified applicant names are found, they are added to the core search script. The algorithm combines these manual techniques with automated ones, using PatSeer's AI and its Assignee Index Lookup. The AI tool does not automatically lead to entity-linking decisions, it is only used to generate potential linkages, a fourth control for reducing false negatives. No linkage is added or removed solely because it is flagged by the AI, there is a manual one-by-one entity-linking verification for each of the flagged entities. Verified misspellings (for example, "PETOROREO BURAJIREIRO SA" for Petróleo Brasileiro S.A., Petrobras, at the Japanese Patent Office) were always included at all steps, a fifth control for reducing false negatives. If verified entities do not have a non-Latin version, the core search script is run and a final

[22] PatSeer is an advanced proprietary dataset and software for patents. Its most advanced version, ProX, was used for the research.

[23] Eikon Refinitiv is a proprietary database and workspace that also provides extensive company trees, sometimes over a thousand entities, including parent companies, subsidiaries, affiliates and joint-ventures

verification seals the result. If instead non-Latin script is involved, a similar step-by-step finding and verification process is followed, leading to the same final verification. The verification of non-Latin script constitutes the sixth control against false negatives. The algorithm is described in further detail in figure 2-A.

Figure 2-A: “Entity-linking Algorithm”


Start
Add NOC full name to search prompt
SEARCH
Manually check and add all assignees (including misspellings) linked to entity to core search script
Prepare Name Elements for search ex. PTT Global Chemical => "PTT" "Global" "Chemical"
SEARCH
Manually check and add all assignees (including misspellings) linked to entity to core search script
Prepare All Combinations of Name Elements ex. "PTT Global" "PTT Chemical" "Global Chemical"
SEARCH
Manually check and add all assignees (including misspellings) linked to entity to core search script
Run PatSeer AI search with prompt "Please provide a complete list of patents for the company *name of the company/name element/name element combination*, check also for mispellings"
Manually check and add all assignees (including misspellings) linked to entity to core search script
Run Patseer Assignee Index Lookup with the core script
Manually check and add all assignees (including misspellings) linked to entity to core search script
Are there not-previously-searched subsidiaries?
YES
NO
Analyse one subsidiary with full name as search prompt
Have all companies' full-names in core search script been checked for non-latin version?
YES
NO
RUN CORE SEARCH SCRIPT
Manually check
Add new names to core search script
New linked names?
YES
NO
End
Analyse one non-latin full name (core company or subsidiary) as search prompt
Manually check and add all assignees (including misspellings) linked to entity to core search script
Prepare Name Elements for search ex. พีทีที โกลบอล เคมิคอล => "พีทีที" "โกลบอล" "เคมิคอล"
SEARCH
Manually check and add all assignees (including misspellings) linked to entity to core search script
Prepare All Combinations of Name Elements ex. "พีทีที โกลบอล" "พีทีที เคมิคอล" "โกลบอล เคมิคอล"
SEARCH
Manually check and add all assignees (including misspellings) linked to entity to core search script
Run PatSeer AI search with prompt "Please provide a complete list of patents for the company *name of the company/name element/name element combination*, check also for mispellings"
Manually check and add all assignees (including misspellings) linked to entity to core search script
Run Patseer Assignee Index Lookup with the core script
Manually check and add all assignees (including misspellings) linked to entity to core search script

Source: Author's.

Implied in the de-composition of names, the algorithm also deals with *general names removal* (such as "LTD", "LLC" or "Company Limited"). Among the five options presented by the literature (namely, manual assignments, community-based efforts, unsupervised clustering that group nouns by similarity, supervised methods that utilise manually compiled training sets, methods that go beyond pairwise analysis of explicit information; Smalheiser & Torvik, 2009) the paper takes a mixed approach of manual assignments (highly accurate but time-consuming and possible only for a relatively moderate number of firms) combined with the use of AI thanks to PatSeer capabilities.

Some case-specific issues to be noted have to do with Thailand and PTT. In the case of Thailand, the country name had to be adjusted to include TH$ and Thai script in addition to TH. For PTT the main challenge was to include all PTT patents without using just the acronym "PTT" as the PTT acronym is linked to an *adversarial case* ("PTT Netherlands") and many other firms unrelated to original Thai PTT (in Thai script: ปตท). PTT also made several acquisitions with high impact on patent applications (such as "Myriant", now "PTTGC Innovation America", and NatureWorks), so the analysis was repeated with several rounds of robustness checks, including and removing certain elements in the core search script and comparing results according to the algorithm.

While the techniques involved in the entity-linking algorithm are time-consuming, the quality of data is greatly improved by the complete elimination of false positives and by the great reduction of false negatives with mixed methods of finding (recognition) and verification (resolution, deduplication, and disambiguation) using manual and automated techniques.

It should be noted that a structural limitation of patenting data remains. While trade data is available up to 2023[24], because of the usual delays in data on patenting activity due to the length of the patenting process, there is an underestimation of patenting activity for the most recent years. The analysis uses all available PTT patenting data up to December 2023 to off-set part of this tendency, but this structural underestimation of

[24] To off-set the disruption to patent offices and trade caused by COVID19, 2018-2023 6-year averages for trade and patenting data were used for building Thailand's technological and product spaces.

patenting data for the most recent years means that patenting data still likely underestimates PTT's actual patenting activity.

For the selection of green patents, the paper has adopted the most common method in the literature (Barbieri et al., 2020, 2023; Haščič & Migotto, 2015), which entails a 3-digit level of categorisation, with green patents being those that display (among others) the CPC-code Y02 code: "Technologies or Applications for Mitigation or Adaptation against Climate Change". Around 27% of PTT's patents do not have a CPC code, however, if other patents in the same family are taken into account, the percentage decreases to around 10% (because many Thai-priority patents have foreign patents within the same family that adopt the CPC classification). Furthermore, it should be noted that not all patents in IPC-only classification would have a Y02-code green patenting classification. In fact, in the likely scenario in which the share of "greenness" in PTT patenting is similar between patents that have CPC codes and IPC-only patents, the underestimation of green patents out of total patents is reduced from 27% to around 3%, and from 10% to 1% if families are taken into account.

The paper also relies on well-established methodology on technology and product spaces (Alstott et al., 2017; Caldarola et al., 2024; Hausmann & Hidalgo, 2013), using patent and export data sourced from PatSeer and UN Comtrade, respectively. The methodology used in this paper to build product and technological space reflects established approaches on the usability of similar procedure for both types of data (Balland et al., 2022; Pinheiro et al., 2025). UN Comtrade data (UN Comtrade) is freely available and it is compiled by the United Nations Statistics Division, covering almost 200 countries. With more than 100 matching countries, the two databases together provide extensive data that covers not just all major economies, but also an incredibly vast array of countries at all levels of development. The economic complexity methodology employed spatially reflects the relatedness of patent and product codes in real-world technologies and trade, highlighting each nation's revealed comparative advantages (revealed CA or RCA). The comparative advantages of Thailand are represented in purple in the product and technological spaces.

The coding for building the product and technological spaces was done using Python. The visualisations are done according to a maximum spanning tree plot (MST), meaning that the network reflects only the strongest connections, thus producing a tree-

like structure. The process first focuses on importing data, then on calculating co-occurrences while controlling for product ubiquity and country's diversification for the product space. The draw function is defined and produces the visualisation of the product space. The process follows similar steps for patent data, albeit with some modifications[25]. The appendix provides here a detailed description of the equations involved and of the main steps taken to build the product and technological spaces, including coding.

A) Mathematical formalisations:

A1- Co-occurrences:

$$C_{p,p'} = \sum_{c} M_{c,p}\, M_{c,p'}$$

C represents the proximity matrix, it tells us how close together two products are. In particular, the (p,p′) entry of the proximity matrix $[C_{p,p'}]$, measures how many countries simultaneously export (have a RCA) both product p and product p′. $M_{c,p}$ represents the binarised export matrix of the country c and, in particular, the (c,p) entry is:

$$M_{c,p} = \begin{cases} 1, & if\ country\ c\ has\ RCA \geq 1\ in\ product\ p \\ 0, & otherwise \end{cases}$$

$M_{c,p}M_{c,p'}$ will result as 1 if the country has an RCA in both products, or 0 otherwise. $C_{p,p'}$ is then obtained by repeating for c (number of countries) the sum of the times in which countries simultaneously have an RCA in both product p and p′, giving us the proximity of the two products.

A-2 Co-occurrences controlled for ubiquity:

$$C_{p,p'} = \frac{1}{\max\,(U_p, U_{p'})} \sum_{c} M_{c,p}\, M_{c,p'}$$

The fraction now included before the sum aims to control for product ubiquity. $1/\max\,(U_p, U_p')$ controls for the maximum ubiquity between among the two products.

[25] A main difference is in the calculation of the RCA. Patents counts are more noisy than product data which motivates, in order to reveal the backbone of capabilities, the stricter RCA condition set to >1 instead of >=1 which is the standard for product spaces (see equation (2) in Cicerone et al., 2019). The result is a clearer technological space focused on truly specialised technological capabilities rather than coincidental patenting.

Controlling for maximum ubiquity ensures that even if one product is highly ubiquitous (exported by many countries), the co-occurrence is normalized to its scale. Using the average between p and p′ would still allow ubiquitous products to dominate, while the sum would over-penalize pairs where one product is rare and the other is ubiquitous.

A-3 Co-occurrences controlled for ubiquity and diversification:

$$C_{p,p'} = \frac{1}{\max(U_p, U_{p'})} \sum_c \frac{M_{c,p} M_{c,p'}}{D_c}$$

Some countries are highly diversified and are able to export hundreds of products competitively. Unless the calculations control for diversification, a highly diversified country would artificially inflate co-occurrences across the board, even for product-pairs that aren't truly proximous. This equation aims to control for diversification as well by including the term D_c (number of products that the country c exports competitively).

B) Steps followed and relative coding:

1. Importing data and relevant libraries

```
import pandas as pd
import numpy as np
import seaborn as sns
import networkx as nx
import matplotlib.pyplot as plt
export = np.stack([pd.read_csv(data_folder+'/'+str(digits)+'digits/exports_'+str(yr)+'.csv',
countries = pd.read_csv(...).index.values
products = pd.read_csv(...).columns.values
```

2. Product-product co-occurences function, computation of the RCA (revealed comparative advantage) matrix, and binarisation of the matrix

```
def Cooccurrencies(mcp):
    return np.dot(mcp.T, mcp)
def compute_rca(exportmatrix):
    with np.errstate(invalid='ignore', divide='ignore'):
        rca = ((exportmatrix.T / exportmatrix.sum(1)).T /
            (exportmatrix.sum(0) / exportmatrix.sum()))
    rca = np.nan_to_num(rca)
    return rca
rca = np.stack([compute_rca(exp) for exp in export])
mcp = (rca >= 1).astype(float)
```

3. Build product space network: calculate product co-occurences controlled for ubiquity

```
def ProductSpace(mcp):
    C = np.dot(mcp.T, mcp)
    ubiquity = mcp.sum(0)
    norm = np.array([[max(ubiquity[p1], ubiquity[p2])
                for p1 in range(len(C))] for p2 in range(len(C))])
```

```
    return C / norm
C = ProductSpace(mcp[-1])
```

4. Build “taxonomy” matrix: product space network controlled for both ubiquity and diversification of countries’ exports

```
def Taxonomy(mcp):
    ubiquity = mcp.sum(0)
    mcp = (mcp.T / np.sqrt(mcp.sum(1))).T
    C = np.dot(mcp.T, mcp)
    norm = np.array([[max(ubiquity[p1], ubiquity[p2]) for p1 in range(len(C))] for p2 in range(len(C))])
    C = C/norm
    return C
C = Taxonomy(mcp[-1])
list_of_dict = []
for c1 in range(len(C)):
    for c2 in range(c1, len(C)):
        list_of_dict.append({'p1': descr[c1],
                             'p2': descr[c2],
                             'Taxonomy': C[c1,c2]})
taxonomy_df = pd.DataFrame(list_of_dict)
```

5. Define draw network function, use maximum spanning tree (MST) approach, and a graphical support based on Bokeh

```
import networkx as nx
import matplotlib.pyplot as plt
from bokeh.plotting import figure, from_networkx, show
from bokeh.io import output_notebook
from bokeh.models import Circle
from matplotlib.colors import LinearSegmentedColormap, to_hex
def draw_network(df, colors=None):
    df.columns = ['source', 'target', 'weight']
    df = df.loc[df.source != df.target].copy()
    label2ix = {v:k for k,v in enumerate(descr)}
    ix2label = {k:v for k,v in enumerate(descr)}
    df.loc[:, 'source'] = df.source.apply(lambda x: label2ix[x]).values
    df.loc[:, 'target'] = df.target.apply(lambda x: label2ix[x]).values
    graph = nx.from_pandas_edgelist(df,
                                    create_using=nx.Graph, edge_attr=True)
    mst = nx.maximum_spanning_tree(graph)
    wgt = np.array([e[-1]['weight'] for e in mst.edges(data=True)])
    for _, row in df.sort_values('weight', ascending=False).head(150).iterrows():
        mst.add_edge(row.source, row.target, weight=row.weight)
    p = figure(x_range=(-3, 3), y_range=(-3, 3),
           x_axis_location=None, y_axis_location=None,
           tools="hover, pan", tooltips="@label", aspect_ratio=1)
    p.grid.grid_line_color = None
    graph = from_networkx(mst, nx.kamada_kawai_layout, scale=1.8, center=(0,0))
    p.renderers.append(graph)
    graph.node_renderer.data_source.data['label'] = [d.replace(";", "\n") for d in descr]
    if colors is not None:
        colors = colors/max(colors)
        graph.node_renderer.data_source.data['colors'] = [to_hex(cmap(m)) for m in colors]
        graph.node_renderer.glyph.update(size=12, fill_color='colors')
    else:
        graph.node_renderer.glyph.update(size=12)
    output_file("graph.html")
```

6. Visualize Thailand's product space: using draw network function to plot network highlighting Thailand's comparative advantages in products

```
country = 'THA'
draw_network(taxonomy_df.copy(),
        colors=mcp[-1,np.where(countries == country)[0][0]])
```

7. Load patent data for technological space: import technology data and align with country codes

```
tech_complete = pd.read_csv(data_folder+'/patents/complete.csv', index_col=0)
tech_desc = pd.read_csv(data_folder+'/cpc3digits.csv')
tech_code2desc = {k:v for k,v in tech_desc.values}
```

8. Compute technology RCA for patents: calculate technological comparative advantage

```
def compute_rca(patmatrix):
   with np.errstate(invalid='ignore', divide='ignore'):
      rca = np.array(
         (patmatrix.T / patmatrix.sum(1)).T / (patmatrix.sum(0) / patmatrix.sum()),
         dtype=float)
   rca[np.where(np.isnan(rca))] = 0.
   rca[np.where(np.isinf(rca))] = 0.
   return rca
mct = (compute_rca(tech_complete.values) > 1).astype(float)
```

9. Build technology taxonomy network: align technology matrix and transpose, compute co-occurences, create technological similarity network adjusted for ubiquity and diversification

```
mct = (compute_rca(tech_complete.values)>1).astype(float)
countries=countries[mct.sum(1)>0]
mct=mct[mct.sum(1)>0]
mct=mct.T
tech = tech_complete.columns.values
tech=tech[mct.sum(1)>0]
mct=mct[mct.sum(1)>0]
mct=mct.T
mct.shape

C = np.dot(mct[-1].T, mct[-1])
C.shape

def Taxonomy(mct):
   ubiquity = mct.sum(0)
   mct = (mct.T / np.sqrt(mct.sum(1))).T
   C = np.dot(mct.T, mct)
   norm = np.array([[max(ubiquity[t1], ubiquity[t2])  for t1 in range(len(C))] for t2 in range(len(C))])
   C = C/norm
 return C
C = Taxonomy(mct)
tech_taxonomy = Taxonomy(mct)
```

10. Visualize Thailand's technological space: plot Thailand's comparative advantages in technologies

```
country = 'THA'
draw_network(taxonomy_df.copy(),
```

```
colors=mct[np.where(countries == country)[0][0]]
```

This economic complexity methodology exhibits two main limitations. The first limitation is that relatedness hides the nature of the relationship, which can be of complementarity or similarity. To address this, the paper critically analyses results and qualifies the relationships through technological clusters (TC) and product areas beyond standard spatial positioning. For instance, the electric vehicles (EVs) TC shows how EV-related technologies have brought electricity (H02, H05, codes similar to each other) and vehicles (B60, B62, codes similar to each other) classification codes closer in a relationship of complementarity.

The second limitation is that established economic complexity tools are at the macro-national level and struggle to account for micro-firm dynamics, which are instead essential for explaining how complexity-based policy recommendations can be implemented. For this reason, the paper adopts the case study method with the use of semi-structured interviews, which play a fundamental role in understanding patent evolution processes identified through quantitative patent analysis. The paper also introduces a firm-level analysis within the technological and product spaces, highlighting which codes are already CA at the national level and which, instead, are frontier firm developments by the NOC. While the number of product codes matching with PTT's productions are relatively few (eight) and all produced at industrial scale, hence there is no need to select those most representative of PTT's capabilities, the same is not true for patents. PTT has patents covering 121 patent codes, therefore a threshold that selects those most representative of PTT's technological capabilities had to be implemented. The firm-level analysis highlights in green (no national-level RCA) and blue (with national-level RCA) in the graph those codes in which PTT holds at least 30 patents, which also represent the top decile of PTT's most common patent codes[26]. This threshold excludes the flat section of the distribution[27]. The threshold selects those primary codes

[26] The analysis includes only specialised technology classifications codes, excluding the Y category, because it constitutes a catch-all cross-functional classification category. Category Y's heterogeneous and policy-oriented scope risks conflating the study of the pathway with broad non-domain-specific green tagging.

[27] A code reflecting 30 patents implies around 1.4% of patents having that code. A threshold of 1.4% enables the exclusion of the flat section of the distribution. For example, while only 6 codes reflect between 2% and 1% of PTT's patents, 108 codes are between 1% and 0.003%.

representing the top 13 patent codes out of 121 patent codes involved in PTT patenting activity.

The exceptional alignment between the technological and product spaces confirms the methodological accuracy of complexity tools in that, although from different data sources, both effectively mirror Thailand's and PTT's technological and production capabilities and CA. The "cement" CA reflects the size of SCG Cement group, one of the largest and most advanced firms in Thailand. CA in "Vehicles in general" and "land vehicles" reflect Thailand's role in the automotive value-chain (Asawachintachit, 2012; Natsuda & Thoburn, 2013). The CA in "non-woven fabrics" in the technological space mirrors the CA in "cables, non-woven" in the product space, as does the CA in "animal or veg. fats, oils fatty acids" technologies with the CA in "animal and veg. fats, waxes" products.

References

Alstott, J., Triulzi, G., Yan, B., & Luo, J. (2017). Mapping technology space by normalizing patent networks. *Scientometrics*, *110*(1), 443–479. https://doi.org/10.1007/s11192-016-2107-y

Asawachintachit, D. (2012). *THAILAND: AUTOMOTIVE HUB OF ASIA*. Thailand Board of Investment (BOI).

Balland, P.-A., Broekel, T., Diodato, D., Giuliani, E., Hausmann, R., O'Clery, N., & Rigby, D. (2022). The new paradigm of economic complexity. *Research Policy*, *51*(3), 104450. https://doi.org/10.1016/j.respol.2021.104450

Barbieri, N., Marzucchi, A., & Rizzo, U. (2020). Knowledge sources and impacts on subsequent inventions: Do green technologies differ from non-green ones? *Research Policy*, *49*(2), 103901. https://doi.org/10.1016/j.respol.2019.103901

Barbieri, N., Marzucchi, A., & Rizzo, U. (2023). Green technologies, interdependencies, and policy. *Journal of Environmental Economics and Management*, *118*, 102791. https://doi.org/10.1016/j.jeem.2023.102791

Caldarola, B., Mazzilli, D., Napolitano, L., Patelli, A., & Sbardella, A. (2024). Economic complexity and the sustainability transition: A review of data, methods, and literature. *Journal of Physics: Complexity*, *5*(2), 022001. https://doi.org/10.1088/2632-072X/ad4f3d

Cicerone, G., McCann, P., & Venhorst, V. A. (2019). Promoting regional growth and innovation: Relatedness, revealed comparative advantage and the product space. *Journal of Economic Geography*. https://doi.org/10.1093/jeg/lbz001

de Rassenfosse, G., Kozak, J., & Seliger, F. (2019). Geocoding of worldwide patent data. *Scientific Data*, *6*(1), 260. https://doi.org/10.1038/s41597-019-0264-6

Haščič, I., & Migotto, M. (2015). *Measuring environmental innovation using patent data* (OECD Environment Working Papers No. 89; OECD Environment Working Papers, Vol. 89). https://doi.org/10.1787/5js009kf48xw-en
Hausmann, Ricardo., & Hidalgo, C. A. (2013). *The atlas of economic complexity: Mapping paths to prosperity / edited by Ricardo Hausmann and César A. Hidalgo.* (Updated edition.). The MIT Press.
Natsuda, K., & Thoburn, J. (2013). Industrial policy and the development of the automotive industry in Thailand. *Journal of the Asia Pacific Economy*, *18*(3), 413–437. https://doi.org/10.1080/13547860.2012.742690
OECD. (2015). *Measuring environmental innovation using patent data* (OECD Environment Working Papers No. 89; OECD Environment Working Papers, Vol. 89). https://doi.org/10.1787/5js009kf48xw-en
Pellegrino, G., Penner, O., Piguet, E., & De Rassenfosse, G. (2023). Productivity gains from migration: Evidence from inventors. *Research Policy*, *52*(1), 104631. https://doi.org/10.1016/j.respol.2022.104631
Pezzoni, M., Lissoni, F., & Tarasconi, G. (2014). How to kill inventors: Testing the Massacrator© algorithm for inventor disambiguation. *Scientometrics*, *101*(1), 477–504. https://doi.org/10.1007/s11192-014-1375-7
Pinheiro, F. L., Balland, P.-A., Boschma, R., & Hartmann, D. (2025). The dark side of the geography of innovation: Relatedness, complexity and regional inequality in Europe. *Regional Studies*, *59*(1), 2106362. https://doi.org/10.1080/00343404.2022.2106362
Smalheiser, N. R., & Torvik, V. I. (2009). Author name disambiguation. *Annual Review of Information Science and Technology*, *43*(1), 1–43. https://doi.org/10.1002/aris.2009.1440430113
UN Comtrade. (2025). *UN Comtrade Dataset* [Data set]. https://comtradeplus.un.org/

Appendix B – Case study and Interviews

The case study method was fundamental in order to understand the role of PTT within Thailand's technological and product spaces and to address the limitations of quantitative patent data analysis. Indeed, case studies are the most effective methodological tool to answer research questions in areas with little prior theory and established evidence (Eisenhardt, 2021), as is the case for the green technological transformation of NOCs in general, and of PTT more specifically.

In the paper, the case study selection is extensively justified and relevant contextual factors are identified to promote transparency and replicability. The case selected, PTT, is an "outlier illustrative case", given that only a handful of NOCs have effectively transformed, with DONG being the only other clear outlier among over 50 NOCs (although, unlike PTT, the case of DONG has already been extensively covered by the literature; Algers & Kattel, 2021; McKinsey, 2020; Sheppard, 2020; Tagliani et al., 2025; Voldsgaard & Rüdiger, 2020). This type of case offers to the researcher the opportunity to study how green technological transformations could play out for other actors similar to the one under analysis (in this case, other NOCs) and, primarily, to identify the factors that set apart a trajectory of success in the outlier illustrative case from those of other similar actors. The external validity of PTT's case of green technological transformation is greater than DONG's given that the majority of NOCs are in middle-income countries with starting conditions closer to those of Thailand than those of Denmark.

The case study of PTT relies on secondary documental sources, semi-structured interviews, and PTT-related patent data. The documental sources include PTT's sustainability and annual company reports from 2007 to 2023, secondary literature (including Thailand-specific literature such as: ADB, 2009; Anuchitworawong et al., 2012; ASEAN Japan Centre, 2019; Aung, 2021; Aung et al., 2020; Bell et al., 2011; Chiengkul, 2019; Delina, 2018; Doner, 2009; Fielding & Aung, 2018; Lamonphet, 2017; RobecoSAM, 2018), and data from international agencies (IEA, FAO, UN Comtrade, WIPO, World Bank, UNCTAD) and government offices (Office of Industrial Economics, NSTDA, NESDC, EEC, BOI, NXPO, OCSB). Of particular value was the dataset

PLASTAT (PLASTAT, 2023), a dataset developed by the research institute PITH (Plastic Institute of Thailand), which provides detailed data on plastics (including bioplastics).

Fifty semi-structured interviews were carried out between 2022 and 2024 in Bangkok (Thailand) and remotely. The interviews collected ranged from 30 to 140 minutes, for a total of 3085 minutes of interview data. Participants included 10 current and ex-members of PTT, including three top executives[28], a director, a vice-president, and a division manager[29]. Participants were chosen based on the following criteria: actors mentioned in relevant document analyses, individuals recommended by PTT informants, and those identified during interviews using the snowball sampling method. Three interviewees served as key individual informants because of their role within the firm or in the NIA project. The overall structure of the interviews was made of four sections with eleven items:

1. industrial and value chain structure: 1.1 open questions on industry (ex. interviewee's role, main actors, their role, government), 1.2 industry linkages (supplies, buyers, exports), 1.3 value chain positioning (product-side).

2. success factors: 2.1 open questions on success factors, 2.2 innovation (role of intermediaries and projects), 2.3 size and acquisitions (external engagement), 2.4 endowments (pre-existing capabilities), 2.5 open questions on PTT-related success factors.

3. green technologies: 3.1 general green technologies (interviewee's role in tech transformation), 3.2 questions on feedstock and technological linkages between technologies.

4. interviewee- and PTT-specific: 4.1 internal PTT-specific questions (highly dependent on the specific role and information of the interviewee *vis-à-vis* PTT).

[28] This category of interviewees includes only *Chief Executive Officer (CEO), Chief Financial Officer (CFO), Chief Scientific Officer (CSO), President and Executive Director.*

[29] Other participants were from twelve other bioeconomy-related firms, three producers' associations, one farmers' association, eleven public sector agencies and ministries, three professors and top executives from major universities and research centres, and two interviewees from foreign partners in PTT's external engagement.

While the interviews followed the same structure (in terms of sections, and items for each section), the specific questions were different for each interviewee, following item-related prompts. Finally, not all items were relevant for all interviewees.

PTT's case study is based on a triangulation of multiple data sources (secondary documental sources, interviews, patent data, quantitative data from international and government offices), each analysed with the method best suited to its nature and to the degree needed for its purpose. Documental and patent data were examined using descriptive statistics and complexity tools. Interviews and document excerpts provided information, contextualisation, clarifications and illustrative examples, for instance, on lactic-acid polymerisation technologies, biofuels, and niche-experimentation projects leading to sensing capabilities. They also served to validate and explain the quantitative findings with key individual informants (sometimes quoted in the core empirical section). Interviews followed a consistent guide but were not subject to formal thematic analysis. Interviews confirm, inform and enrich the discussion of PTT's green technological transformation with a fundamental role in understanding patent evolution processes identified through quantitative patent analysis.

References

ADB. (2009). *Status and Potential for the Development of Biofuels and Rural Renewable Energy: Thailand*.

Algers, J., & Kattel, R. (2021). EQUINOR AND ØRSTED: HOW INDUSTRIAL POLICY SHAPED THE SCANDINAVIAN ENERGY GIANTS. *IIPP POLICY BRIEF*.

Anuchitworawong, C., Leangcharoen, P., & Thampanishvong, K. (2012). *Green growth and green jobs in Thailand: Comparative analysis, potentials, perspectives* (p. 81). Friedrich Ebert Stiftung.

ASEAN Japan Centre. (2019). *Global Value Chains in ASEAN: Thailand* (pp. 2–52). ASEAN Japan Centre. https://www.asean.or.jp

Aung, M. T. (2021). *Bioeconomy In Thailand: At a glance*. Stockholm Environment Institute.

Aung, M. T., Nguyen, H., & Denduang, B. (2020). Power and influence in the development of Thailand' s bioeconomy. *Stockholm Environment Institute*, *July 2019*, 1–8.

Bell, D. R., Silalertruksa, T., Gheewala, S. H., & Kamens, R. (2011). The net cost of biofuels in Thailand-An economic analysis. *Energy Policy*, *39*(2), 834–843. https://doi.org/10.1016/j.enpol.2010.11.002

Chiengkul, P. (2019). Uneven development, inequality and concentration of power: A critique of Thailand 4.0. *Third World Quarterly*, *40*(9), 1689–1707. https://doi.org/10.1080/01436597.2019.1612739
Delina, L. L. (2018). Energy Research & Social Science Whose and what futures? Navigating the contested coproduction of Thailand's energy sociotechnical imaginaries. *Energy Research & Social Science*, *35*(March 2017), 48–56. https://doi.org/10.1016/j.erss.2017.10.045
Doner, R. (2009). *The Politics of Uneven Development: Thailand's Economic Growth in Comparative Perspective*. Cambridge University Press.
Eisenhardt, K. M. (2021). What is the Eisenhardt Method, really? *Strategic Organization*, *19*(1), 147–160. https://doi.org/10.1177/1476127020982866
Fielding, M., & Aung, M. T. (2018). *Bioeconomy in Thailand: A case study*. Stockholm Environment Institute.
Lamonphet, A. (2017, April 22). Mitr Phol, PTT mull biotech. *Bangkok Post*. https://www.bangkokpost.com/business/1236358/mitr-phol-ptt-mull-biotech
McKinsey. (2020). *Ørsted's renewable-energy transformation*. https://www.mckinsey.com/capabilities/sustainability/our-insights/orsteds-renewable-energy-transformation#/
PLASTAT. (2023). *PLASTAT, Database by PITH (Plastic Institute of Thailand)* [Dataset]. http://www.plastats.com/about.php
RobecoSAM. (2018). *Industry Leader Report: PTT PCL*. RobecoSAM AG.
Sheppard, D. (2020). Can Orsted be the first green energy supermajor? *Financial Times*. https://www.ft.com/content/74b377c8-4435-11ea-abea-0c7a29cd66fe
Tagliani, G., Furnaro, A., Manley, D., & Romero, C. (2025). *DONG to Ørsted: Seven insights to transform national oil companies*. Natural Resource Governance Institute.
Voldsgaard, A., & Rüdiger, M. (2020). Innovative Enterprise, Industrial Ecosystems and Sustainable Transition: The Case of Transforming DONG Energy to Ørsted. In M. Lackner, B. Sajjadi, & W.-Y. Chen (Eds.), *Handbook of Climate Change Mitigation and Adaptation* (pp. 1–52). Springer New York. https://doi.org/10.1007/978-1-4614-6431-0_160-1