Research areas for Decarbonisation and Beyond Carbon Neutrality

UTokyo IMPERIAL HITACHI

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1 Collaborating on decarbonisation and further action for sustainability goals

Through establishing research centres and the creation of strategic partnerships, Hitachi, The University of Tokyo, and Imperial College London have stated their motivation and mission to contribute to decarbonisation and promote further actions for sustainability goals.
"Hitachi The University of Tokyo Laboratory" was established in June 2016 with the goal of realising Society 5.0, where the cyber and physical spaces are intricately connected attending in detail to the various needs of society by providing necessary items or services to the people who require them, when they are required, in the amount required. To help realise this vision, activities are focused on two projects entitled "Energy Systems" and "Habitat Innovation" [1]-[3].
"Hitachi-Imperial Centre for Decarbonisation and Natural Climate Solution" was established in August 2022 as a 5-year initiative between Hitachi Ltd, Hitachi Europe and Imperial College London to help tackle the issue of global pollution initially focused on decarbonisation and climate repair, and with the ambition of extending beyond net zero challenges. The activities of the centre are across three research pillars: Carbon Management and Decarbonisation, CO2 Removal (Technology and Nature-based Solutions), and Socioeconomic and Policy work [4].
Building on the above two industry-research centres, in May 2023, Imperial College London and the University of Tokyo announced a major new strategic relationship for cleantech and energy research with the shared ambition to create a sustainable society and accelerate the transition to zero pollution [5]. To further strengthen the partnership between the three organisations targeting the transition to carbon neutrality and beyond, in October 2024, a series of collaborative events took place at Imperial's campuses. This white paper summarises the outcome describing the need of a holistic approach in the sustainability transition, the methodology implemented to explore research topics beyond carbon neutrality, and clustered research topics with an integrated framework and priorities.

2 The need of a holistic approach

As there are diverse issues, it is necessary to have a holistic approach, such as planetary boundaries, to avoid conflicts among objectives and instead target potential co-benefits, and integrated solutions to address climate, environmental, and social issues. Examples of key points are not leaving carbon behind and the uncertainties of, for example, carbon storage.
It is important to note that the three organisations, Hitachi, The University of Tokyo, and Imperial College London, have agreed that a "holistic" approach is applied in addressing the issues of energy and climate transitions. A common pitfall in pursuing research in these fields is that they tend to look for solutions based on a narrowly defined view of the problems. Researchers may tend to focus on a small set of technologies to solve an aspect of a larger and more complexed issue. However, siloed approaches may result in oversimplifying the dynamics of the reality and obscure the connections among different factors constituting the problems.
In recent years, the Hitachi-UTokyo Lab has paid close attention to a more holistic approach into the energy and climate transition in Japan by analysing the wide-ranging actors affecting and being affected across different sectors. The notion of "socio-technical transition" by Frank Geels has informed their exploration of the systemic changes to be required to achieve carbon neutrality in Japan by 2050. Likewise, the multidisciplinary approach and the three pillars of the collaboration between Hitachi and Imperial College London, was conceived with a holistic approach in mind and the research efforts are continuously targeting it.
The collaborative research among the organisations will benefit from applying the holistic or systemic approach. Such approach will help the researchers to discuss innovative solutions based on a more accurate and complexed understanding of the social context. It also encourages to look for synergies between different actions to develop more effective policies. This approach is highly relevant to the unique, interdisciplinary set of scientists involved in the collaboration among the three parties, allowing them to contribute to the research from diverse perspectives. The outcomes of the research collaboration will ideally include recommendations for a systemic transformation to achieve a greener and more sustainable world.

3 Method to identify research priorities

As part of the collaborative events, workshops took place to produce clustered research topics to communicate them publicly through this white paper as guidance for global actions and for the three organisations to consider the next steps of the collaboration. The main goals or the workshops were to build concrete ideas integrating carbon neutrality and nature positive, and to define interdisciplinary research topics to contribute beyond achieving carbon-neutrality, for example, linking physical and digital technologies, integrating carbon-neutrality with nature positive, integrating social issues and wellbeing, etc.
The method used in the workshops is shared in this section as a reference that can be implemented for other purposes. The method is based on two key topics: Affinity diagrams to gather and organise the insights from the participants, and the holistic approaches that go beyond carbon neutrality. The workshops had the following four steps: Self-introduction, Group work, Share and merge clusters, and Cluster deep-dive. The panel discussion on "Innovation and Opportunities of the Green Economy" that took place in between the workshop sessions provided inspiration to the participants.

3-1. Self-introduction

The purpose of this step is to get to know each other and to get inspired about how to contribute beyond achieving carbon-neutrality. Each participant used the table below to introduce current or past research topics. The fields of the table cover multiple perspectives to promote considerations beyond the research itself.

3-2. Group work

In preparation for this step, each participant prepared three ideas, using the same format as in the Self-introduction step, about new research topics in their field that could contribute beyond achieving carbon-neutrality. To enrich proposed research topics with interdisciplinary perspectives, group work has the following steps:

1. Introducing the ideas in each group: After each participant shares one of the ideas, group members provide feedback using post-it. In rounds, each group member introduces one idea beginning with the most interesting for the author
2. Clustering of research topics: Begin with one research topic as the first cluster in the Government-Finance-Industry-Academia diagram. For each subsequent research topic, put it in an existing cluster or make a new cluster
3. Identifying categories or themes for clusters and finding connections between clusters

The figure below shows an example of the outcome of one of the groups where multiple clusters were identified merging all the ideas from the group participants.

3.3. Share and merge clusters

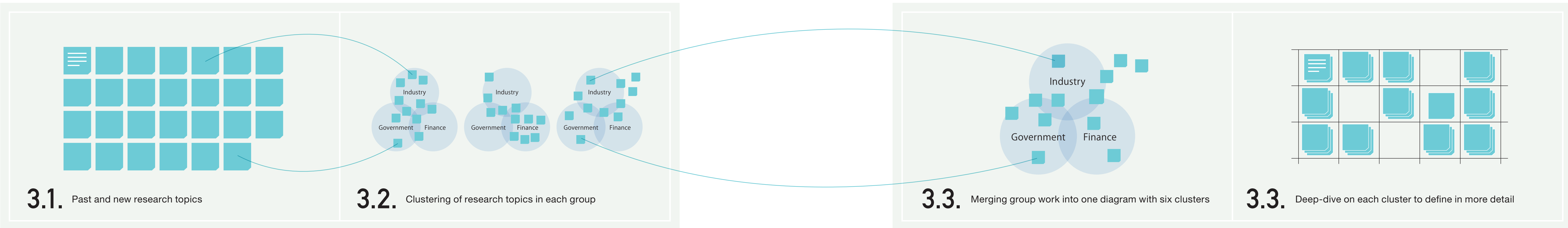
In this step, the "All groups" diagram is created gathering all clusters. The process begins with the clusters of Group 1 positioned in the Government-Finance-Industry-Academia diagram. Group 1 explains to other Groups the details of each cluster. If another Group has a cluster like any explained by Group 1, it is merged or placed nearby. Then, each of the remaining groups add to the "All groups" diagram its clusters that have not been merged and explains to other Groups the details of each cluster. The figure below shows the "All groups" diagram created in the workshops integrating the clusters from the three groups.

Based on the "All groups" diagram, six clustered themes were constructed as follows and are described in detail in Section 4:

1. Measurement and standardisation: From decarbonisation focused measurements to universal and comparable metrics for all planetary boundaries
2. Resource management: Identify critical resources and measures to alleviate severe circumstances using circularity approaches and accountability
3. Socio-economic aspect of sustainability transitions: Recommendations for stakeholders to deliver socio-economic prosperity in sustainability transitions
4. Data driven asset operation: Assess the contribution from modelling and optimisation of asset operation including the impact of energy consumption of using AI
5. Social and environmental economics including biodiversity finance: Integration of environmental and biodiversity considerations into financial instruments tracking allocation, attribution, accountability of externalities, and benefits
6. Comparative best practices, particularly among cities: Promote learning opportunities based on identifying useful thinking and best practices based on experiences and attempts to achieve sustainability transitions in cities.

3-4. Cluster deep-dive

New groups were formed based on the interest and expertise of each participant to do a deep dive into each of the clustered research topics. As shown in the table below, the focus of the discussions was on defining more concretely each clustered research topic and exploring the practical approaches combining the capabilities of the three organisations. This served as the basis for the more in-depth description of each clustered research topic that is presented in Section 4, as well as the proposed actions of Section 5.



3.1. Past and new research topics

3.2. Clustering of research topics in each group

3.3. Merging group work into one diagram with six clusters

3.3. Deep-dive on each cluster to define in more detail

4 Clusters of research topics

4.1. Cluster 1: Measurement and standardisation

Now that average increase in global temperature has exceeded 1.5 degrees, the effective implementation and scaling of Carbon Dioxide Removal (CDR) technologies are critical to achieving global climate goals. However, their success hinges on robust measurement systems, standardisation frameworks, and a thorough understanding of regional dynamics through bottom-up studies. Existing knowledge gaps limit our ability to evaluate the environmental impacts of CDR technologies on ecosystems, their economic viability, and their alignment with broader sustainability targets. To bridge these gaps, research must address key interconnected areas. These include the development of standardised evaluation frameworks for comparing nature-based and engineered solutions, the need for regional-scale impact studies, and improvements in transparency and data-sharing mechanisms [6], [7]. Within this clustered research topic, the following two areas are particularly relevant:

A Fair Comparison of Nature-Based and Engineered Solutions

CDR technologies impact ecosystems in diverse ways, necessitating a standardised evaluation framework to assess these influences comprehensively. To facilitate informed decision-making, CDR solutions—whether nature-based or engineered—must be evaluated on a common scale. Developing metrics for comparison requires accounting for biodiversity, ecosystem functions, trade-offs, and co-benefits specific to each approach. It is also important to develop quantifiable metrics to quantify the benefits of biodiversity and linking these to measurable outcomes. The success of CDR technologies also depends on understanding their impact not just on a global scale, but also at more granular levels, such as regional, local, and even city-wide scales. By conducting bottom-up analyses, researchers can better evaluate the socio-economic, environmental, and ecological consequences of implementing CDR strategies in specific regions.

Data Sharing and Transparency

Transparency and secure data sharing are critical to building trust and ensuring comparability in CDR technologies. Establishing approach-specific databases can facilitate knowledge exchange at different regional and global levels and improve capabilities in project deployment. Enhancing transparency in Carbon Markets is necessary to improve their credibility, research on mechanisms such as anonymised data sharing and blockchain-based systems can enhance security and trust.

4.2. Cluster 2: Resource management

To address critical challenges in sustainability and resilience, research on comprehensive tools and frameworks that integrate carbon accounting with resource management strategies is needed. The aim of these tools would be to enhance transparency, promote sustainability transitions, and provide actionable outputs for policymakers, industries, and researchers working on national and international resource management challenges. For their implementation, they would need to leverage open-source data and methodologies to provide a unified approach for tracking resource flows, evaluating environmental impacts, and identifying inefficiencies across supply chains. Regarding the frameworks, by combining carbon accounting with broader metrics such as water use, energy intensity, and biodiversity impacts, they could allow stakeholders to make informed decisions that balance environmental, economic, and geopolitical considerations. The frameworks need to 1) analyse resource dependencies, 2) enable scenario-based modelling for waste reduction, resource circularity, and supply chain resilience, and 3) incorporate geospatial and temporal dimensions to offer dynamic insights into resource flows and their local and global implications.

Framework details

A core capability of the framework is to integrate carbon accounting methodologies, Environmentally Extended Input-Output (EEIO) models, and future scenario analysis to address critical resource management challenges. By mapping resource flows and evaluating environmental impacts across geospatial and temporal dimensions, the framework would enable a holistic approach to understand resource dependencies and their implications. Carbon accounting frameworks, Life Cycle Assessment (LCA) tools and EEIO models [8] are needed to quantify environmental impacts, such as emissions, water use, and biodiversity changes, under various scenarios. These scenarios may include Business-As-Usual (BAU), decarbonisation pathways requiring critical minerals for 2050 targets, domestic versus international resource dependencies, circular economy strategies, and accelerated decarbonisation pathways. By integrating open-source databases [9] with these methodologies, the framework would provide actionable insights for policymakers and industry stakeholders, highlighting trade-offs and opportunities to enhance resource management, improve supply chain resilience, and support sustainable economic development. A tool built on this framework would serve as a decision-making aid, enabling effective planning for resilient and sustainable resource systems.

4.3. Cluster 3: Socio-economic aspect of sustainability transitions

Achieving sustainability transitions requires overcoming socio-economic challenges such as economic inequality, regional disparities, and shifts to new economic structures and market mechanisms [10]. These challenges are further complicated by insufficient policy implementation capacity in governments and the financial sector, uneven resource and infrastructure distribution across regions, and policy designs prioritising short-term gains [11]. Despite increased attention, gaps persist, including the absence of systematic approaches to economic inequality and the constraints of existing governance models [12]. This clustered research topic tackles socio-economic challenges in sustainability transitions through targeted interventions and addresses these gaps using system dynamics and integrated assessment models to develop policy tools and technology roadmaps. System dynamics and integrated assessment models examine the links between economic inequality, regional disparities, and technological innovation. Region-specific case studies focus on identifying localised policy interventions, especially in the UK and Japan focused on just energy transitions and rural innovation. Collaborative efforts with policymakers, industry, and academia aim to design incentive structures, align investments, and promote community-led initiatives, offering practical, scalable pathways for sustainable transitions. Additionally, these efforts hold significant value for corporations, fostering innovation and securing competitive advantages in emerging markets. Based on these insights, it is expected that 1) adaptive governance frameworks and incentive structures will be developed to align public and private goals, and that 2) multi-stakeholder platforms will co-create actionable strategies, evaluated by metrics such as reduced inequality and increased technology adoption.

4.4. Cluster 4: Data driven asset operation

The Data-Driven Asset Operation cluster focuses on leveraging data-driven methods and AI/ML-based optimisation to improve the performance and efficiency of various facilities, such as railway operations, factories, and other industrial assets. The emphasis is on balancing power load with the availability of clean energy while addressing real-world operational constraints [13], [14]. Optimisation of Facilities and Operations is a key research theme covering 1) Developing models to optimise the operation of diverse assets, including railway systems, factories, and other facilities, 2) ensuring operations align with clean energy availability and real-world constraints, such as demand-side responses, and 3) balancing power loads to improve energy efficiency and sustainability. Another approach is ML/AI-Based Optimisation and Research Prioritisation on critical research areas for machine learning and AI-based optimisation and investigating under-researched domains, such as the life-cycle environmental impact of AI systems. Environmental and Cross-Domain Impact can also benefit from this research cluster through assessing the net climate impact of optimisation strategies, particularly in energy-intensive industries, and exploring how optimisation models can be transferred to other case studies, such as material flow in supply chains.

With a research focus on integrating multi-level data, such as underground-space data and low-cost sensing technologies, to monitor surroundings, nature, and biodiversity (e.g., sound and air samples), this cluster enables end-user decision-making and optimisation beyond carbon neutrality. For this focused area, the key research areas to consider are optimisation of machine usage and time-based goods production, timetable, and predictive modelling for railway operations, incorporating dynamic pricing tied to renewable energy availability, and demand-side response and storage acceptability.

4.5. Cluster 5: Social and environmental economics including Biodiversity Finance

The social and environmental economics cluster examines the complex relationship between financial systems and environmental outcomes, centred on accountability, value allocation, and ecosystem sustainability without relying solely on government support. Key research areas include tracking dependencies related to environmental sustainability, clarifying value distribution mechanisms, and supporting the evolution of relevant business models and instruments. This research would explore how markets can deliver environmental outcomes, with specific attention to implementing fundamental policy influences and converting environmental data into actionable financial insights. The research addresses practical challenges such as integrating environmental and social considerations into financial decisions, developing tailored solutions, and establishing routes for stakeholder engagement. Current gaps include the creation of pilot projects that could lead to the creation of frameworks to generate returns while enabling co-funding opportunities.

The goal of the research is to understand how to bring together advanced financial strategies and policy frameworks to drive decarbonisation, underpinned by social and environmental economics. The central aim is to reduce emissions through targeted measures, such as increasing reliance on rail transport, employing dynamic pricing, or creating avoidance credits. Alongside these measures, sustainability metrics are integrated into more complex financial tools to reinforce climate objectives and ensure transparent tracking of environmental impacts. Crucially, the development of fintech and blended finance mechanisms helps to mitigate adaptation risks, thereby attracting private investment and strengthening financial resilience. Finally, facilitating long-term business models, standardising environmental impact accounting, and establishing supportive policies, are key to lower financial risks but also to accelerate the commercial viability of decarbonisation efforts.

4.6. Cluster 6: Comparative studies about cities

The emphasis of this research cluster is identifying and examining the similarities and differences among urban centres, focusing on their social, economic, cultural, political, and environmental dimensions. This analysis considers how historical trajectories, governance structures, and spatial dynamics shape urban experiences and developmental pathways.

Examining sustainable and resilient urban development approaches and innovative actions in a comparative manner is promising for understanding context-specific challenges, evaluating knowledge transfer between cities, if applicable, and identifying best practices. This approach enables us to facilitate an understanding of how cities adapt to global challenges such as climate change, rapid urbanisation, and technological transformations. By focusing on cross-city collaboration and approaches, a comparative framework can contribute to formulating comprehensive and context-sensitive strategies, which help achieve urban sustainability and resilience while driving innovation in urban governance and infrastructure planning [15], [16].

Potential questions to explore for the collaboration include: Research questions that this cluster could address are, for example, what city-level actions are possible to leverage sustainable city technologies and ensure they are inclusive for all residents? what similarities and differences can be observed in terms of urban governance, infrastructure development, technological integration, socio-economic conditions, and environmental sustainability? what opportunities and challenges do cities face? What lessons and policy implications can be drawn from the comparative analysis for the future approaches, and what best practices for sustainable urban development can be identified?

5 Proposed actions

5.1. Integrated framework

Each cluster contains other clusters as well as individual ideas of research topics. And there are relations among clusters. This section highlights these relations that can lead to synergies as well as strategies on where to start and what to do next. “Cluster 1: Measurement and standardisation” is a research cluster that creates strong foundations, and it benefits from government and industry support. At the same time, it could be a moving target, so it requires feedback from other clusters to provide the outcome that benefits them the most. With comparable measurements, and metrics following unique standards, research on “Cluster 4: Data driven asset operation” becomes more efficient and their applications globally scalable, particularly solving compatibility and interoperability issues. Additionally, the comparable metrics of, for example, environmental performance of systems managing or optimising the operation of assets serves decision-making processes, including financial decisions to support further deployment. Research on “Cluster 2: Resource management” involves monitoring and controlling the use and flow of resources to avoid depleting resources, assess circularity and effects on ecosystems, improve resiliency, and reduce waste and cost. Clear standards and metrics are needed for this and depending on the application, the resource management is data driven and done systematically. Depending on how the aggregated actions towards sustainability are steered through policy or incentives, “Cluster 3: Socio-economic aspect of sustainability transitions” analyses at the level of society the different impacts that they have on employment, well-being, fairness, etc. Financial instruments and certificates are also strong tools to steer actions towards sustainability, and to be effective they both need a solid foundation of agreed measurements and standards. Research on “Cluster 5: Social and environmental economics including Biodiversity Finance” integrates the observed socio-economic aspect of sustainability transitions to inform the desired conditions for new financial instruments and certificates and promotes awareness of biodiversity considerations to include in portfolio analysis and accounting practices. Lastly, depending on the comparative study and the cities, research on “Cluster 6: Comparative studies about cities” can benefits from any of the clusters and can provide testbeds to demonstrate their findings.

5.2. Research priorities

As the scope of all clustered research topics is wide and it is difficult to conduct research covering such scope at once, based on the analysis of Section 5.1, the relations among clusters, and the activities at each research centre, identified research priorities are presented.

Cluster 1: Measurement and standardisation
Bridge technology, ecology, and regional analysis to ensure robust CDR deployment using interdisciplinary expertise and comprehensive biodiversity and ecosystem function databases.

Cluster 2: Resource management
Develop a practical, scalable tool that integrates policy, academic research, and industrial needs to address resource management challenges collaboratively. For this purpose, develop a robust framework for resource management, designing it with expertise in carbon accounting, whole-systems modelling, and policy analysis. Also, integrate regional and governmental insights, operational data, emissions metrics, and supply chain expertise.

Cluster 3: Socio-economic aspect of sustainability transitions
Create and disseminate effective policy instruments and technology roadmaps starting with the creation of a framework merging policy, societal, and technological perspectives that integrates 1) modelling energy system transformations and socio-economic impacts, 2) policy formulation and social consensus-building, and 3) technological innovation and practical implementation.

Cluster 4: Data driven asset operation
Address the gaps in data availability and transferability of optimisation models while exploring robust carbon accounting frameworks for AI systems based on combining industry data and simulation expertise, advanced ML/AI analysis, and LCA standardisation capabilities.

Cluster 5: Social and environmental economics including Biodiversity Finance
Clarify roadblocks to achieve real-world implementation of technology and methodologies for sustainable and biodiversity finance, through business initiatives supported by academic research that also serve to inform evidence-based environmental policies.

Cluster 6: Comparative studies about cities
Select two cities and a specific domain to conduct comparative studies. For example, smart mobility in London and Tokyo, would be ideal to investigate, and the potential research questions to explore include: What city-level actions are London and Tokyo implementing to leverage smart mobility technologies and ensure they are inclusive for all residents? What similarities and differences exist in different settings - Europe and Asia)? What lessons can be drawn from the experiences of London and Tokyo, and what best practices for sustainable urban development can be identified?
This research would provide many ingredients for researchers to gain insights into policy approaches, multi-stakeholder engagements (including governmental, industrial, and financial actors), technological innovations, governance strategies, and SDG performances (with a particular focus on SDG 11 on sustainable cities and communities).

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The research areas presented in this white paper were generated to raise awareness and to inspire global action to address them as we continue joining efforts to achieve the sustainability transition.