Technology List and Perspectives for Transition Finance in Asia

Technology Deep-dive Research Outcome

2nd Version – Phase 2-1

Economic Research Institute for ASEAN and East Asia

Technology List and Perspectives for Transition Finance in Asia: Technology Deep-dive Research Outcome

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Published in April 2025

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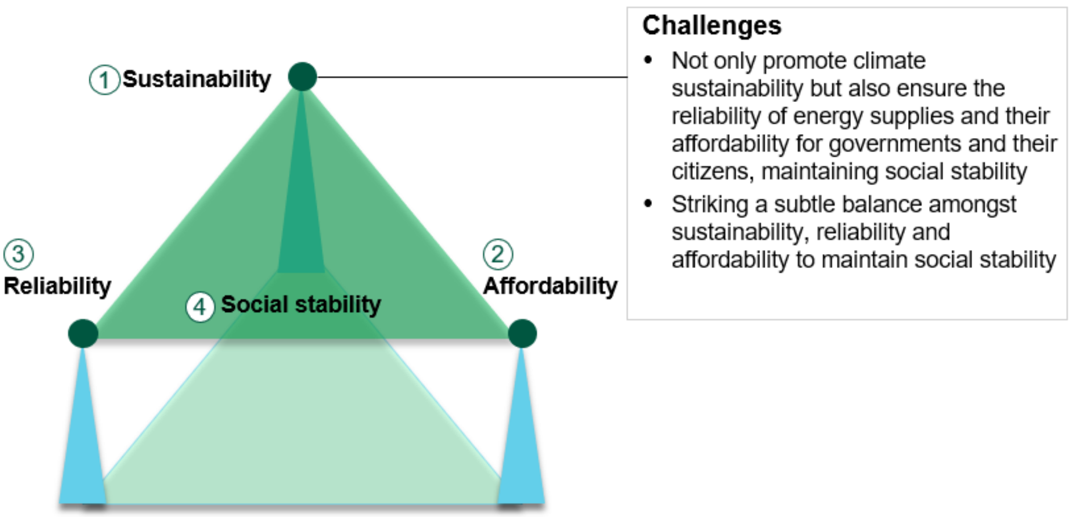
1 The Purpose of This Report

1.1 The importance of a just and orderly transition in developing Asia

In the face of climate change impacts affecting our daily lives, the transition from a predominantly fossil fuel-based energy system to one based on renewable and sustainable sources is crucial worldwide. However, developing Asia faces challenges in transitioning to a low-carbon economy due to infrastructure limitations, energy insecurity and high cost to integrate variable renewable energies (VRE) such as solar and wind. Additionally, rapid industrialisation and economic development relying on fossil fuels such as coal to power industries and to meet the growing demand adds complexity. Climate sustainability alone therefore cannot dictate technology choices for emission reduction. Approaches to decarbonisation should be tailored to each nation's circumstances, ensuring that the transition is just and orderly and maintains sustainability, affordability, and reliability to prevent sudden disruptions and potential social unrest (Exhibit 1) (ERIA, 2022).

Exhibit 1. Important Factors for a Just and Orderly Transition



Source: Economic Research Institute for ASEAN and East Asia (2022).

1.2 Green and transition technologies

Technologies that reduce but do not completely eliminate carbon emissions play a crucial role in facilitating a just and orderly transition. These are referred to as transition technologies and are the focus of this document. In addition, green technologies are defined as those with zero emissions throughout their operation, are key components of the broader technology solution package to achieve net-zero emissions.

1.3 Need for a list of transition technology information and assessment framework

Governments and international organisations have established standards and guidelines to ensure financial flows align with a pathway to net-zero carbon dioxide (CO_2) emissions. One such effort is the development of taxonomy – a classification system that defines criteria for economic activities in line with sustainability goals. In addition to taxonomies, there has been significant effort to compile comprehensive lists of clean energy technologies and to develop detailed technology road maps.

Despite the progress made in creating taxonomies, technology lists, and assessment frameworks for green and transition activities, financial institutions still face significant challenges in gathering the necessary information to evaluate transition technologies. This document aims to provide a fact-based overview of each selected transition technology and help financial institutions and other stakeholders better understand their suitability for transition finance. It was anticipated that this would catalyse the release of funding for transition technologies, thereby supporting a just and orderly pathway towards achieving net-zero emissions. Additionally, it will offer a framework to provide an overview of potential transition technologies.

1.4 Different stakeholders who may benefit from using TLP

TLP provides two types of outputs: 1) an inclusive list of potential green and transition technologies and 2) a deep-dive research outcome of selected transition technologies (Exhibit 2). These outputs are intended for different stakeholders, serving various purposes (Exhibit 3). Although TLP is primarily designed for financial institutions, it may also be useful for other public and private organisations. For example, it can assist corporations in decarbonising their operations or identify new business opportunities and assist policymakers in understanding the technology landscape in Asia to inform their technology road maps, taxonomies, and decarbonisation policies. Two deep-dive research outcomes are planned – one for the end-use and industries sectors which is included in the latter part of this report, and another for the other sectors.

Exhibit 2. Two Outputs in the Second Version of TLP

#	Document	Technology Types to be Included	Main Purpose
1	Inclusive list of potential sustainable/transition technologies (Long list)	Green and transition technologies across all sectors for both energy-related and non-energy-related emissions	To showcase available green and transition technologies for each sector.
2	Deep-dive research outcome of selected transition technologies	Selected transition technologies investigated across six framework dimensions	For financial institutions and other stakeholders to assess the suitability of transition technologies for financing and implementation.

Source: Author.

Exhibit 3. How Different Stakeholders Can Use the Two Outputs

	Inclusive list of potential sustainable/transition (Long list)	Deep-dive research outcome of selected transition technologies
Financial institutions	To understand the landscape of potential green and transition technologies.	To assess the suitability of transition technologies for financing.
Corporations	To identify technologies for decarbonising their businesses.	To plan decarbonisation activities using specific technologies.
Policymakers	To quickly understand the technology landscape and see what can support decarbonisation road maps, strategies, and policies.	To understand how specific technologies can contribute to achieving decarbonisation road maps, strategies, and policies.

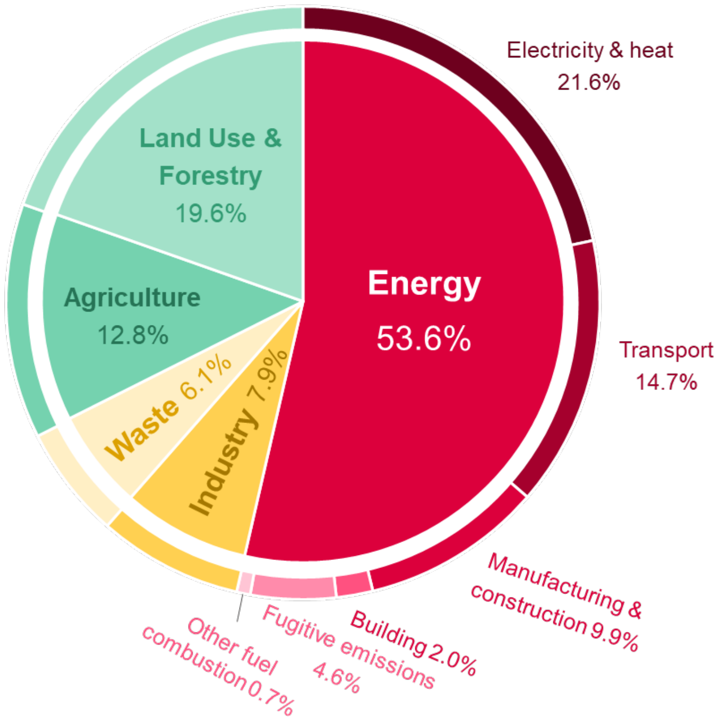
Source: Author.

1.5 Scope of TLP

(1) Greenhouse gas (GHG) emission profile of ASEAN

As shown in Exhibit 4, the energy sector, including direct fuel combustion and electricity use, is the largest contributor to greenhouse gas (GHG) emissions in ASEAN. Within this sector, the generation of electricity and heat is the largest emitter, followed by direct fuel combustion in transport, manufacturing, construction, and buildings. Fugitive emissions are associated with the fossil fuel production.

Exhibit 4. GHG Emissions by Sector in ASEAN (2021)



Source: Mitsubishi Research Institute Inc. analysis based on Climate Watch, Historical GHG Emissions (2022).

(2) The focus of TLP

TLP focuses on energy-related emissions, including emissions from electricity and heat production and direct fuel combustion. However, in some sub-sectors in the end-use and industries, such as cement, concrete, glass, iron, and steel, significant emissions arise from chemical processes rather than energy use. For these sub-sectors, technologies addressing process emissions are also considered.

In ASEAN's forestry and other land use (FOLU) sector, major emission sources include peatland management (e.g. peat fires and decomposition), and land-use changes (e.g. conversion to settlements). Peatland management is particularly critical in Indonesia, home to more than half of the world's tropical peatland. Peat fires can be prevented through improved firefighting and surveillance, whilst peat decomposition can be mitigated by restoration initiatives such as soil management planning. Land conversion to settlements, driven by urban expansion, contributes to emissions from reforestation and land use. To reduce these emissions, sustainable soil management must be integrated into urban planning processes. Addressing emissions from the FOLU sector relies more heavily on regulations, law enforcement, and planning rather than technology alone (IPCC,2006d; UNEP, 2024). Therefore, the FOLU sector has been opted from the scope of TLP.

(3) Five sectors of energy- related activities covered by TLP

In TLP, sectors are categorised into five groups based on energy-related activities: upstream, power, midstream, downstream, and end-use and industry sectors. These sectors are defined as follow:

Upstream sector:	The production of fuels for direct combustion and power generation.
Power sector:	The generation of power utilising renewable sources and/or the combustion of renewable or non-renewable fuels.
Midstream sector:	The transmission, transport, storage, and distribution of electricity and fuels.
Downstream sector:	The provision of electricity and fuels to end-users.
End-use and industry sector:	The use of electricity and fuels to provide services and produce goods.

In this report, transition technologies, which can be deployed to address emissions in the end-use and industry sector, are examined to provide fact-based overviews while taking into consideration ASEAN situations. It must be kept in mind that lack of inclusion in this report does not disqualify a technology from being considered as a transition technology important to ASEAN.

2 How to Use the Framework

2.1 Role that TLP aims to play

TLP aims to offer stakeholders an overview of potential transition technologies, functioning as an interim reference until more comprehensive technology road maps or taxonomies are published by Asian governments (Exhibit 3). It is important to note that the framework is not intended as a definitive tool for deciding whether to provide transition finance. For instance, it does not assess a particular technology's suitability in specific contexts or predicts its financial performance. Instead.

Exhibit 5. How to Use the TLP

The document

- Provides **a framework** for assessing a potential transition technology
- Provides **relevant, practical information** on various potential transition technologies in **a fact-based manner**
- Focuses upon major potential transition technologies, initially in a limited number of sectors. (Other sectors will be addressed in future updates.)

The document

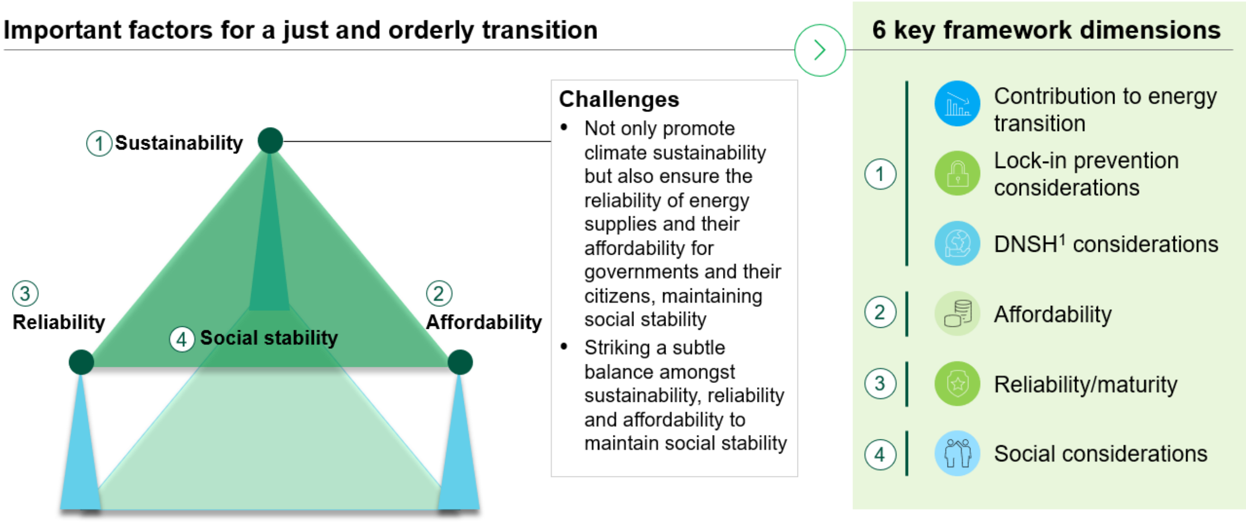
- Does **not** provide **absolute criteria** for what constitutes a transition technology.
- Is **not restricted to** offering a set of **principles**; it provides example information on individual technologies
- Is **not an exhaustive list** of potential transition technologies in Asia

TLP = Technology List and Perspectives for Transition Finance in Asia.
Source: Economic Research Institute for ASEAN and East Asia (2022).

2.2 Six framework dimensions

TLP provides guidance on assessing a technology's suitability as a transition technology based on six dimensions that reflect a just and orderly transition to net-zero emissions. These are divided into two categories: three pertaining to the technology itself and three involving broader considerations linked to climate change mitigation and the three essential criteria (ECs) of the ASEAN taxonomy (Exhibit 4).

Exhibit 6. Six Framework Dimensions Addressing Important Factors for a Just and Orderly Transition



DNSH = do no significant harm.
Source: Economic Research Institute for ASEAN and East Asia (2022).

2.3 Technology characteristics

The following characteristics determine how a technology contributes to a just and orderly transition to net-zero emissions.

- **Contribution to energy transition:** This assesses the sustainability of the technology, measuring how effectively it directly reduces emissions or enables others to do so, thereby contributing to the decarbonisation of projects, companies, and countries.
- **Reliability:** This assesses the maturity of a technology. A commercially available technology at scale is considered more reliable than one still in the pilot phase. Reliability was gauged using the IEA’s Technology Readiness Levels (TRL).
- **Affordability:** The cost of the technology influences the affordability of the transition, whether it be the cost of abatement for upstream technologies or the lifetime cost of energy for power sector technologies.

Exhibit 7. Technology Readiness Levels (TRL) and Descriptions

	Level	Description
Mature	11	Proof of stability reached – Predictable growth has been achieved.
Market uptake	10	Integration required at scale – The solution is commercial and competitive but requires further integration efforts.
	9	Commercial operation in relevant environment – The solution is commercially available, though it requires evolutionary improvement to stay competitive.
Demonstration	8	First-of-a-kind commercial – The solution is undergoing commercial demonstration, with full-scale deployment in final conditions.
	7	Pre-commercial demonstration – The prototype is working in expected conditions.
Large prototype	6	Full prototype at scale – The prototype has been proven at scale in the conditions where it will be deployed.
	5	Large prototype – Components have been validated in the conditions where they will be deployed.
Small prototype or lab	4	Early prototype – This prototype has been proven in test conditions.
	3	Concept requires validation – The solution needs be prototyped and applied.
	2	Application formulated – The concept and application have been formulated.
	1	Initial idea – The basic principles have been established.

Sources: Economic Research Institute for ASEAN and East Asia (2022), International Energy Agency (2024b).

2.4 Additional considerations

Three additional factors help financial institutions determine the suitability of a technology as a transition technology.

- **Lock-in prevention considerations:** In the ASEAN taxonomy, this factor is part of the risk management tool (RMT). It examines potential paths for a technology to transition towards zero-emission or net zero-emission when there is a remaining emission which cannot be completely eliminated by the technology.
- **Do no significant harm (DNSH) considerations**: This evaluates whether the technology could negatively impact other environmental objectives, such as ecosystem health, biodiversity, resource resilience, or the circular economy. It also assesses possible preventative measures, which are part of the RMT

requirements in the ASEAN taxonomy.

- **Social considerations:** This assesses whether the technology could negatively impact society, such as by reducing employment opportunities.

Exhibit 8. Assessments Along the Six Framework Dimensions

	Framework dimensions	Description
Technology characteristics	**Contribution to energy transition**	GHG emissions intensity and/or reduction impact required to contribute to decarbonisation of a country or company
	Affordability	Estimated cost for technology
	Reliability/ maturity	Readiness for technology (e.g. commercial at scale, pilot, etc.).
Additional considerations	**Lock-in prevention considerations**	Eventual emissions reduction plan to reach zero or near-zero emissions.
	DNSH considerations	'Do No Significant Harm' to environmental objectives other than GHG emissions.
	Social considerations	Mitigate the negative effects of transition activities to the society, e.g. unemployment

1. All the environmental objectives in EU taxonomy are covered in the six framework dimensions. All environmental objectives and essential criteria in ASEAN Taxonomy for Sustainable Finance are similarly covered in the six framework dimensions.

DNSH = do no significant harm, GHG = greenhouse gas.
Source: Economic Research Institute for ASEAN and East Asia (2022).

When examining the DNSH and social considerations dimensions, the following key questions are addressed (Exhibit 8).

Exhibit 9. Key Considerations for the DNSH and Social Dimensions

Framework dimensions	Considerations/Key questions	
DNSH conside-rations	Protecting healthy ecosystems and biodiversity	• Would the technology be detrimental to the health and resilience of ecosystems and biodiversity? What preventative measures should be implemented? • Beside GHG, would the technology lead to a significant increase in the emissions of pollutants into the air, water, or land? What preventative measures should be implemented?
	Promotion of transition to circular economy	• Would the technology run on sustainably-sourced raw materials? • Would the technology increase the generation, incineration, or disposal of waste? What measures should be taken to avoid or minimise waste?
Social conside-rations	Are there plans to mitigate the negative social impacts of the technology?	• Would the technology lead to negative changes in job opportunities?
		• Would the technology lead to negative changes in working environments?

DNSH = do no significant harm, GHG = greenhouse gas.
Source: Economic Research Institute for ASEAN and East Asia (2022).

2.5 Links between TLP and the ASEAN taxonomy

TLP provides guidance on assessing of suitability of each technology for transition finance, closely aligning with the ASEAN taxonomy in hopes that TLP will help users answer criteria set in the taxonomy. The ASEAN taxonomy defines four environmental objectives (EOs):

EO1: Climate change mitigation

EO2: Climate change adaptation

EO3: Protection of healthy ecosystems and biodiversity

EO4: Resource resilience and transition to a circular economy.

For an activity to be classified under the ASEAN taxonomy, it must contribute to at least one of these EOs. Amongst these, EO1 is the most relevant to TLP, as the focus is on energy transition. To meet EO1 criteria, an activity must show its contribution to one or more of the following:

1) avoiding GHG emissions;
2) reducing GHG emissions; and
3) enabling others to avoid or reduce GHG emissions.

Additionally, activities must meet the following three ECs:

EC1: Do no significant harm (DNSH). Activities must not cause significant harm to any EO. This includes ensuring that contributing to one EO does not detract from another.

EC2: Remedial measures to transition. Activities must have plans and measures in place to mitigate any potential significant harm within 5 years. (Please see the reference[1] for more details.)

EC3: Social aspects: Activities must adhere to social safeguards, including human rights, labour rights, and minimising impacts on vulnerable communities.

The three framework dimensions of TLP provide useful information and insights to assess an activity's suitability against EO1, EC1, and EC2 under the ASEAN taxonomy criteria.

Exhibit 10. Links Between Framework Dimensions of TLP and Relevant ASEAN Taxonomy Criteria

Framework dimensions of the TLP		Relevant ASEAN Taxonomy criteria
Contribution to energy transition		**EO1: Climate Change Mitigation** **1) Avoids GHG emissions** **2) Reduces GHG emissions** **3) Enables others to avoid or reduce GHG emissions**
Lock-in prevention considerations		
DNSH considerations	Potential negative impacts	**EC1: DNSH**
	Mitigation measures	**EC2: Remedial Measures to Transition (RMT)**

ASEAN = Association of Southeast Asian Nations, DNSH = do no significant harm, EC = essential criteria, GHG = greenhouse gas, TLP = Technology List and Perspectives for Transition Finance in Asia.
Source: Author.

[1] ASEAN Taxonomy Board (ATB) (2024), 'ASEAN taxonomy for sustainable finance Version 3', https://www.sfinstitute.asia/wp-content/uploads/2024/07/ASEAN_Taxonomy_Version_3.pdf (accessed 10 October 2024)

3 Technologies Covered by TLP

As mentioned in the previous section, TLP provides transition technologies that can be deployed for the five energy-related sectors

3.1 Scope of the Inclusive List of Green and transition technologies

ASEAN faces unique challenges in transitioning to a low-carbon economy. These challenges have been thoroughly investigated for each sector to identify green and transition technologies that are appropriate to address the region's specific needs. Based on GHG emissions data from direct combustion and electricity consumption of electricity by sector, the following sub-sectors have been prioritised for technology identification: Please note that although food and tobacco manufacturing, textile & leather manufacturing, etc. are identified as high emitting industries, the decarbonisation technologies that can be deployed to address emission from those sectors can be used cross-sectoral and thus summarised under the 'industries cross-cutting' sub-sector.

Exhibit 11. High-emission End-use and Industry Sub-sectors in ASEAN Selected for Technology Identification

Transport (use of vehicles)	
Building	Residential
	Non-specific/commercial
Manufacturing industries and construction	
	Iron and steel production
	Cement production
	Chemical production
	Food and tobacco
	Machinery
	Textile and leather
	Non-metallic minerals
Agriculture	
Waste	

Source: Author.

Exhibit 12. Number of Technologies Identified by Sector

#	Category		Inclusive List of Both Green and Transition Techs (Long-list)
I	Upstream		32
II	Power		35
III	Midstream		19
IV	Downstream		4
V	End-use & Industries	Building	17
VI		Transport	25
VII		Industry (cement, concrete and glass)	12
		Industry (chemicals)	4
		Industry (iron and steel)	11
VIII		Industry (cross-cutting)	10
IX		Agriculture	4
X		Waste	3
TOTAL			**176**

Source: Author.

3.2 Scope of the In-depth Research

The upstream and power sectors were examined in 2022, detailing ten transition technologies (Exhibit 13).

Exhibit 13. Coverage of Technologies in the First Version of TLP

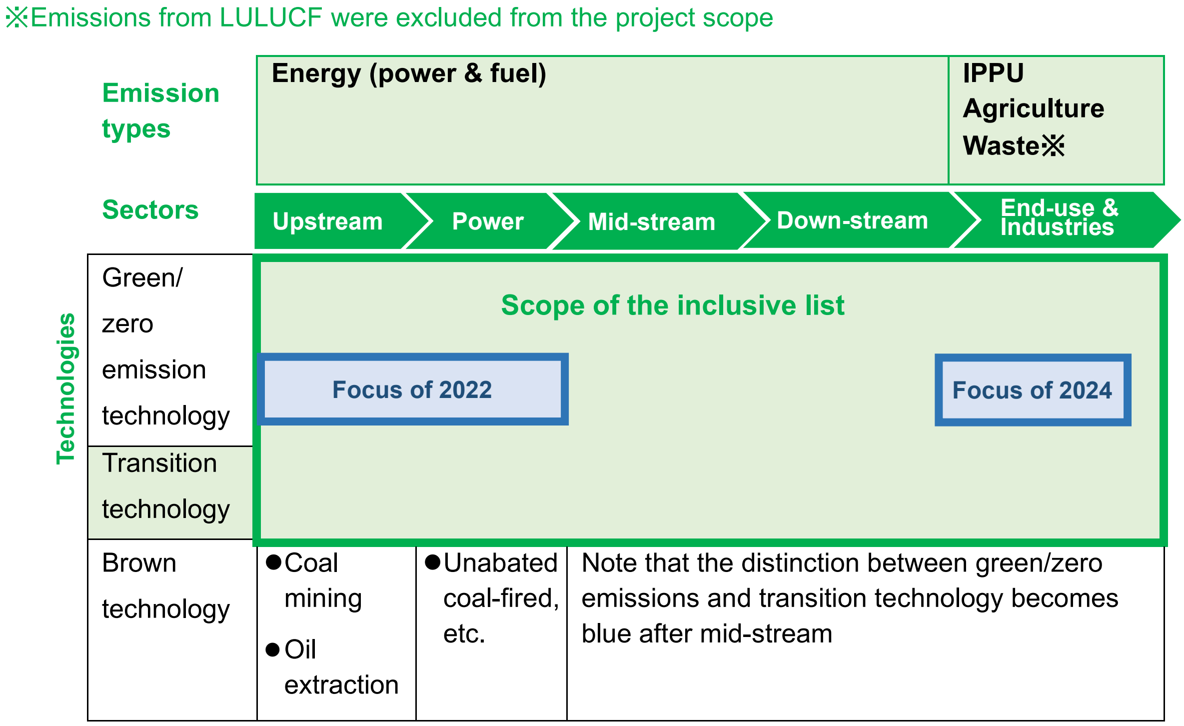
Classification of technologies/solutions relative to fulfilling decarbonisation goals

Category	Technologies/solutions	Coverage
Green technologies Zero or near-zero emissions	• Renewable energy (solar, wind, biomass, small hydro, geothermal…) • Battery storage & other storage solutions • Grid interconnections, grid flexibility • BECCS • Direct air carbon capture • Large hydro and nuclear (subject to DNSH considerations)	Focus of green finance taxonomies
Transition technologies Significantly lower emissions	• Coal avoidance by early retirement and/or gas power generation • Inefficient plant phase out or upgrade (e.g. OCGT to CCGT) • Co-firing of low-carbon fuels • Venting and fugitive emissions reduction by leak detection and repair • Process electrification in gas production and processing • Low-carbon fuels production (ammonia, hydrogen) • CCUS	Focus of this document
Brown technologies	• Unabated coal-fired power generation[1] • Unabated oil (including diesel)-fired power generation	Progressively restricted from financing

BECCS = bioenergy with carbon capture and storage; CCGT = combined-cycle gas turbine; CCUS = carbon capture, utilisation, and storage; DNSH = do no significant harm; OCGT = open cycle gas turbine; TLP = Technology List and Perspectives for Transition Finance in Asia.
1. In line with the Glasgow climate pact, this document assumes any coal-fired plants without co-firing or CCUS is classified as unabated, regardless of its efficiency (e.g. subcritical, supercritical, ultra supercritical, integrated gasification combined cycle, etc.)
Source: Economic Research Institute for ASEAN and East Asia (2022).

This year transition technologies for the end-use and industries sector were closely examined. These technologies were identified based on emission profiles and the challenges of accelerating the transition to a low-carbon economy in ASEAN. Subsequent phases will examine the mid-stream and down-stream sectors, conducting deep-dive research on selected transition technologies in those sectors. The end-use and industries sector was prioritised as technology selection in this sector will influence choices for the down-stream and mid-stream sectors.

Exhibit 14. Coverage of TLP



IPPU = industrial processes and product use, LULUCP = land use, land use change and forestry, TLP = Technology List and Perspectives for Transition Finance in Asia.
Source: Author.

(1) Selection criteria for transition technologies for the close examination

From the inclusive list of green and transition technologies, 31 technologies were further prioritised from the upstream and end-use & industries sector for close examination based on the three criteria described below. It must be noted that the agriculture and waste sub-sectors were not prioritised for the close examination because often emissions from those sub-sectors are originated from fermentation, chemical reaction, etc. not relevant to production or use of energy.

- Relevance to ASEAN : To prioritise technologies that can address emissions more relevant to ASEAN
- Technology maturity : To prioritise technologies financial institutions have more need to understand their suitability for financing
- Contribution to energy transition : To prioritise technologies that have higher emission reduction potential

In the end-use and industrial sectors, each of the above criteria was specifically adapted to the sector to ensure greater clarity and consistency throughout the selection process, as can be seen in Exhibit 15.

Exhibit 15. Criteria and Its Description Tailored to the End-use and Industries Sector

Criteria	Description
Relevance to ASEAN	Technologies address emissions from higher emissions industries in ASEAN 【Examples】 Highest emission industries in ASEAN ・ Transport (Road) ・ Non-metallic minerals (Cement, concrete & glass) ・ Building Medium emission industries ・ Cross-cutting ・ Chemical production ・ Iron & steel ・ Transport (Aviation, marine) Lower emission industries ・ Food & tobacco ・ Machinery ・ Textile & leather ・ Transport (Rail)
Technology maturity	The higher TRL technologies are more likely to become a financing project. ・ TRL 7-8: Technologies are undergoing pre-commercial or commercial demonstration. ・ TRL 9-10: Technologies are available in the market but have not reached the stability stage and further integration efforts are required. ・ TRL 11: Technologies are widely available and predictable growth has been achieved. *TRL 6 or below were deprioritised because
Expected emissions impact/ Contribution to energy transition	Technologies that have higher emission reduction potential. Depending on types of transition technologies, different viewpoint was adopted: ・ How likely more power/fuel can be saved ・ How likely more CO_2 can be captured

Source: Author.

(2) Selected transition technologies in the end-use and industries sector for the deep-dive research

Ten transition technologies were selected for the upstream and power sectors and detailed in the TLP published in September 2022. Further 21 transition technologies for the end-use and industries sector were selected for close examination, which results are detailed in the latter part of this report.

Exhibit 16. Selected Transition Technologies for the Deep-dive Research

Version of TLP		Sector	Sub-sector	Selected Transition Technology
TLP of 2022	Will be updated in TLP of 2025	Upstream	-	Fugitive emissions: Leak detection and repair
				Process electrification in gas production
				CCUS in coal/gas power plant
				Blue hydrogen & blue ammonia production
				CCUS in gas production
		Power	-	Combined cycle gas turbine
				Waste to energy (WtE) power plant
				Biomass co-firing
				Low-carbon ammonia co-firing
				Low-carbon hydrogen co-firing
TLP of 2025 (planned)		Midstream	-	TBD
		Downstream	-	TBD
TLP of 2024 (this document)		End-use and industries	Building	Heat pumps
				Fuel combustion co-generation
				Fuel cell co-generation
				Home energy management system (HEMS)
			Transport	Hydrogen fuel cell vehicles (HFCV)
				Battery electric vehicles (BEV) & Plug-in hybrid vehicles (PHEV)
				Flex fuel vehicles (FFV)
				LNG-fuelled ship
				Biofuel-fuelled ship
				Ammonia fuelled ship

Version of TLP	Sector	Sub-sector	Selected Transition Technology
		Cement, concrete and glass sub-sector	Carbon mineralisation
			New Suspension Preheater (NSP) kiln
		Chemicals sub-sector	Production of chemicals using captured CO_2
		Iron & steel sub-sector	Electric arc furnace (EAF)
			Direct reduced iron (DRI)
		Cross-cutting	Carbon capture
			Lower emission fuel fuelled equipment
			Large-scale industrial heat pump
			Waste heat recovery
			Electric heating
			Small-scale once-through boiler

Source: Author.

4 Summary of Key Findings

4.1 Key findings of technology groups

(1) Transition technologies for the building sub-sector

In the building sector, GHG emissions primarily stem from electricity consumption, with the residential sector consuming more electricity than the commercial sector, primarily for space cooling and lighting. Promoting the adoption of transitional technologies that enhance energy efficiency and conservation (EE&C) is therefore crucial in this context. Amongst the technologies assessed, heat pumps show considerable potential for reducing electricity usage in cooling applications, while co-generation systems are effective for both water heating and electricity generation. Although its immediate EE&C impact may be limited, HEMS could play a pivotal role in future efforts to stabilise the electricity grid, addressing the challenges posed by the rising renewable energy capacity being installed across ASEAN countries.

(2) Transition technologies for the transport sub-sector

In the transport sub-sector, most emissions originate from road transport, including automobiles and motorcycles, with a minor contribution from marine navigation. This report, therefore, examines four alternative fuel vehicle options and two alternative ship types. HFCVs offer zero operational emissions when powered by sustainably produced hydrogen; however, the high costs and limited availability of hydrogen present a substantial barrier to their widespread deployment, not only in ASEAN but globally. Amongst the available alternatives, FFVs appear most viable for ASEAN's transition to a low-carbon economy, given that certain ASEAN governments are implementing biofuel mandates, and ethanol-gasoline blends can leverage existing refuelling infrastructure. The extent of GHG emission reductions achievable by BEVs and PHEVs is highly dependent on national grid emission factors, which vary significantly across ASEAN Member States. These technologies will become more impactful in reducing emissions as the region increases its renewable energy capacity.

(3) Transition technologies for the cement sub-sector

Two transition technologies were selected for in-depth analysis to mitigate emissions within the cement sub-sector. Carbon mineralisation, a process that utilises CO_2 captured from industrial emitters as a raw material in the production of cement and concrete, holds the potential to offset 5-10% of sector emissions. However, high costs currently impede its widespread deployment. To encourage adoption, policy measures that incentivise the use of construction materials produced through carbon mineralisation would be essential. Conversely, the NSP kiln represents a well-established technology capable of increasing energy efficiency by around double compared to traditional wet-process kilns. With its superior thermal energy efficiency relative to other kiln types, the NSP kiln stands as the most viable option for the cement industry's transition toward reduced emissions.

(4) Transition technologies for the iron and steel sub-sector

In the iron and steel sub-sector, two technologies – EAF and DRI – were selected for in-depth analysis. EAF operates entirely on electricity and can substantially reduce GHG emissions when electricity is generated from renewable energy sources. Primarily used for producing steel from scrap metal, the widespread adoption of EAF technology depends significantly on the availability of scrap metals. In contrast, the DRI process can use various reducing agents, with lower-emission alternatives, such as natural gas and hydrogen, becoming increasingly viable. Hydrogen-based DRI is projected to achieve substantial GHG reductions, with some studies estimating up to a 90% decrease in emissions compared to traditional steel-making methods. However, hydrogen-based DRI remains in the prototype stage of technological development and expects more than a decade to be widely introduced across various regions. Natural gas-based DRI, on the other hand, is already commercially accessible and provides significant GHG reductions, though the extent of reduction varies across studies. Both hydrogen and natural gas-based DRI entail higher costs than conventional methods, with natural gas offering a more cost-effective option relative to hydrogen.

(5) Transition technologies for the chemicals sub-sector

In the chemicals sub-sector, a single technology was selected for analysis: the production of chemicals using captured CO_2 instead of fossil fuels. This production pathway not only decreases emissions but also reduces reliance on fossil resources. Methanol was chosen as a representative example, given its versatility and broad applicability across multiple industries. The capital investment required for a methanol synthesis facility utilising captured CO_2 and renewable hydrogen is estimated to be comparable to that of a conventional methanol plant, particularly in terms of synthesis equipment. The bulk of production costs, however, are associated with generating hydrogen from renewable sources and sourcing CO_2 from carbon capture installations. The potential for GHG emission reduction largely hinges on the specific method of hydrogen production employed.

(6) Transition technologies for the cross-cutting industrial sub-sector

Six transitional technologies applicable across various industries were selected for in-depth analysis: carbon capture, low-emission fuel-powered equipment, large-scale industrial heat pumps, waste heat recovery, electric heating, and large-scale once-through boilers. All selected technologies, aside from carbon capture, are focused on heat generation, a primary source of emissions in the manufacturing sector. Carbon capture, particularly through chemical absorption, is a mature technology capable of achieving high CO_2 capture rates. However, the current lack of infrastructure for CO_2 processing and transportation presents a significant barrier to its deployment. For heat-generating technologies, GHG emission reduction potential varies based on fuel type, specific applications, grid decarbonisation and the baseline technology each replaces. Given the widespread adoption of conventional heat generation technologies, incentivising manufacturing plants to replace the existing conventional technologies with low-carbon alternatives will be crucial for broader adoption across the industry.

4.2 Comparison with the ASEAN Taxonomy technology screening criteria (TSC)

(1) TSCs for transition technologies selected in the TLP

Technical screening criteria (TSC) is a set of criteria tailored to each economic activity of a focus sector under the ASEAN Taxonomy. A user must meet the criteria of the selected EO, and the labelling of its economic activity of question is determined by TSC and EC.

For the TLP, TSCs of climate change mitigation were examined and where a relevant TSC is available for a selected transition technology, its emission reduction and energy efficiency levels were compared to TSCs. As the ASEAN Taxonomy is still under development, not all the transition technologies examined in the TLP had a matching TSC.

Exhibit 17. Relevant TSCs for Transition Technologies Examined in the TLP

Sub-sector	Transition technology	Relevant TSC
Building	Heat pump	Production of heating/cooling using electric heat pump
		Production of heating/cooling from geothermal energy (Only applicable to ground source Heat Pump (HP))
		District heating/cooling distribution (only applicable when HP is used for a district heating purpose)
	Fuel combustion co-generation	Electricity generation from fossil gas
		Electricity generation from bioenergy, including co-firing with fossil fuels
	Fuel cell co-generation	Electricity generation from renewable non-fossil gaseous and liquid fuels, including co-firing with fossil fuels
Transport	Hydrogen fuel cell vehicles	Urban and suburban transport, road passenger transport
		Transport by motorbikes, passenger cars, and light commercial vehicles
	Battery electric vehicles (BEV) and Plug-in hybrid vehicles (PHEV)	Freight transport services by road
		Transport by motorbikes, passenger cars, and light commercial vehicles
		Freight transport services by road
	Hybrid electric vehicles (HEV)	Urban and suburban transport, road passenger transport
		Transport by motorbikes, passenger cars, and

Sub-sector	Transition technology	Relevant TSC
		light commercial vehicles
		Freight transport services by road
	Flex fuel vehicles (FFV)	Urban and suburban transport, road passenger transport
		Transport by motorbikes, passenger cars, and light commercial vehicles
		Freight transport services by road
	LNG fuelled ships	Sea and coastal freight water transport, vessels for port operations and auxiliary activities
	Biofuel fuelled ships and Ammonia fuelled ships	Sea and coastal freight water transport, vessels for port operations and auxiliary activities
Cross-cutting	Lower-emission fuel fuelled equipment	Production of heating/cooling from renewable non-fossil gaseous and liquid fuels
		Production of heating/cooling from fossil gas
	Large-scale industrial heat pumps	Production of heating/cooling using electric heat pump
	Waste heat recovery	Production of heating/cooling using waste heat
	Small-scale once-through boiler	Production of heating/cooling from renewable non-fossil gaseous and liquid fuels
		Production of heating/cooling from fossil gas

Source: Created by author based on ASEAN Taxonomy Board (2024).

(2) Challenges in comparing TSCs with transition technologies

It is important to note that TSCs are made for economic activity and not for technology, which makes it difficult to make a direct comparison between TSC and transition technology sometimes. An example is the TSC for sea and coastal freight water transport. The TSC sets thresholds based on how much zero direct CO_2 emission fuels are used in a fuel mix of ship. This is not something the ship technology itself determines, but rather how the ship is used determines, and therefore the direct comparison is not available for the ship technologies examined in the TLP.

Additionally, some TSCs set thresholds on lifecycle emissions and others set thresholds on direct emissions. An example of thresholds for direct emissions is TSCs for road transport, including one for urban and suburban transport and road passenger transport. This TSC sets a threshold on direct (tailpipe) CO_2 emissions, which makes it easier to compare the TSC with a transition technology, such as BEV, FFV, etc. On the other hand, the TSC for 'electricity generation from renewable, non-fossil nauseous and liquid fuels, including co-firing', sets thresholds on lifecycle GHG emissions per electricity generated. Lifecycle GHG emissions would vary depending on how fuel is produced and transported and how electricity generation equipment is used and decommissioned. It is not easy to calculate lifecycle GHG emissions and it has to be assessed on a project-to-project basis. On the other hand, for some economic activities, a specific characteristic of technology is used as a TSC. An example of this is the TSC for 'production of heating/cooling using an electric heat pump', which sets a threshold on the global warming potential of a refrigerant used in a heat pump. A refrigerant used in a heat pump varies over products, and it was unable to compare heat pumps in general against the TSC.

The fact that TSCs are set for economic activity and not for technology makes it complicated for financial institutions to assess a potential transition technology or project against TSCs sometimes, as they have to take into account how a transition technology is going to be used. Further work on user-friendliness would help the wider use of the taxonomy.

4.3 Policy Recommendation

Our research has revealed that the existence of advanced transition technologies itself is insufficient to drive the financial mobilisation necessary for their widespread deployment within the end-use and industrial sector. Instead, it is the presence of well-designed policies that incentivise the adoption of these technologies which plays an equally critical role in unlocking and channelling finance toward their implementation.

Effective policies for the deployment of transition technologies vary depending on technologies. The below summarises potential policies to accelerate the deployment of transition technologies for the end-use and industries sector briefly by policy type.

(1) Carbon pricing

Carbon pricing is an essential tool to internalise the external costs of GHG emissions, promoting cleaner technologies and energy efficiency. It ensures that emitters bear the social costs of their activities, thereby incentivising reductions. This policy is applicable to all technologies on TLP. Transition technologies often require higher implementation cost compared to conventional technologies, which may discourage technology users from implementing these technologies. Carbon pricing policies such as carbon tax and emissions trading scheme provide financial incentive to implement technologies with less GHG emissions.

(2) Performance standards

Performance standards set regulatory thresholds to ensure technology and infrastructure meet minimum energy efficiency and environmental performance levels, driving advancements in cleaner technologies. Possible implementation types include the minimum energy performance standards (MEPS), performance labelling and building codes. MEPS and performance labelling are applicable to heat pumps, fuel combustion co-generation, fuel cell co-generation, HEMS, HFCV, BEV, PHEV and FFV. Building codes are applicable to technologies in the building sector, namely heat pumps, fuel combustion co-generation, fuel cell co-generation and HEMS. Mandating a certain environmental performance supports the development of transition technology by manufacturers. By providing information on the energy efficiency of those technologies, which allows users to make comparisons, users are able to make better-informed decisions.

(3) Investment subsidies

Transition technologies often require higher implementation costs compared to conventional technologies, which may discourage technology users from implementing these technologies.

Investment subsidies, such as grants, tax credits, and financing programmes, lower the financial barriers to adopting advanced technologies, accelerating the transition toward sustainable practices. This policy is applicable to all technologies on TLP, and it is particularly relevant for the technologies which require a large capital investment for deployment, such as carbon capture, LNG-fuelled ships, biofuel-fuelled ships, etc.

(4) Infrastructure development

Developing infrastructure such as stable utility supply systems and vehicle charging stations is crucial for supporting the wide adoption of clean technologies and ensuring sustained progress. For technologies such as heat pumps, fuel cell co-generation, fuel combustion co-generation EAF, Electric heating which require grid electricity, stable utility supply is crucial for successful adoption of technologies. For BEV, PHEV/HFCV, LNG-fuelled ship and Biofuel/Ammonia-fuelled ship, development of charging and refuelling infrastructure is necessary.

(5) R&D support

Investments in R&D are vital for technological innovation and the discovery of new solutions to environmental and energy challenges. Public and private collaboration enhances the impact of these efforts. This policy is especially applicable to technologies with lower TRL such as ammonia fueled ship, production of chemicals using captured CO_2, DRI, carbon capture and large-scale industrial heat pumps.

However, even for technologies with higher TRLs, support for technological development and demonstration could contribute to increasing the performance or bringing down cost, leading to increased adoption of technologies. Possible implementation types include public investment in research and public-private partnerships.

(6) Biofuel mandate

A biofuel mandate requires a certain percentage of biofuel to be blended with traditional fossil fuels, reducing reliance on non-renewable energy sources and lowering GHG emissions. This policy is applicable to biofuel fuelled-ship, FFV, lower emission fuel fueled equipment and fuel combustion co-generation using biofuels. Technologies using biofuels often require additional technology development, resulting in higher costs, but biofuel mandates send a clear message to technology manufacturers from the government to utilise biofuel, ensuring technology commercialisation.

5 The Next Phase

The TLP document is a living resource, with ongoing updates to reflect emerging technologies and changing needs. The next phase will examine the midstream and downstream sectors, conducting in-depth research and analysis on selected transition technologies in these areas. The prioritisation of the end-use and industries sector was strategic, as technology selection in this sector will influence choices for the downstream and midstream sectors. After completing the deep-dive research on the end-use and industries sector, technologies for the midstream, and downstream sectors will be identified for deep-dive research.

Annex

How to use

Transition technologies for the end-use and industries sector

- Building sub-sector
- Transport sub-sector
- Cement, concrete and glass sub-sector
- Chemicals sub-sector
- Iron & steel sub-sector
- Industries cross-cutting sub-sector

Appendix

1 - Examples of AMS' technology introduction roadmap towards net zero emissions

2 - Examples of international aids towards decarbonisation of the industries and end-use sector in ASEAN

3 - Potential policy instruments that can support widespread deployment of transition technologies

The document aims to provide a framework for assessing transition technology suitability, rather than a rigid classification

The document

- Provides **a framework** for assessing a potential transition technology
- Provides **relevant, practical information** on various potential transition technologies in **a fact-based manner**
- Focuses upon major potential transition technologies, initially in a limited number of sectors. (Other sectors will be addressed in future updates.)

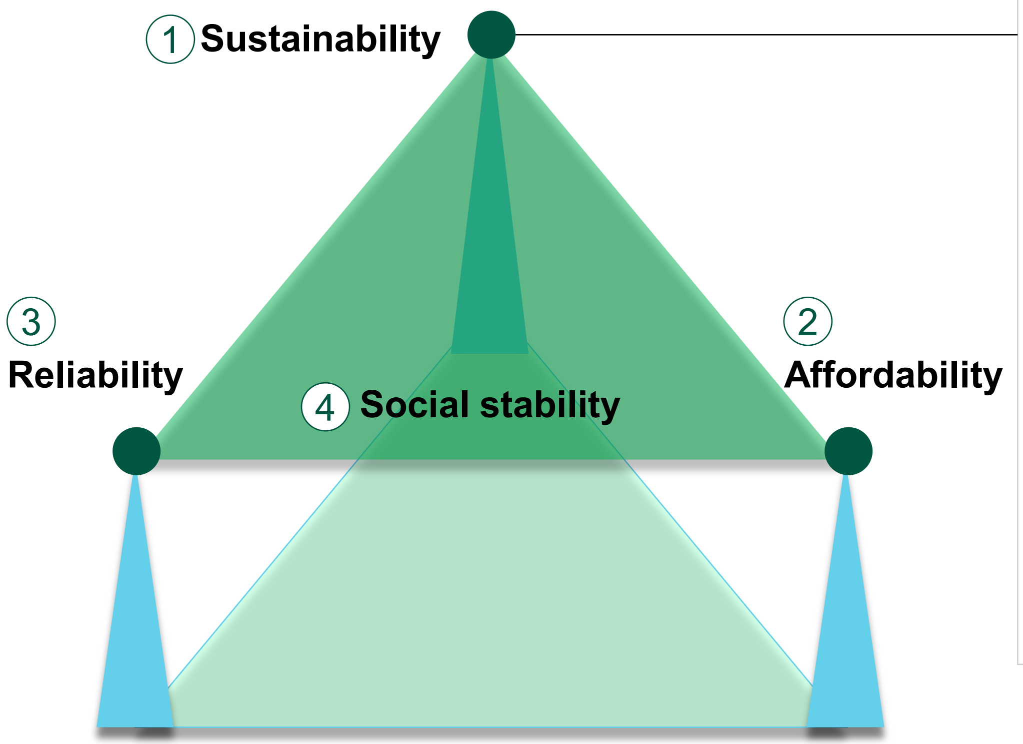
The document

- Does **not** provide **absolute criteria** for what constitutes a transition technology.
- Is **not restricted to** offering a set of **principles**; it provides example information on individual technologies
- Is **not an exhaustive list** of potential transition technologies in Asia

Transition technologies are assessed on 6 framework dimensions to address important factors for a just and orderly transition

Deep dive

Important factors for a just and orderly transition



Challenges

- Not only promote climate sustainability but also ensure the reliability of energy supplies and their affordability for governments and their citizens, maintaining social stability
- Striking a subtle balance amongst sustainability, reliability and affordability to maintain social stability

6 key framework dimensions

1. Contribution to energy transition; Lock-in prevention considerations; DNSH[1] considerations
2. Affordability
3. Reliability/maturity
4. Social considerations

Note:
1. Do no significant harm

Source: ATF (2022)

Assessments along the 6 framework dimensions leverages specific questions and data sources

ILLUSTRATIVE

	Framework dimensions	Description	Reference
Technology characteristics	**Contribution to energy transition**	GHG[1] emissions intensity and/or reduction impact required to contribute to decarbonisation of a country or company	Literature
	Affordability	Estimated cost for technology	Literature
	Reliability/ maturity	Readiness for technology (e.g. commercial at scale, pilot, etc.).	Literature and expert insights. IEA[2]'s definition of each TRL[3] was referred.
Additional considerations	**Lock-in prevention considerations**	Eventual emissions reduction plan to reach zero or near-zero emissions.	Literature and expert insights
	DNSH considerations	'Do No Significant Harm' to environmental objectives other than GHG emissions.	
	Social considerations	Mitigate the negative effects of transition activities to the society, e.g. unemployment	

Note:
1. Greenhouse gases
2. International Energy Agency
3. Technology Readiness Levels

Source: IEA (2024b)

[Reference] Framework for DNSH and Social considerations

Framework dimensions	Considerations/Key questions		Reference
DNSH conside-rations	**Protecting healthy ecosystems and biodiversity**	• Would the technology be detrimental to the health and resilience of ecosystems and biodiversity? What preventative measures should be implemented? • Beside GHG, would the technology lead to a significant increase in the emissions of pollutants into the air, water, or land? What preventative measures should be implemented?	Literature and expert insights
	Promotion of transition to circular economy	• Would the technology run on sustainably-sourced raw materials? • Would the technology increase the generation, incineration, or disposal of waste? What measures should be taken to avoid or minimise waste?	
Social conside-rations	**Are there plans to mitigate the negative social impacts of the technology?**	• Would the technology lead to negative changes in job opportunities?	
		• Would the technology lead to negative changes in working environments?	

Source: EC (n.d.), ASEAN Taxonomy Board (2024)

[Reference] Reliability dimension is assessed with the TRL published by IEA

	Level	Description
Mature	**11**	Proof of stability reached – Predictable growth
Market uptake	**10**	Integration required at scale – Solution is commercial and competitive, but requires further integration efforts
	9	Commercial operation in relevant environment – Solution is commercially available. requires evolutionary improvement to stay competitive
Demonstration	**8**	First of a kind commercial – Commercial demonstration. Full- scale deployment in final conditions
	7	Pre-commercial demonstration – Prototype working in expected conditions
Large prototype	**6**	Full prototype at scale – Prototype proven at scale in conditions where it will be deployed
	5	Large prototype – Components proven in conditions where it will be deployed
Small prototype or lab	**4**	Early prototype – Prototype proven in test conditions
	3	Concept requires validation – Solution must be prototyped and applied
	2	Application formulated – Concept and application have been formulated
	1	Initial idea – basic principles have been derived

Source: IEA (2024b)

[Reference] The ASEAN Taxonomy

- TLP refers to the technical screening criteria (TSC) of the ASEAN Taxonomy. TSC is available for some economic activities of the six focus sectors under Plus Standard. As the ASEAN Taxonomy is going through on-going work of updating and TSCs are not yet available for all the focus sectors.
- TSC provides quantitative or qualitative criteria which determine a label, i.e. green, amber, and red, of an economic activity. Where TSC is available, it is compared to the carbon emission reduction levels of transition technologies in TLP.

Foundation Framework (FF)

- FF is applicable to all the sectors
- User must select one of the environmental objectives (EOs)
  1. Climate change mitigation
  2. Climate change adaptation
  3. Protection of Healthy Ecosystems and Biodiversity
  4. Resource Resilience and the Transition to a Circular Economy
- User must meet all the essential criteria (EC)
  1. Do no significant harm (DNSH)
  2. Remedial measures to transition (RMT)
  3. Social aspect (SA)
- User must meet criteria of the selected EO and all of the ECs

Plus Standard (PS)

- PS is applicable to the 6 focus sectors and 3 enabling sectors

[Focus sectors]

1. Agriculture, forestry & fishing
2. Electricity, gas, steam and air conditioning supply
3. Manufacturing
4. Transportation & storage
5. Water supply, sewage, water management
6. Construction & real estate

[Enabling sectors]

1. Information & communication
2. Professional, scientific & technical
3. Carbon capture, storage & utilisation

- **Technical screening criteria (TSC)** is a set of criteria tailored to each economic activity of a focus sector.
- User must meet the criteria of the selected EO and labelling of its economy activity of question is determined by TSC and EC

Source: ASEAN Taxonomy Board (2024)

List of Technologies

Building sub-sector

- Heat Pumps
- Fuel Combustion Co-generation
- Fuel Cell Co-generation
- Home Energy Management System (HEMS)

Transport sub-sector

- Hydrogen Fuel Cell Vehicles (HFCV)
- Battery Electric Vehicles (BEV)
- Plug-in Hybrid Vehicles (PHEV)
- Hybrid Vehicles (HEV)
- Flex Fuel Vehicles (FFV)
- LNG-fuelled Ship
- Biofuel-fuelled Ship (Methanol & Ethanol)
- Ammonia-fuelled Ship

Cement, concrete and glass sub-sector

- Carbon mineralisation
- NSP Kiln

Chemicals sub-sector

- Production of Chemicals using Captured CO_2

Iron & steel sub-sector

- Electric Arc Furnace (EAF)
- Direct Reduced Iron (DRI)

Industries cross-cutting sub-sector

- Carbon Capture
- Lower Emission Fuel Fuelled Equipment
- Large-scale Industrial Heat Pump
- Waste Heat Recovery
- Electric Heating
- Small-scale Once Through Boiler

BACK TO THE LIST OF TECHNOLOGIES

Four potential transition technologies for the building sub-sector

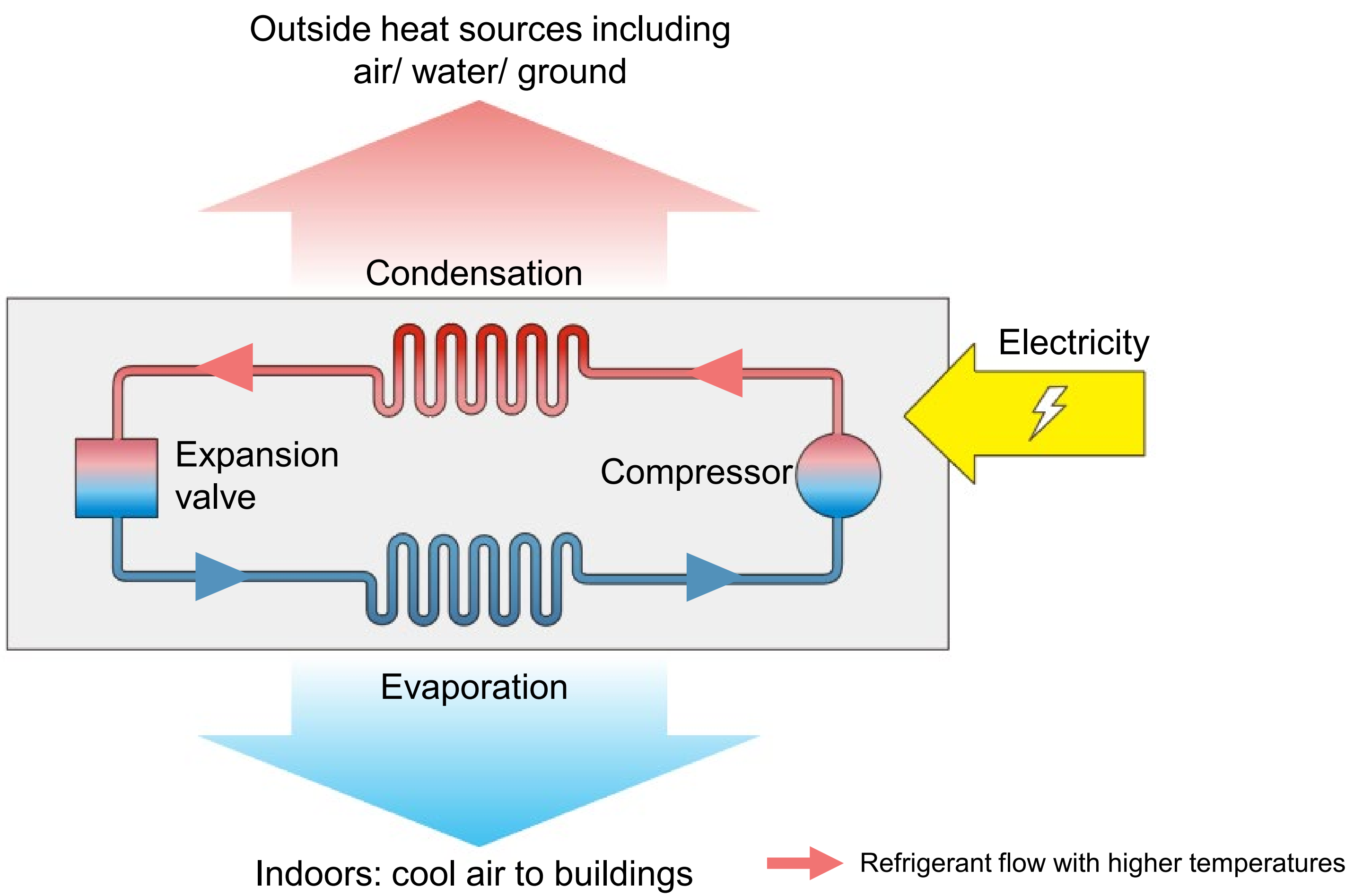
Heat Pumps

Fuel Combustion Co-generation

Fuel Cell Co-generation

Home Energy Management System (HEMS)

(1) Heat pumps– Technology schematics and overview



Source: Author created based on various literature

*Heat pumps can also operate in a reverse cycle for heating use in buildings.

Heat pumps transfer heat from one place to another and can effectively provide **both cooling and heating**.

It extracts heat from a source, such as the surrounding air, geothermal energy stored in the ground, or nearby sources of water. It can be roughly divided into the following 3 types based on heat source:

- Air-source heat pump (ASHP)
- Water-source heat pump (WSHP)
- Ground-source heat pump (GSHP)

Worldwide, almost **85%** of all heat pumps sold for buildings are **air-source**, requiring the least effort to install. As cooling needs are rising among most ASEAN[1] countries, heat pumps could be a potential transition solution for energy saving due to their high efficiency. Considering the usage in ASEAN countries, heat pumps specifically for air conditioning will be discussed.

Note:

1. ASEAN = The Association of Southeast Asian Nations

Source: IEA (2022b)

(2) Heat pumps– Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• Although heat pump systems do not burn fossil fuels, they indirectly cause emissions due to electricity consumption. High energy-efficiency heat pumps will contribute to energy transition and reduce emissions. • Compared to the suggested COP[1] for Minimum Energy Performance Standards (MEPS) in ASEAN, heat pump/air conditioner(AC) with high COP can save annual energy consumption up to 47%.
Affordability	• Abatement cost range from USD0.5-3.6/kWh. The cost varies by factors such as region, heat source, and capacity. • Ground-source and water-source heat pumps tend to require higher installation costs compared to air-source heat pump.
Reliability	• Heat pump technology is mature and commercialised. Ground-source and water-source heat pumps still have some room for further cost reduction (TRL of air-source heat pumps: 11, TRL of water-source heat pumps: 9, TRL of ground-source heat pumps: 9).
Lock-in prevention considerations	• Path 1: Improve energy efficiency to reduce electricity consumption. • Path 2: Cut F-gas[2] emissions by preventing leaks of the refrigerants and using low GWP[3] or natural refrigerants. • Path 3: Develop clean energy to achieve lower carbon intensity of local electricity.
DNSH considerations	• Heat island effect from air-source heat pumps should be minimised. • Maximum reuse, remanufacturing or recycling at end of life should be ensured. • F-gas emissions during use and decommissioning should be minimised.
Social considerations	• Job creation: global employment in heat pump supply is expected to nearly triple to over 1.3 million workers to 2030 in the APS[4]. A shortage of skilled installers is already starting to create bottlenecks in the deployment of heat pumps in several countries since it requires additional specialisations.

Notes:
1. COP: Coefficient of Performance. Both are used to measure the energy efficiency of heat pumps or AC. The higher the COP or Energy Efficiency Ratio (EER), the more efficient the device.
2. F-gas: fluorinated gas, which refers to a group of man-made GHG used in various industrial and commercial applications. For heat pumps, hydrofluorocarbons (HFCs) are the main type of F-gas.
3. GWP: Global Warming Potential
4. APS: Announced Pledges Scenario, which assumes that governments worldwide meet all announced energy-and-climate-related commitments in full and on time.

(3) ASEAN Taxonomy – Relevant technical screening criteria

Production of heating/cooling using electric heat pump

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	• Activity is operation of electric heat pumps complying with both of the following criteria: 1. Refrigerant threshold: Global Warming Potential does not exceed 675; 2. Demonstrate a high standard of energy efficiency according to an internationally recognised certifications scheme.
	Tier 2 (Amber T2)	• No TSC available.
Excludes -	**Tier 3 (Amber T3)**	• No TSC available.

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Production of heating/cooling from geothermal energy (Only applicable to ground source Heat Pump (HP))

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	• Lifecycle GHG emissions < 28 gCO_2-eq/MJ per unit of heating and/or cooling produced
	Tier 2 (Amber T2)	• Lifecycle GHG emissions < 65 gCO_2-eq/MJ per unit of heating and/or cooling produced
Excludes • Geothermal heating/cooling as part of co-generation • Geothermal heating/cooling through a combination of geothermal and a combustion process	**Tier 3 (Amber T3)**	• No TSC available.

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

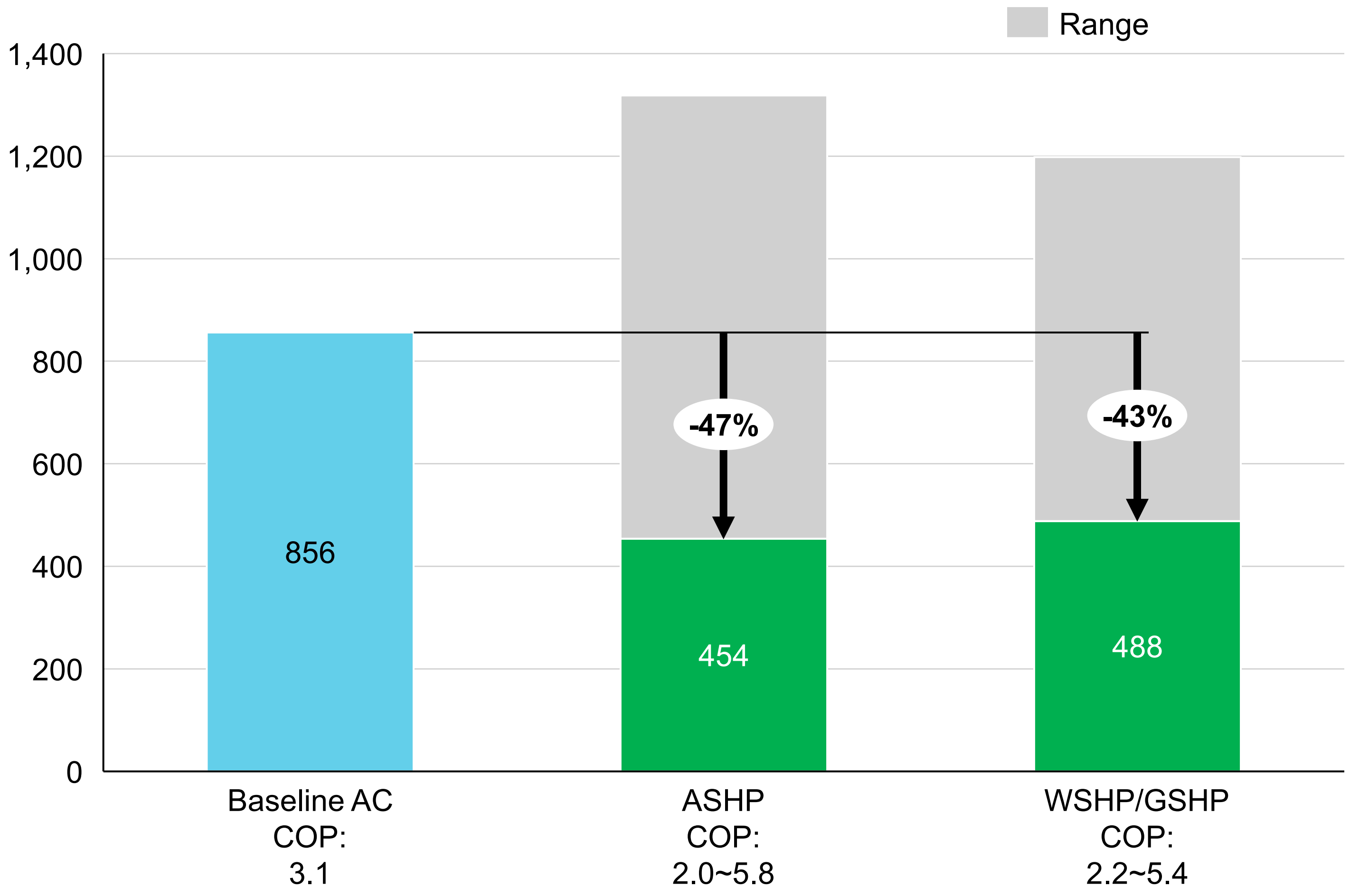
District heating/cooling distribution (only applicable when HP is used for a district heating purpose)

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	1. Activity is operation of an efficient district heating and cooling system; or evidence can be provided to show that the system will become and efficient district heating and cooling system within 3 years of assessment, where an efficient district heating or cooling system is defined as using at least: a. 50% renewable energy; b. 50% waste heat; c. 75% co-generated heat; OR d. 50% of a combination of such energy and heat; OR 2. Activity is an advanced pilot system (control and energy management systems, Internet of Things).
Excludes -	**Tier 2 (Amber T2)**	• No TSC available.
	Tier 3 (Amber T3)	• No TSC available.

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition –Currently available heat pump/AC with high COP can save annual energy consumption up to 47%

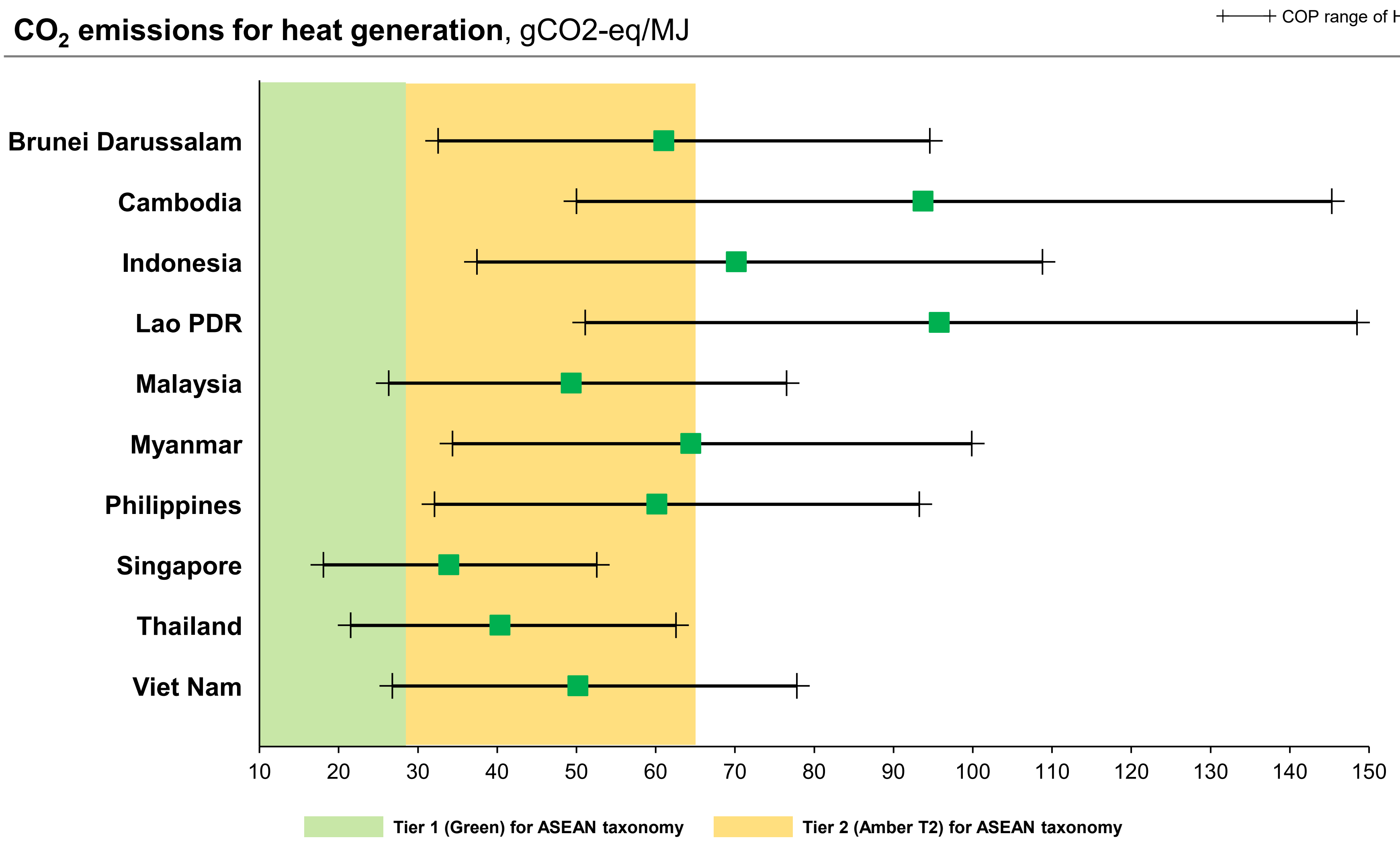
Annual energy consumption per-unit, kWh/year



Source: UNEP (2019), IRENA (2022), HPTCJ (2023)

(4) Contribution to Energy Transition – Higher COP offer greater energy savings; Emission levels vary across ASEAN countries due to different current power mix

CO_2 emissions for heat generation, gCO2-eq/MJ



Tier1 and Tier2 refers to Climate Change Mitigation TSC for Production of heating/cooling from geothermal energy (Only applicable to ground source HP).

Comparison with ASEAN Taxonomy

There are three different TSCs potentially applicable to heat pumps for the building sector.

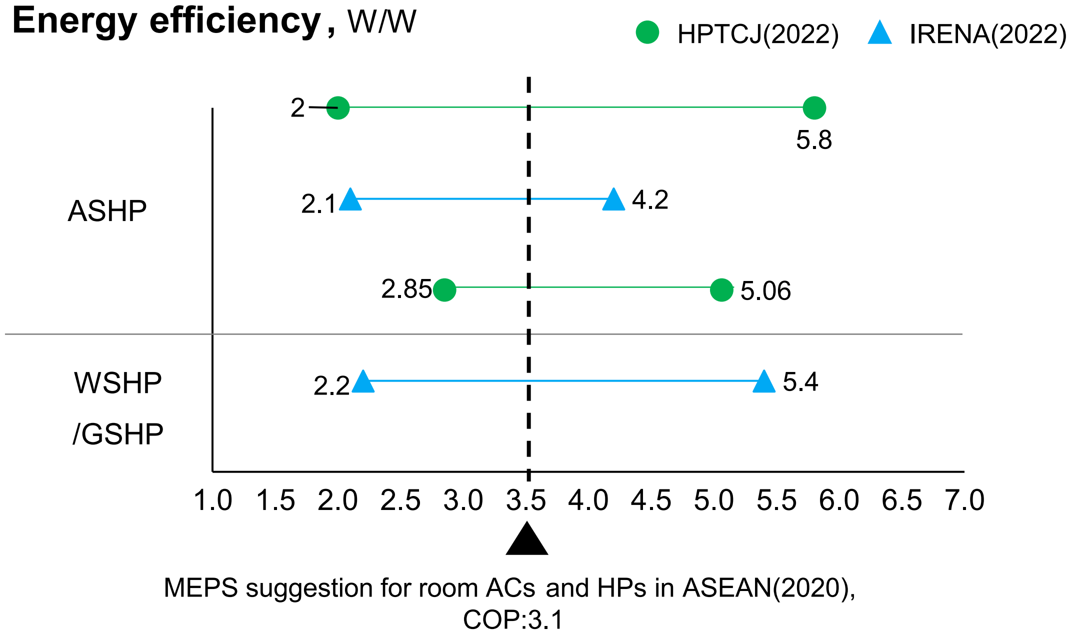
TSC for heating/cooling using electric heat pump sets a threshold on GWP of refrigerant used in a heat pump, which should be assessed on a product by product basis. This TSC was unable to be applied to groups of heat pump technologies, i.e. ASHP, WSHP, GSHP.

TSC for production of heating/cooling from geothermal energy sets a threshold on carbon intensity per produced heating/cooling, which was applied in this slide.

In ASEAN, each AMS has a unique power mix; therefore, even for the same heat pump technology, CO_2 emissions derived from the use of electricity to operate a heat pump vary. This results in different labelling for the same technology in different AMS.

[Reference] Methodologies: Contribution to Energy Transition

Methodology: Annual energy consumption per unit



1. Annual energy consumption per-unit: baseline refers to the annual energy consumption of room ACs under United for Efficiency (U4E) MEPS suggestion assumptions (COP3.1, Fixed speed, 1,817 Hours of use per year). These assumptions only apply to Heat pump/AC with a rated cooling output of at or below 16 kW.
2. W/W represents the ratio of the energy output (heat or cooling energy) to the energy input (electrical energy). This unit expresses COP, which measures the heat pump's efficiency.
3. COP data from HPTCJ are collected based on the catalogue information of major manufacturers in the market.
4. According to U4E, the suggested MEPS for room ACs and Heat pumps is at 3.1

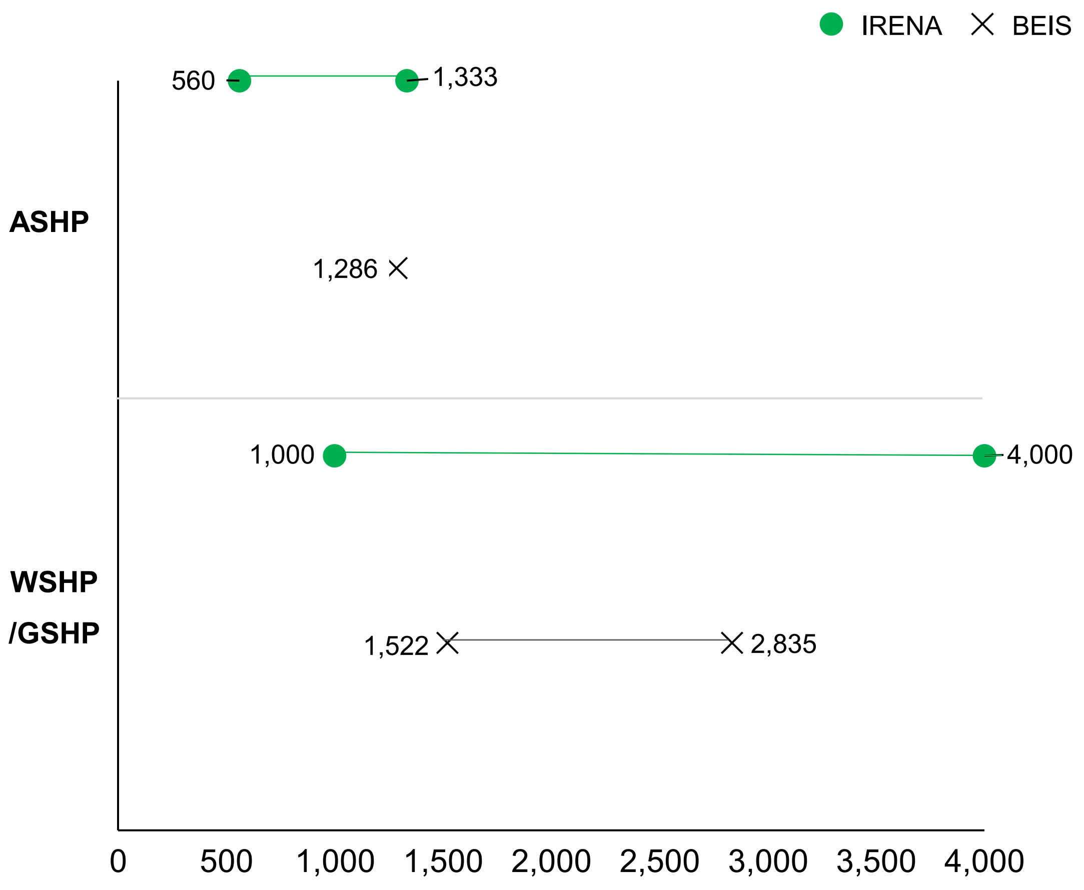
Methodology: CO_2 emissions for heat generation

1. The ranges reflect variations in the efficiency of heat pump installations, with assumed COP from 2.0-5.8. The maximum emission for each range assume COP at 2.0, while the minimum emission assume COP at 5.8. The higher COP indicates greater energy efficiency which result in lower emission when producing the same amount of heat. Grid Emission Factors for each countries refers to operating margin in the database from United Nations Framework Convention on Climate Change (UNFCCC) (2021),Harmonized Grid Emission Factor data.
2. Baseline refers to the same as previous slide at COP3.1, MEPS of U4E Air Conditioner Policy Guide. This is a voluntary guidance for governments in developing and emerging economies that are considering a regulatory or legislative framework that requires new room ACs to be energy-efficient.

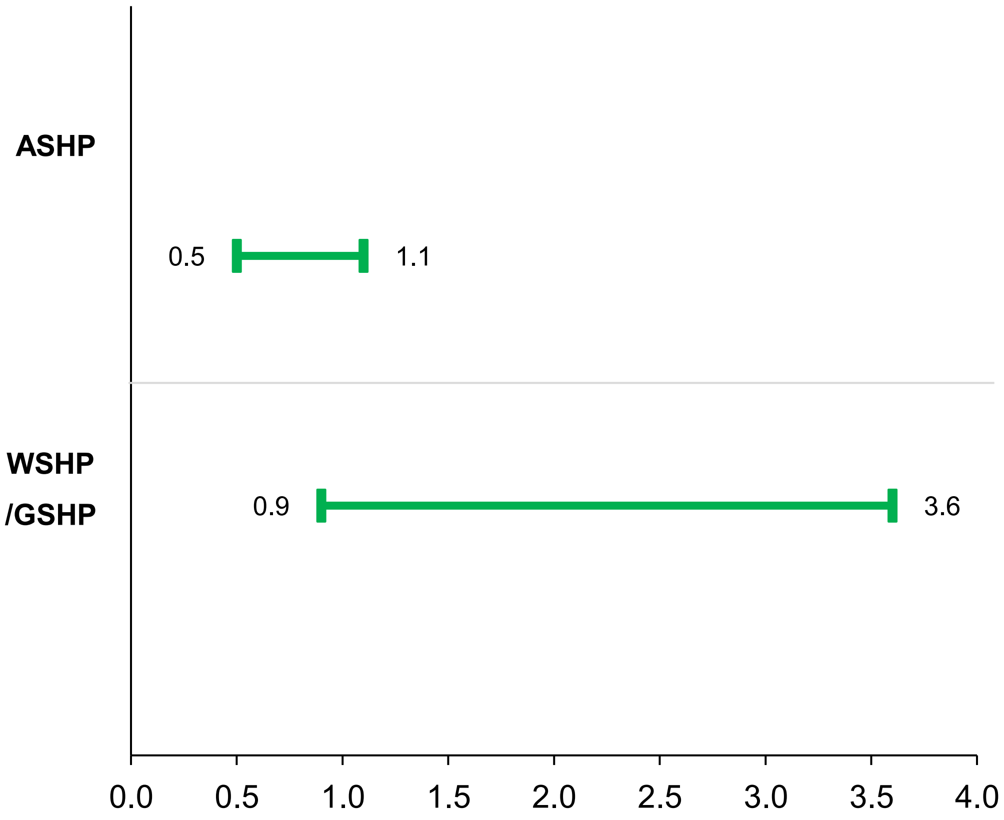
Source: UNEP (2019), IRENA (2022), HPTCJ (2023)

(5) Affordability – Compared to the most popular ASHP, WSHP/GSHP require higher cost at installation

Installation cost, USD/kW



Abatement costs per energy saved, USD/kWh



Source: IRENA (2022), IRENA (2013), BEIS (2024)

[Reference] Methodologies: Affordability

Methodology: Installation cost

1. Installation cost was calculated based on a dataset collected from BEIS (2024) based on the annual reported installation cost of Renewable Heat Incentive (RHI) programme. The cost of WSHP/GSHP refers to tariff band of "small water or ground source heat pumps (<100kW)" and "largel water or ground source heat pumps (>100kW)".

Methodology: Abatement costs per energy saved

1. Abatement cost per energy saved was calculated by using the following formula: {Total installation cost(USD)/(Annual energy saving×Lifetime)}. (Not including operation cost). Annual energy saving refers to the difference between Baseline AC(COP:3.1) and high efficiency ASHP/WSHP/GSHP which shown on previous slide. The typical cooling capacity, referred to U4E "Model regulation guidelines and climate-friendly air conditioners", is 4.5kW, and the lifetime for all types of HPs assumed to be 13.7 years.

Source: IRENA (2022), IRENA (2013), BEIS (2024)

(6) Reliability – ASHP has a relatively higher commercialisation status than WSHP and GSHP in building sector due to its low cost

Estimated commercialisation status

- Air-source (ASHP): TRL 11, the most popular heat pump with over 85% share in the worldwide building heat pump sector. Low installation cost and improving efficiency are the key for its development.
- Water-source (WSHP): TRL 9, less popular than ASHP in ASEAN due to extra water loops equipment needed which causes high installation costs.
- Ground-source(GSHP) : TRL 9, less popular than ASHP in ASEAN due to high installation cost from earthwork.

Recent project examples

Details

At least 8% - 15% of electricity saving by DAIKIN Vietnam

- In 2022, DAIKIN Vietnam[1] launched an ASHP integrated with AI[2] application[3] to optimise electricity usage. A pilot project[4] showed that this technology would **save at least 8% - 15% of electricity consumption per month**.
- As part of a demand response (DR) programme with EVN[5], this technology was widely installed in commercial buildings and offices nationwide after its effectiveness has been confirmed.

Ground source heat pump system installation at Chulalongkorn University in Thailand

- The National Institute of Advanced Industrial Science and Technology (Japan) has installed a GSHP system for air conditioning at Chulalongkorn University in Thailand.
- As a result of the two-month experiment during the hot season in Thailand, it was found that the GSHP systems performed better than ASHP systems in terms of electricity consumption and CO_2 emissions.

Notes:
1. Daikin Air Conditioning (Vietnam) Joint Stock Company
2. AI = Artificial intelligence
3. A typical AC series of ASHP technology: VRV Series 5 is integrated with the SmartDR64 solution.
4. DAIKIN's SMART DR 64 technology and products has just completed the testing phase in KICOTRANS building.
5. EVN = Vietnam Power Group

Source: Widiatmojo, A.; Chokchai, S.; Takashima, I.; Uchida, Y.; Yasukawa, K.; Chotpantarat, S.; Charusiri, P (2019), Vietnam Trade and Industry Review (Tạp chí Công Thương) (2023), IEA (2022b)

(7) Lock-in prevention – Shifting to clean energy is essential; R&D to improve efficiency and switching to low GWP refrigerants is key to achieving zero emission

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Three paths exist for zero-carbon emissions – Path 1: Improve energy efficiency to reduce electricity consumption – Path 2: Cut F-gas[1] emissions by preventing leaks of the refrigerants and using low GWP or natural refrigerants – Path 3: Develop clean energy to achieve lower carbon intensity of local electricity
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Energy efficiency – High cost for high-efficiency equipment. According to industry experts, the current top-of-the-market equipment is reaching the highest possible COP without a significant increase in costs. • Path 2: F-gas emissions – Current high cost and safety concerns for heat pumps equipment using low GWP or natural refrigerants. • Path 3: Clean energy – Nearly 76.7% of the electricity in ASEAN still generated from fossil fuel power plants. Shift from fossil fuel to clean energy is required for indirect emission reduction of heat pumps.

Source: IEA (2022b), Radermacher, R. and V. Baxter (2024), ACE (2023)

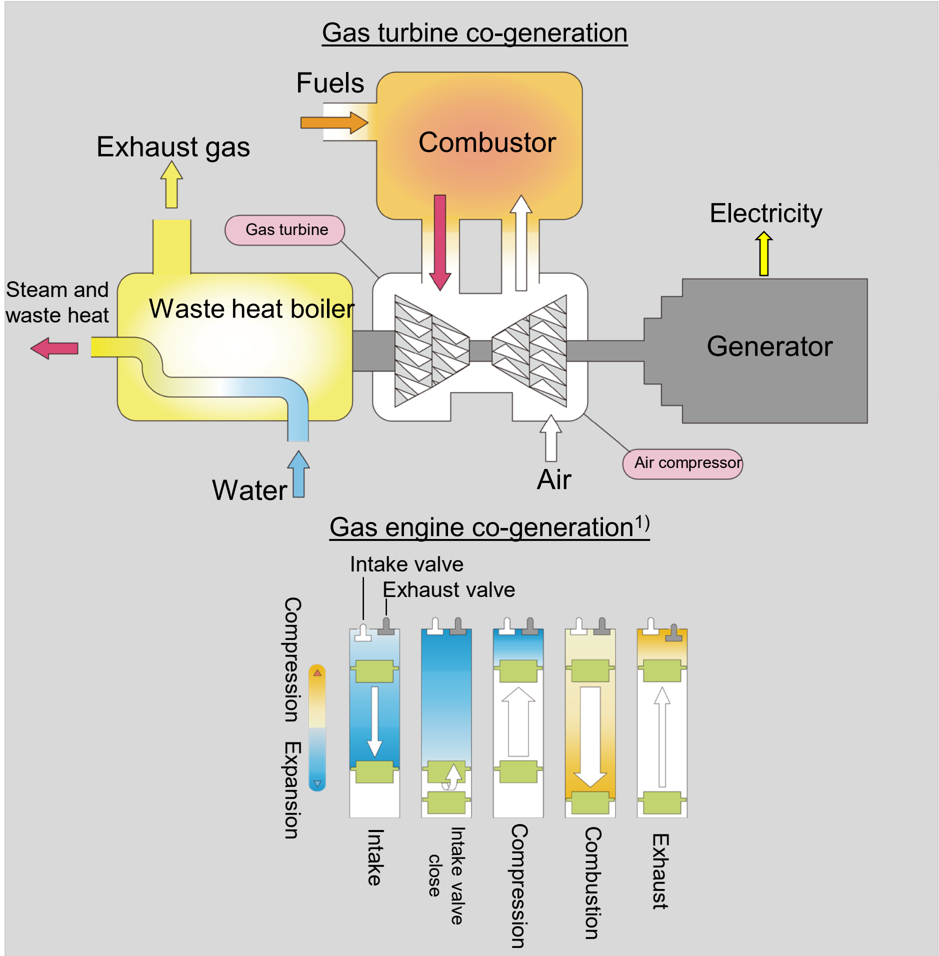
(8)(9) DNSH/social considerations – urban heat island effect, F-gas emission, and workforce shortages may need to be addressed

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• ASHP expels heat from the indoor to the outdoor environment which contributes to causing the urban heat island effect. Decentralised air-source heat pumps and large ground-source heat pumps are potential solutions to limit the urban heat island effect. • Indoor and outdoor sound power levels[1] of heat pumps operation should below the threshold set out in certain regulations. • F-gas emissions occur during the refrigeration cycle when using and decommissioning of heat pumps.
	Transition to circular economy	• European Union (EU) has covered heat pumps and ACs under the Waste Electrical and Electronic Equipment Directive, which sets criteria for the collection, treatment and recovery of waste equipment. However, effective systems for handling obsolete devices may not be in place globally.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Global employment in the heat pump market is expected to nearly triple to over 1.3 million workers to 2030 including O&M[2] worker and installers. A shortage of skilled installers is already starting to create bottlenecks in the deployment of heat pumps in several countries since it requires additional specialisations.

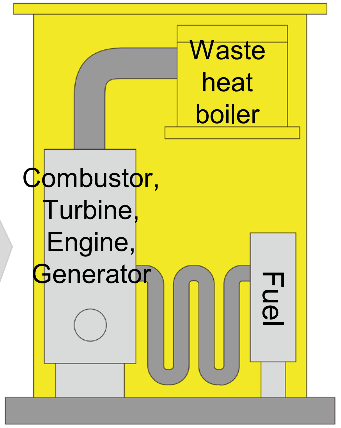
Notes:
1. Sound power levels: A-weighted sound power level [dB(A)] indoors and/or outdoors measured at standard rating conditions for cooling or heating. EU taxonomy indicates that sound power levels for air heat pumps with rated capacity of 12kW or below should below 60-70 dB.
2. O&M: operation and maintenance

Source: EHPA (2022b), IEA (2022b).

(1) Fuel Combustion Co-generation– Technology schematics and overview



Source: MRI created based on ACEJ (2024b) and ACEJ (2024c)



Fuel Combustion Co-generation Equipment

Source: EPA Combined Heat and Power Partnership (2017)

Fuel combustion co-generation (combined heat and power, CHP) is a system that generates electricity and simultaneously recovers the waste heat. It is a technology that allows efficient use of energy.

There are several types of CHP systems; gas engines, gas turbines, steam turbines and microturbines which provide heat and electricity to a wide range of users, including homes, industrial complexes, and entire towns.

Systems using natural gas as fuel is common, but it is possible to convert parts of the system so that renewable fuels can be used, preventing lock-in of GHG emissions.

Note:
1. The schematic for gas engine cogeneration only shows the engine part of the power source. As same as gas turbine cogeneration, there is a boiler that uses the engine waste heat and a generator that uses the kinetic energy obtained from the engine crank.

(2) Fuel Combustion Co-generation– Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• CHP systems utilise less fuel compared to technologies which generate heat and power separately for the same level of output, it therefore emits less GHG than separate systems.
Affordability	• O&M costs and installation costs depend on the types of CHP systems and their capacities.
Reliability	• CHP technologies are already commercialised and deployed globally in various facilities. It is also deployed in energy-intensive industries. TRL 9-11.
Lock-in prevention considerations	• Path1: Improve the total CHP efficiency • Path2: Install co-generation systems fuelled by renewable fuels
DNSH considerations	• Nitrogen oxides (No_x) is emitted during the combustion process. Further R&D efforts and a regulation to limit NO_x emissions are needed. • Appropriate recycling methods must be deployed for the disposable parts.
Social considerations	• Training should be provided to improve the knowledge on engineering

(3) ASEAN Taxonomy – Relevant technical screening criteria

Electricity generation from fossil gas

Eligibility	Climate Change Mitigation TSC	Details
Includes • Power generation as part of co-generation **Excludes** • Power generation using as derived from coal except where it can be shown that, by abatement through carbon capture, utilisation and storage (CCUS), respective TSC below are fulfilled. • Co-firing of fossil fuels with fuels derived from renewable sources	**Tier 1 (Green)**	• Lifecycle GHG emissions from the generation of electricity by the entire facility <100 gCO_2-eq/kWh.
	Tier 2 (Amber T2)	• Lifecycle GHG emissions from the generation of electricity by the entire facility: ≥100 and <425 gCO_2-eq/kWh.
	Tier 3 (Amber T3)	
	TSC applicable to all Tiers	1. For facilities that are equipped with CCUS, CO_2 from power generation that is captured for underground storage, must be transported and stored in accordance with the TSC for Activities 000[010] and 000[020]. 2. The Activity meets either of the following criteria: a. at construction, measurement equipment for monitoring of physical emissions, such as methane leakage is installed, or a leak detection and repair programme is introduced; OR b. at operation, physical measurement of methane emissions is reported, and leak is eliminated.

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Electricity generation from bioenergy, including co-firing with fossil fuels

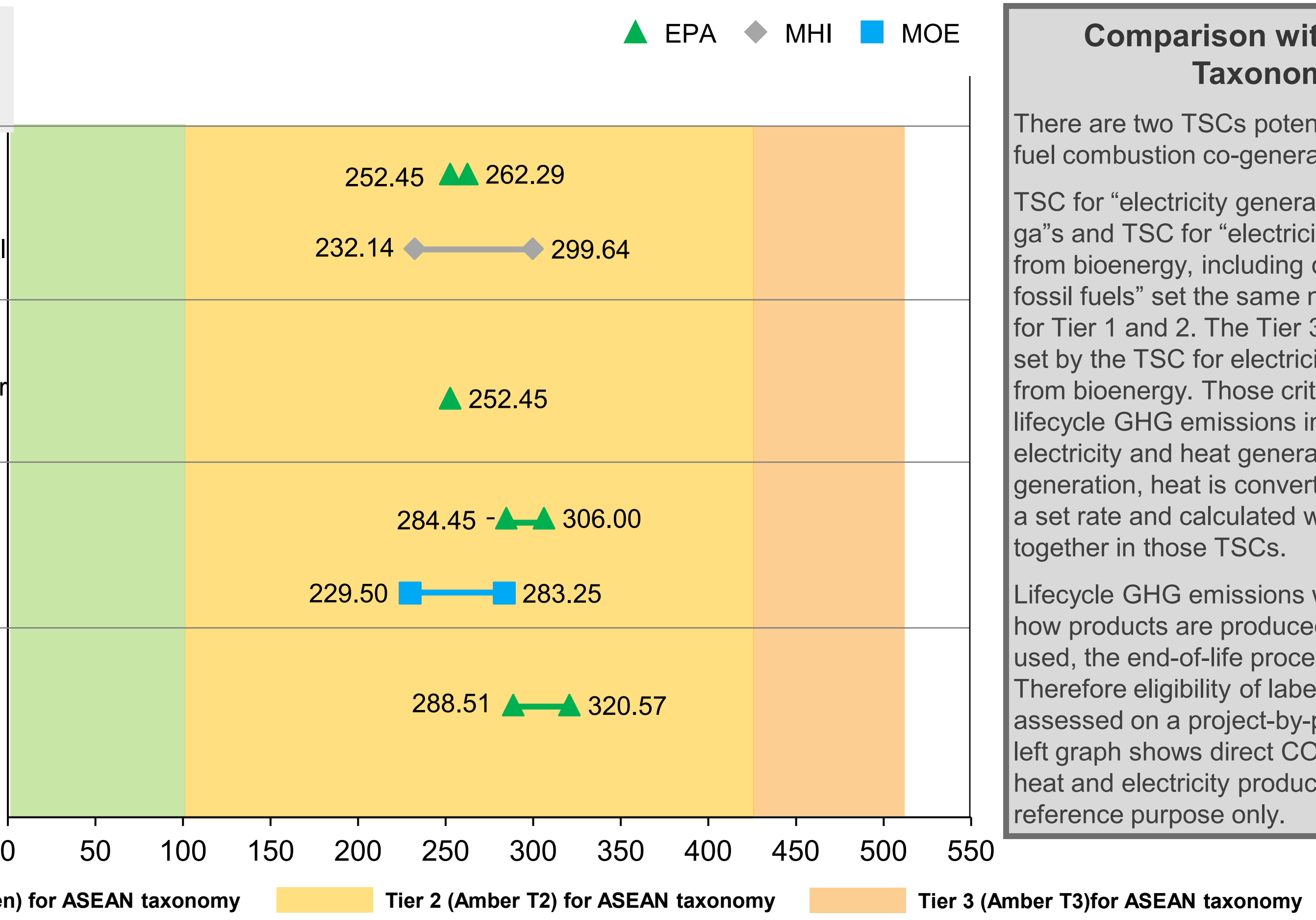
Eligibility	Climate Change Mitigation TSC	Details
Includes • Power generation as part of co-generation	**Tier 1 (Green)**	• Lifecycle GHG emissions from the generation of electricity by the entire facility <100 gCO_2-eq/kWh.
	Tier 2 (Amber T2)	• Lifecycle GHG emissions from the generation of electricity by the entire facility: ≥100 and <425 gCO_2-eq/kWh.
	Tier 3 (Amber T3)	• Lifecycle GHG emissions from the generation of electricity by the entire facility: ≥425 and <510 gCO_2-eq/kWh.
Excludes • Power generation from coal or fuels derived from coal except where it can be shown that, by abatement through CCUS, respective TSC below are fulfilled.	**TSC applicable to all Tiers**	1. Anaerobic digestion of organic biowaste or sewage which is conducted at the site of the power generation must comply with the following: a. Implement monitoring and contingency plan to minimise methane leakage; b. Biogas produced onsite at a facility for the conduct of this Activity must be used only for this Activity or other Activities defined by the ASEAN Taxonomy, etc.; AND c. Any bio-waste that is used for anaerobic digestion is source segregated and collected separately. 2. For facilities that are equipped with CCUS, CO_2 from power generation that is captured for underground storage, must be transported and stored in accordance with the TSC for Activities 000[010] and 000[020].

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition – CO_2 emissions vary over different types of CHP

CO_2 emissions for heat and electricity production, gCO_2/kWh

	Total CHP efficiency (Electric efficiency)	Size	Typical applications
Recip. Engine	77~80% (27~41%)	1kW to 80MW	Universities, hospitals, water treatment facilities, industrial facilities, and commercial and residential buildings
Steam Turbine	80% (5~40%)	50 kW to several hundred MWs	Paper mills, chemical plants, food industry, sugar and palm oil mills
Gas Turbine	66~71% (19~39%)	500 kW to 300 MW	Public buildings, Universities
Microturbine	63~70% (22~28%)	30kW to 250 kW	Hotels, nursing homes, health clubs, public buildings, food and manufacturing sectors



Tier1 to Tier3 refers to Climate Change Mitigation TSC Electricity generation from bioenergy, including co-firing with fossil fuels.

Comparison with ASEAN Taxonomy

There are two TSCs potentially applicable to fuel combustion co-generation.

TSC for "electricity generation from fossil ga"s and TSC for "electricity generation from bioenergy, including co-firing with fossil fuels" set the same numerical criteria for Tier 1 and 2. The Tier 3 criteria is only set by the TSC for electricity generation from bioenergy. Those criteria are based on lifecycle GHG emissions including both electricity and heat generated. For co-generation, heat is converted to electricity at a set rate and calculated with electricity together in those TSCs.

Lifecycle GHG emissions would vary over how products are produced, transported, used, the end-of-life processes etc. Therefore eligibility of labelling should be assessed on a project-by-project basis. The left graph shows direct CO_2 emissions from heat and electricity production for a reference purpose only.

Source: EPA Combined Heat and Power Partnership (2017), MHI (2023a), MOE (2024c)

[Reference] Methodologies: Contribution to Energy Transition

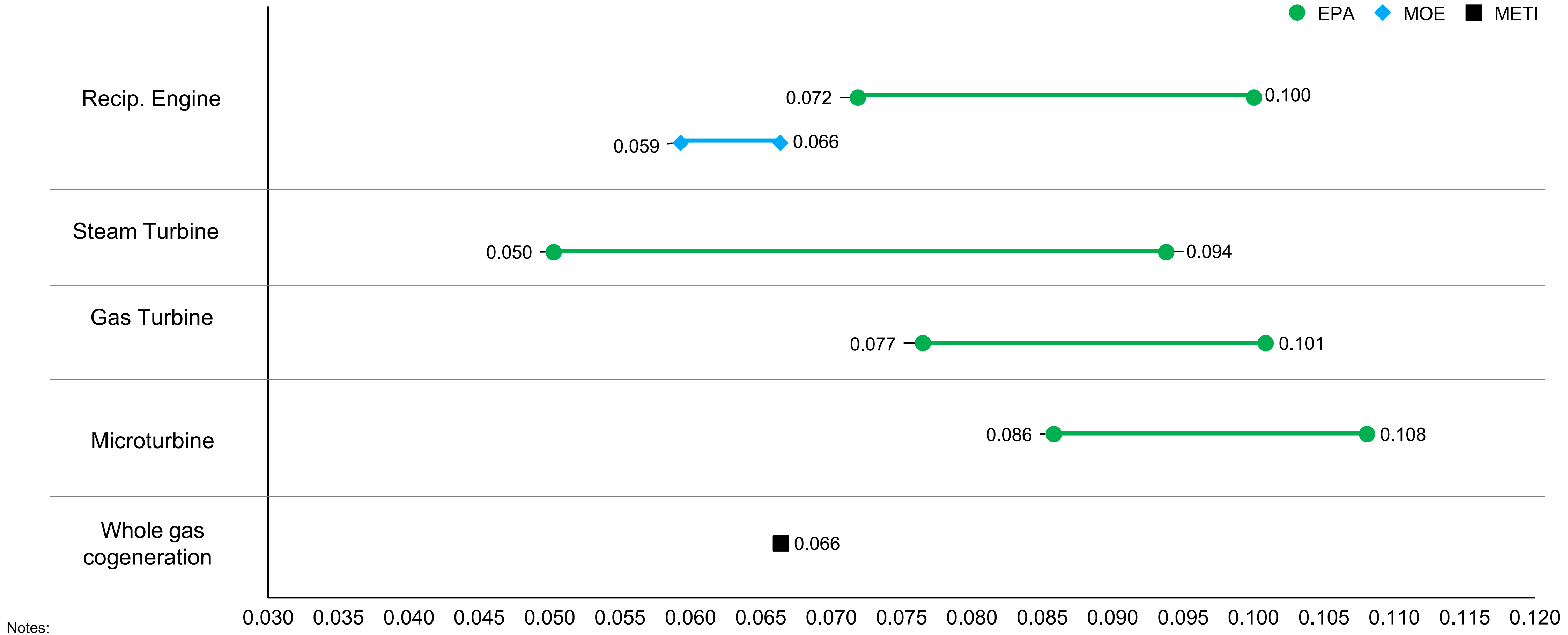
Methodology: CO_2 emissions for heat and electricity production

1. The total CHP efficiency represents the net electrical output plus the net useful thermal output of the CHP system. CO_2 emission per kWh was calculated by the total emission from the entire facility (kgCO_2)/ (electricity generation(kWh) +heat generation(kWh)). 1 MJ of heat energy is deemed to be equivalent to 0.277778 kWh of electricity
2. It was assumed that liquefied natural gas(LNG) is used as an energy source of fuel combustion co-generation systems and the emission factor of LNG was assumed to be 56,100kgCO_2/TJ (IPCC 2006).

Source: EPA Combined Heat and Power Partnership (2017), MHI (2023a), MOE (2024c)

(5) Affordability – Cost of CHP varies depending on its type and capacity; Larger capacity CHP systems consistently have lower O&M and installation costs

CAPEX[1] & OPEX[2] , USD/kWh



Notes:
1. CAPEX: Capital expenditure
2. OPEX: Operating expenditure

Source: EPA Combined Heat and Power Partnership (2017), Japanese government, Cabinet Secretariat (2024), METI (2021c), MOE (2024b)

[Reference] Methodologies: Affordability

Methodology: CAPEX & OPEX

1. This figure shows the total cost of different types of CHP. The total cost is calculated by combining the maximum and minimum values of CAPEX and OPEX obtained from the literature review. CAPEX includes equipment installation, project management, engineering, and interest. OPEX includes fuel costs and non-fuel costs such as routine inspections, scheduled overhauls, preventive maintenance, and operating labour.
2. The installation cost is calculated based on the lifespan and equipment utilisation rates in Asia, as referenced in Japanese government documents. Lifetime: 30 years, Utilisation rate Capacity factor: 70%
3. The fuel cost was calculated by the unit price of natural gas in Asia, and the fuel consumption was estimated from the conditions outlined in the reference source. The unit price of natural gas in Asia: USD13.09/ MMBtu.

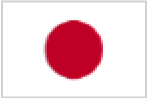
Source: EPA Combined Heat and Power Partnership (2017), Japanese government, Cabinet Secretariat (2024), METI (2021c), MOE (2024b)

(6) Reliability – CHP technologies are already commercialised and deployed globally

Estimated commercialisation status

- TRL 9-11. TRL depends on different fuels used.
- CHP technologies are already commercialised and deployed globally in buildings and energy-intensive industries such as chemicals, pulp and paper, in addition to food and drink.
- Electricity and heat produced in CHP systems are being used in facilities such as hospitals and universities, as well as district heating and cooling networks.

Recent project examples

	Details
Installation of CHP System at Aokijima shopping park 	• Aokijima shopping park in Nagano prefecture, Japan has implemented a CHP system with five 35kW gas engines in 2022. • 22% CO_2 reduction is expected compared to the original system using fuel oil.
Installation of CHP System in Hotel 	• CHP system which consists of a 1,000kW class gas engine and an absorption chiller has been installed in a hotel located in Surabaya, East Java Province. • By supplying electricity and chilled water, this system can replace a part of electricity supplied by the grid, which reduces CO_2 emissions and utility costs. • Estimated GHG emissions reductions: 4,166 tCO_2/year.

Source: ACEJ (2024a), GEC (2024), CWC (2024)

(7) Lock-in prevention – Net zero is achieved through efficiency improvement and low-emission fuel use

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	Two paths exist for zero or near-zero emissions. • Path1: Improve the total CHP efficiency • Path2: Install co-generation systems fuelled by renewable fuels
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Improve the total CHP efficiency – Further technological development is required to increase the efficiency of CHP systems, such as new combustion methods for gas engines and improved heat resistance for gas turbines. • Path 2: Install co-generation systems fuelled by renewable fuels – Renewable fuel-powered CHP facilities can be more expensive to implement than natural gas-powered equivalents due to the additional requirements for raw gas treatment. – Further technological development is required to make renewable fuel powered CHP commercially available.

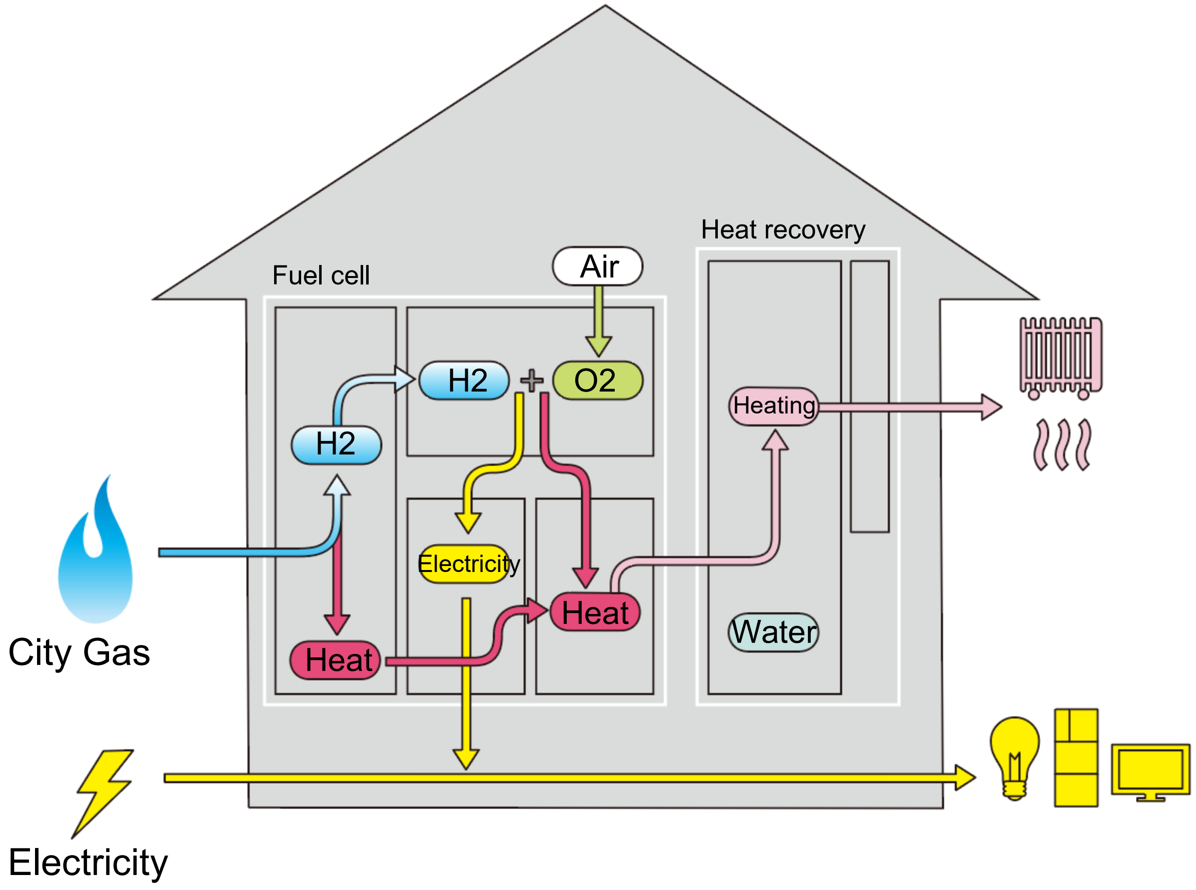
Source : ERIA (2023b), EPA Combined Heat and Power Partnership (2017), ANRE (2024b)

(8)(9) DNSH/social considerations –NO_x and exhaust gas impacts on the surrounding neighbourhood should be addressed

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• Fuel combustion co-generation systems emit NO_x during the combustion process, which could affect the surrounding environment. Denitrification equipment can be introduced to reduce NO_x emissions.
	Transition to circular economy	• Since fuel combustion co-generation systems have disposable parts such as engine oil and oil filters, appropriate recycling methods must be deployed.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Training programmes for O&M workers are necessary to ensure they are familiar with this technology and minimise operational risks.

Source: ERIA (2023b)

(1) Fuel cell co-generation – Technology schematics and overview



Source: Author created based on various literature

Fuel cell co-generation (also known as fuel cell CHP (FC CHP)) can provide highly efficient and reliable energy for residential or commercial buildings.

As its name shows, FC CHP generates heat and electricity by combining H_2 with oxygen in a clean process that produces no local air pollution. Key components of this technology include:

- Fuel cell: converts H_2 and oxygen into water and electricity. H_2 can be produced from city gas in a fuel reformer.
- Heat recovery system: captures and utilises the by-product heat from the fuel cell to provide space heating or hot water.

For the building sector, two typical types of CHP are solid-oxide fuel cell (SOFC) and polymer electrolyte fuel cell (PEFC).

Molten carbonate fuel cell (MCFC) and phosphoric acid fuel cell (PAFC) are two major types which are mainly used in the industrial sector.

Source: METI (2023b), EPA (2015)

(2) Fuel cell co-generation – Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• With an overall system efficiency of up to 95% and electrical efficiencies between 35%-55%, FC CHP can deliver significant energy savings and CO_2 emission reductions compared to traditional heating and electricity systems. • CO_2 emissions of a typical natural gas type FC CHP could be 0.37-0.59kgCO_2-eq/kWh for electric power production, while considering its thermal credit this range could reduce to 0.15-0.25kgCO_2-eq/kWh.
Affordability	• Current capital cost could exceed is around USD10,000/kW depending on the technology type. • The price would reduce relatively as the market expands and mass production is established.
Reliability	• Both SOFC and PEFC are at the early commercialisation stage with TRL 9.
Lock-in prevention considerations	• Path 1: Improve the total CHP efficiency. • Path 2: Shift from natural gas to renewable energy sources for producing H_2.
DNSH considerations	• FC CHP requires rare metals as catalysts. The increased need for such rare metals may cause over-extraction and potentially cause harm to the ecosystem.
Social considerations	• Generally, there is a positive impact on employment by creating new jobs in manufacturing, installation, and maintenance services. • Training programmes for O&M workers are necessary to ensure they are familiar with this technology and minimise operational risks. • The mining of rare metals may cause forced labour and human rights abuses. As the demand for these materials increases, ensuring ethical sourcing through supply chain transparency and alternative materials development will be essential.

Note:
1. CO_2 emissions from FC CHP depend on the original energy source and electrical efficiency.

(3) ASEAN Taxonomy – Relevant technical screening criteria

Electricity generation from renewable non-fossil gaseous and liquid fuels, including co-firing with fossil fuels

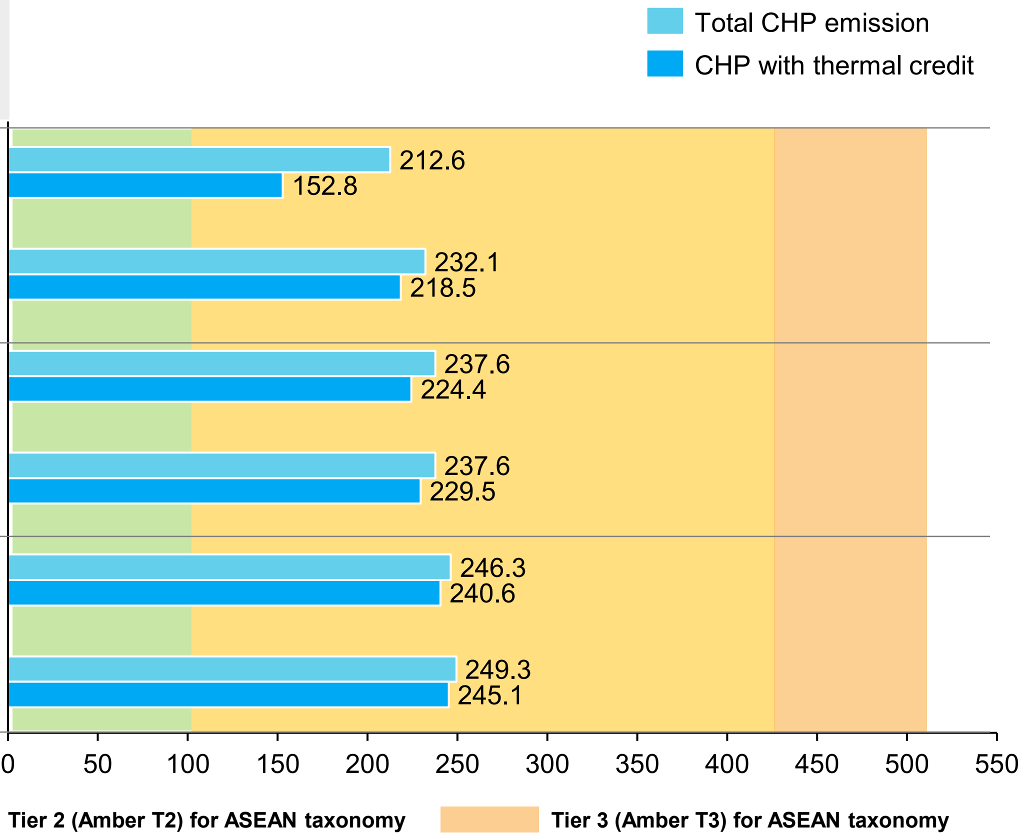
Eligibility	Climate Change Mitigation TSC	Details
Includes • Power generation as part of co-generation.	**Tier 1 (Green)**	• Lifecycle GHG emissions from the generation of electricity by the entire facility <100 gCO_2-eq/kWh.
	Tier 2 (Amber T2)	• Lifecycle GHG emissions from the generation of electricity by the entire facility: ≥100 and <425 gCO_2-eq/kWh.
Excludes • Power generation using gas derived from coal except where it can be shown that, by abatement through CCUS, respective TSC below are fulfilled. • Power generation from fuels derived from waste, other than bio-waste.	**Tier 3 (Amber T3)**	• Tier 3 (Amber T3) Lifecycle GHG emissions from the generation of electricity by the entire facility: ≥425 and <510 gCO_2-eq/kWh.

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition – FC CHP systems provide low emission heat and power production than conventional systems

CO_2 emissions for heat and electricity production, gCO_2/kWh

	Fuel cell type	Total CHP efficiency (Electric efficiency)
Residential (<5kW)	PEFC	95%(38%)
	SOFC	87%(52%)
Commercial (5-50kW)	PEFC	85%(45%)
	SOFC	85%(45%)
Industrial (>50kW)	MCFC	82%(43%)
	PAFC	81%(34%)



Tier1 to Tier3 refers to Climate Change Mitigation TSC for Electricity generation from renewable non-fossil gaseous and liquid fuels, including co-firing with fossil fuels.

Comparison with ASEAN Taxonomy

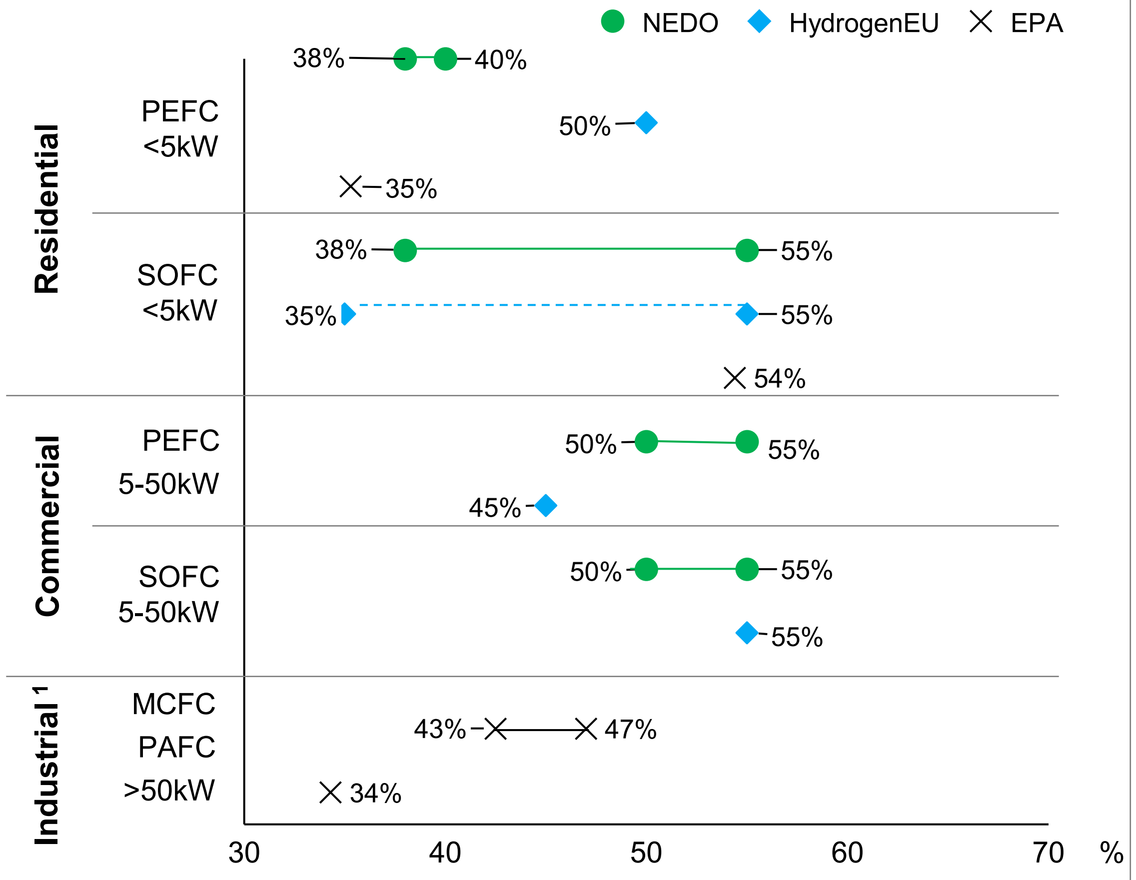
There is one TSC potentially applicable to fuel cell co-generation for the building sector.

TSC for "electricity generation from renewable non-fossil gaseous and liquid fuels, including co-firing with fossil fuels" sets a threshold on lifecycle GHG emissions per electricity and heat generated. TSC for co-generation includes heat converted to electricity at a set rate and is calculated with electricity together. Lifecycle GHG emissions would vary depending on how products are produced, transported, used and the-end-of life processes, etc. Therefore eligibility of labelling should be assessed on a project-by-project basis. The left graph shows CO_2 emissions from heat and electricity production for a reference purpose only.

Source: NEDO (2023), DOE (2016), EU-Japan Centre for Industrial Cooperation (2019), Hydrogen Europe (2020)

[Reference] Methodologies: Contribution to Energy Transition

Methodology: Electrical Efficiency



1. Industrial: FC CHP system with capacities exceeding 50kW is mainly used in the industrial sector. Since this section focuses on the building sector, industrial applications are provided for reference only.

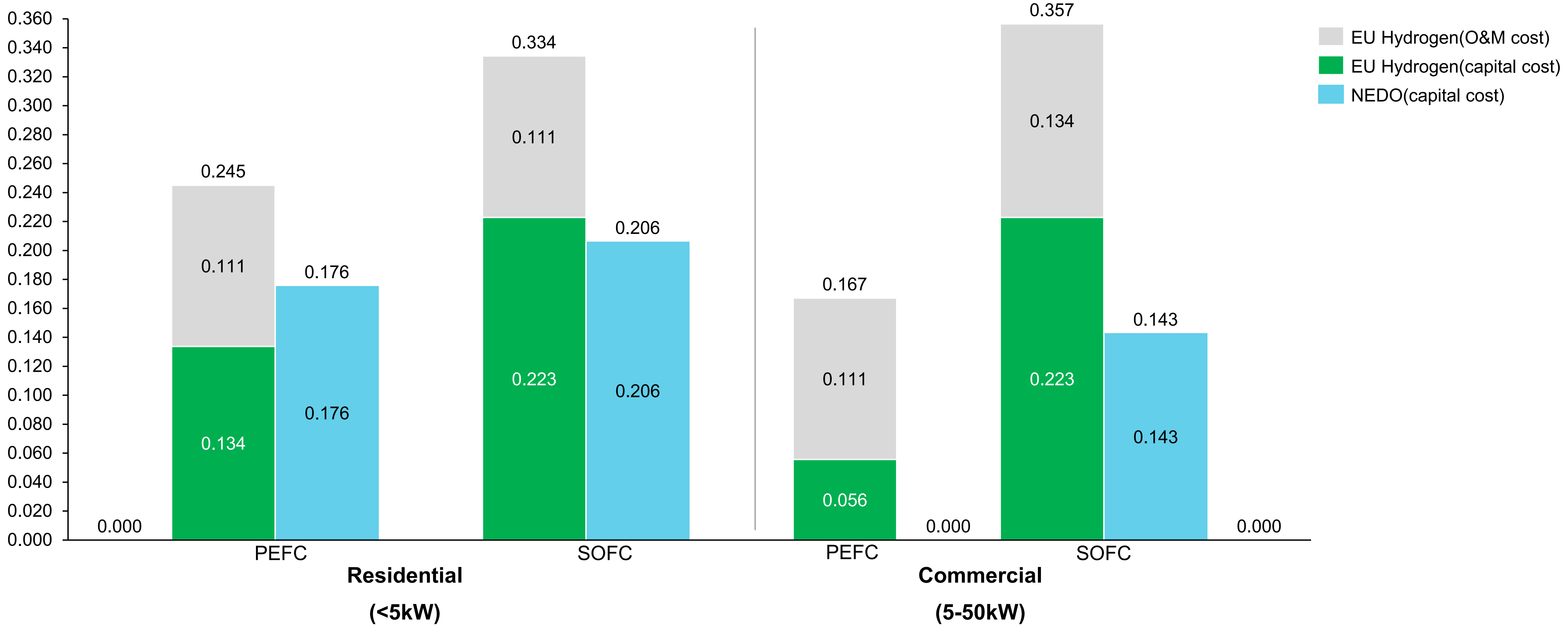
Methodology: CO_2 emissions for heat and power production

1. CO_2 emission per kWh is calculated by the total emission from the entire facility ($kgCO_2$)/(electricity generation(kWh) + heat generation(kWh)). 1 MJ of heat energy is deemed to be equivalent to 0.277778 kWh of electricity.
2. CHP with thermal credit: For CHP with a thermal credit, CO_2 emissions include avoided natural gas fuel emissions that an on-site boiler would otherwise use to produce the same heat. The boiler is assumed to operate on natural gas with an efficiency of 80%.

Source: NEDO (2023), DOE (2016), EU-Japan Centre for Industrial Cooperation (2019), Hydrogen Europe (2020)

(5) Affordability – The current cost for FC CHP remains high, but is expected to decrease as the market expands and mass production gets established

Capital Cost and O&M Cost, USD/kWh



Source: Hydrogen Europe (2020), NEDO (2023)

[Reference] Methodologies: Affordability

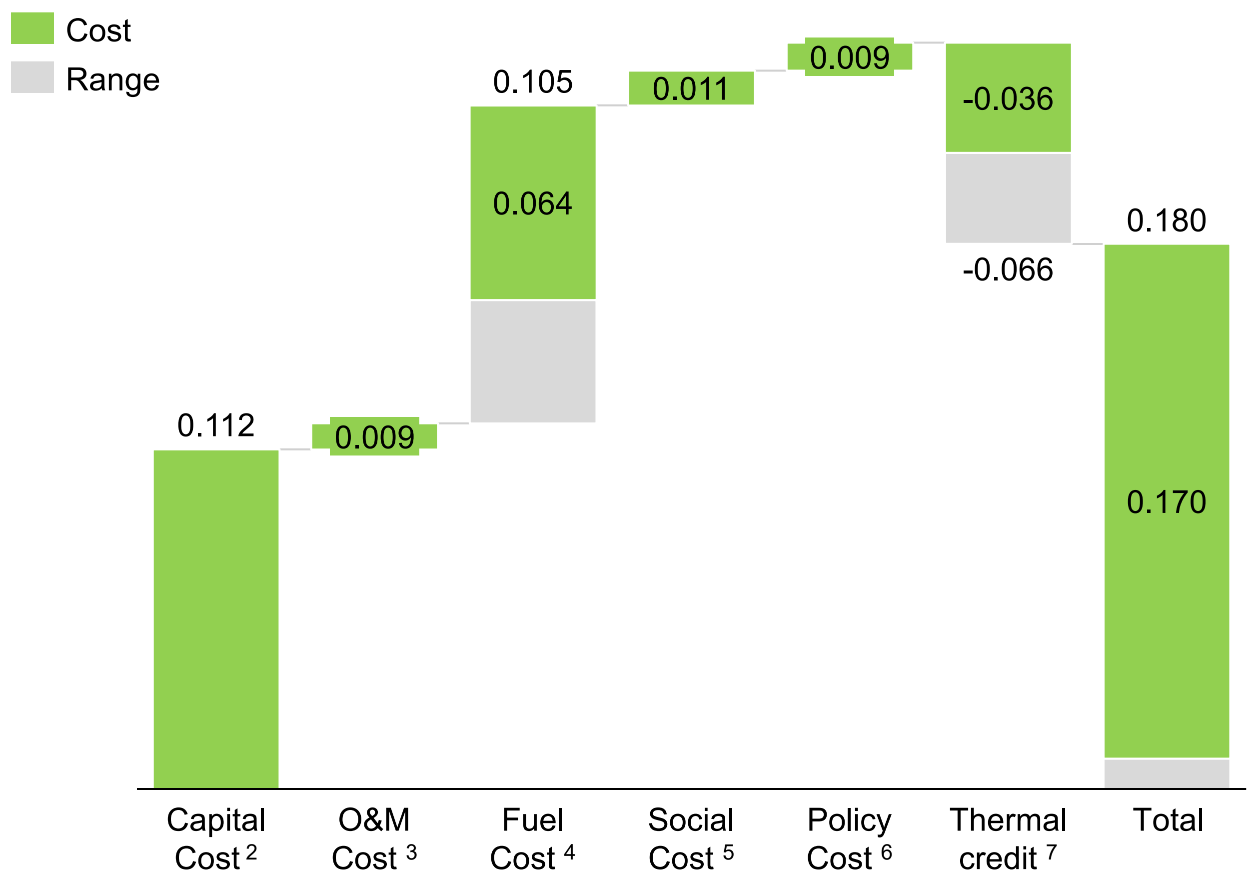
Methodology: Capital Cost and O&M Cost

1. Capital Cost is calculated based on a life span of 50,000 hours.
2. The cost has been converted from the original source using an exchange rate of USD1 = JPY140, and EURO1 = JPY156, as of 13/09/2024.

Source: Hydrogen Europe (2020), NEDO (2023)

[Reference] The Ministry of Economy, Trade and Industry (METI) of Japan calculated the cost of power generation using FC CHP as 0.17 to 0.18 USD/kWh

Cost of power generation of FC CHP in Japan, USD/kWh



- In 2021, the Ministry of Economy, Trade and Industry (METI) of Japan published a calculation result for the cost of power generation using FC CHP.
- The calculation showed a cost range of 0.17 to 0.18 USD/kWh, assuming a capacity of 0.7kW with an operation period of 12 years and 72.4% capacity utilisation.
- By effectively utilising the heat generated during power generation, cost savings among 0.036~0.066 USD/kWh can be deducted as thermal credit.

Notes:
1. The cost has been converted from the original source using an exchange rate of 1 USD = 140 JPY, as of 13/09/2024.
2. Capital cost: costs for equipment and installation
3. O&M cost: costs for operation and maintenance
4. Fuel cost: costs for fuel procurement
5. Social cost: cost for carbon emission during power generation (Same to thermal power)
6. Policy cost: government budget necessary to promote CHP activities
7. Thermal credit: subtracted cost saving for heat generation during the operation of FC CHP compared to conventional gas boilers

Source: METI (2021c)

(6) Reliability – At an early commercialisation in the EU and Japan under governmental supports; High cost and market penetration remain as a challenge

Estimated commercialisation status

- SOFC: TRL 9
- PEFC: TRL 9
- Both SOFC and a PEFC are at the early commercialisation stage. EU and Japan have leading experiences in promoting co-generation technology.
- In ASEAN the technology is not yet commercialised because of cost and infrastructure. Economic measures to compensate for the cost could promote the commercialisation of this technology.

Recent project examples

Details

500,000 Ene-Farm units had been installed and each unit could prevent 1.2t CO_2 emissions per year

- As part of Japan's energy diversification strategy, the Ene-Farm programme was launched in 2009 and provides a large-scale initiative to promote FC CHP.
- By November 2023, 500,000 Ene-Farm units had been installed across Japan and the average Japanese household could prevent 1.2t CO_2 emissions each year with the FC CHP unit.
- The government is making all-out efforts toward the installation of 3 million units by the year 2030 through economic measures such as tax incentives and defraying costs.

Reduce 49% CO_2 emission and 46% annual energy cost by introducing FC CHP systems

- The Pathway to a Competitive European Fuel Cell micro-cogeneration market (PACE) project in Europe, has installed more than 2,600 FC CHP systems with the cooperation of major European manufacturers and research partners.
- The relative performance shows that a house with an FC CHP unit would reduce 49% CO_2 emissions and 46% annual energy cost. Further emission reductions can be achieved by combining a fuel cell unit with a heat pump.

Notes:
1. Ene-Farm is a co-generation system that produces electricity through a chemical reaction between oxygen in the atmosphere and H_2 extracted from city gas.
2. European manufacturers such as BDR Thermea, Bosch, SolydEra, Sunfire and Viessmann. research partners including COGEN Europe (European Association for the Promotion of Cogeneration), BDR Thermea Group, Bosch, SolydEra (previously known as SOLIDpower), Sunfire, Viessmann and etc.
3. Compared to a house with a gas boiler that uses electricity from the grid.

Source: JLPGA (n.d.), Ene-farm Partners (2024), PACE (2019), PACE (2023), EC (2024)

(7) Lock-in prevention – Achieving zero emissions requires improvement in CHP; Energy transition from natural gas to renewable energy sources is essential

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Two paths exist for FC CHP in the building sector to be zero or near-zero emissions – Path 1: Improve the total CHP efficiency – Path 2: Shift from natural gas to renewable energy sources for producing H_2.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Improve the total CHP efficiency – Further increase in the efficiency would require technological development. • Path 2: Shift from natural gas to renewable energy sources – Technically, it is possible to directly use green H_2 for FC CHP. The difficulty to use renewable energy sources would be the availability of renewable energy sources such as green H_2 or renewable natural gas (RNG).

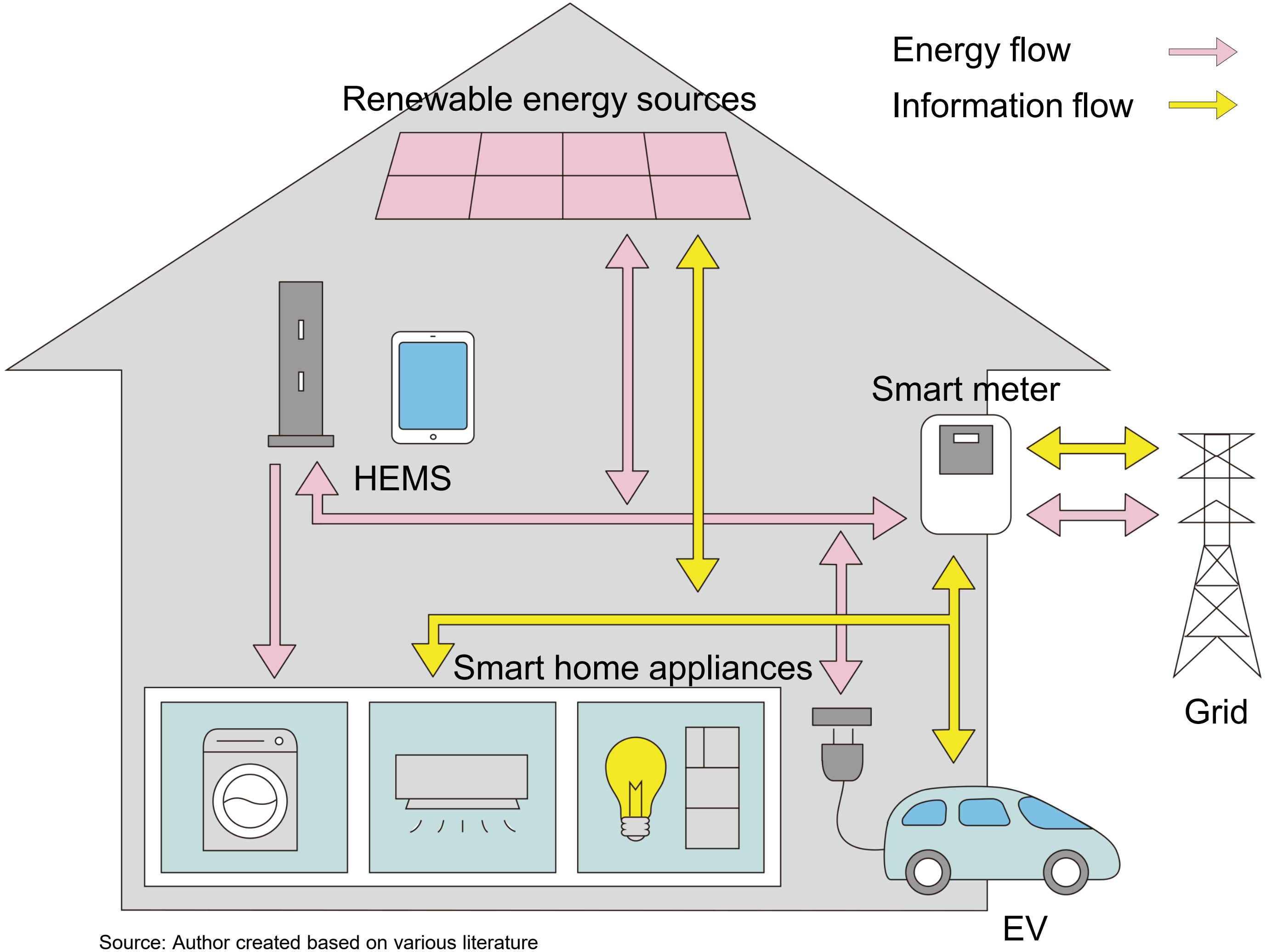
Source: EPA (2022) and expert interview.

(8)(9) DNSH/social considerations – Proper recycling process is required to safely recycle rare materials and PFAS

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• FC CHP requires rare metals as catalysts. The increased need for such rare metals may cause over-extraction and potentially cause harm to the ecosystem. However technological development has allowed to decrease the amount of platinum used in PEFCs . • For PEFCs, leakage of per- and polyfluoroalkyl substances (PFAS) during manufacturing, usage, and decommission is a concern.
	Transition to circular economy	• Proper recycling process is required for recycling of rare metals.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Generally positive impact on employment by creating new jobs in manufacturing, installation, and maintenance. • The mining of rare metals may cause forced labour and human rights abuses. As the demand for these materials increases, ensuring ethical sourcing through supply chain transparency and alternative materials development will be essential.

Source: ene.field (2017) and expert interview.

(1) Home energy management system (HEMS) – Technology schematics and overview



Source: Author created based on various literature

HEMS is a system that efficiently manages and controls energy consumption at home.

It monitors the use of electricity, gas, and water, providing real-time data to residents via smartphones or tablets, helping reduce waste and promote efficient energy use.

HEMS can integrate with smart devices, electric vehicles (EVs), demand response (DR) systems powered by smart meters, and renewable energy sources such as solar power to enable sustainable energy consumption.

Source: IEA, under 4E Programme, with contributions from EDNA (2018)

(2) Home energy management system (HEMS) – Transition suitability assessment overview

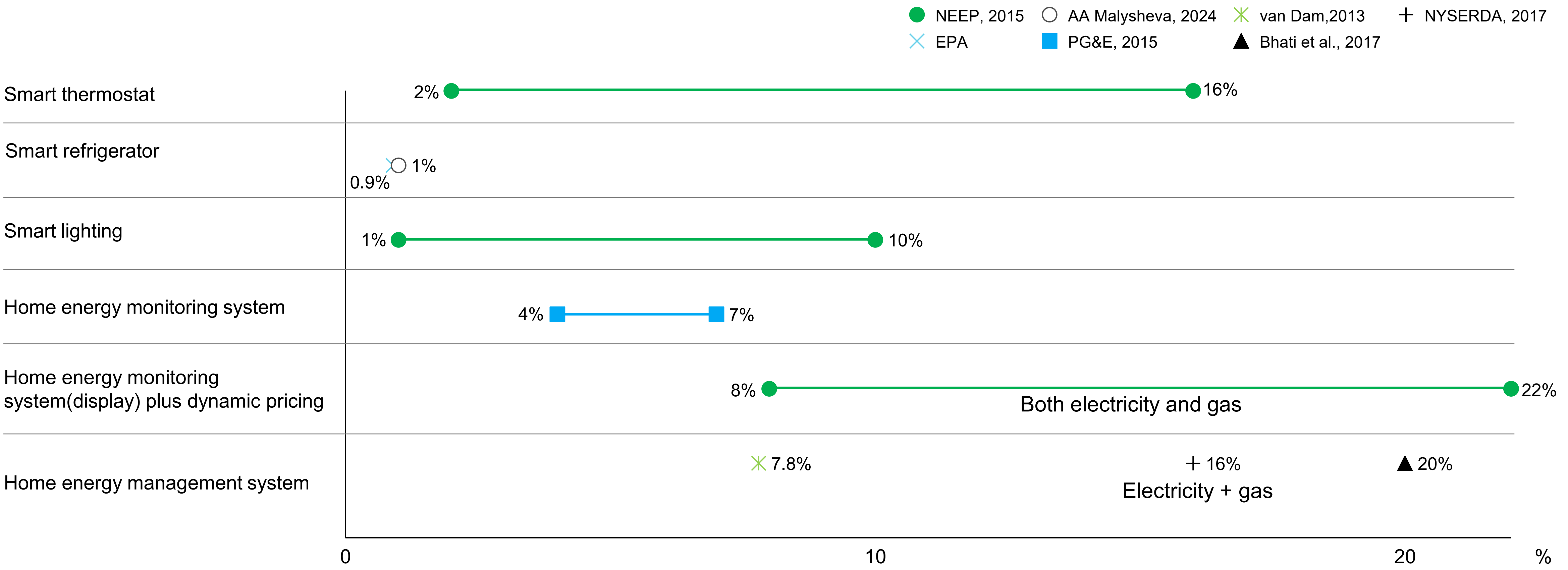
Framework dimensions	Description
Contribution to energy transition	• For the annual energy consumption of single-family homes, the introduction of HEMS can achieve up to a 20% reduction in energy use, while the introduction of smart lighting can save up to an additional 10%. The energy-saving effects of smart appliances include up to 16% for smart thermostats and approximately 10% for smart refrigerators.
Affordability	• Considering the HEMS installation cost and its lifespan, the CO_2 reduction cost is estimated to be between USD108-1,342/t-CO_2.
Reliability	• The technological maturity of HEMS is progressing rapidly, with increasing integration of smart devices and open-source platforms, though widespread adoption still faces challenges in interoperability and cost. TRL 9.
Lock-in prevention considerations	• HEMS provides pathways to transition to low or zero carbon emission systems by integrating with renewable energy sources such as solar and wind, DR management, smart grids, and energy storage systems such as batteries.
DNSH considerations	• By properly recycling HEMS equipment and replacing appliances, resource reuse and the promotion of a circular economy can be achieved.
Social considerations	• The cost of the system, uncertainty about energy savings, and concerns over security and trust are key barriers to adoption. • Lack of standards and communication protocols, as well as difficulties in setup and technical support, hinder widespread use.

(3) ASEAN Taxonomy – There is no relevant technical screening criteria

Eligibility	Climate Change Mitigation TSC
Includes	**Tier 1 (Green)**
	Tier 2 (Amber T2)
Excludes	**Tier 3 (Amber T3)**

(4) Contribution to Energy Transition– HEMS can save annual energy consumption up to 20%

Emissions impact by HEMS and smart appliances, %/unit



Notes:
1. NEEP: Northeast Energy Efficiency Partnerships
2. NYSERDA: New York State Energy Research and Development Authority
3. EPA: The U.S. Environmental Protection Agency
4. PG&E: Pacific Gas and Electric Company.

Source: IEA, under 4E Programme, with contributions from EDNA (2018), NEEP (2015) , EPA (n.d.), Malysheva, A.A., B. Rawat, N. Singh, P.C. Jena, and Kapil (2024)

[Reference] Methodologies: Contribution to Energy Transition

Methodology: Emissions impact by HEMS and smart appliances

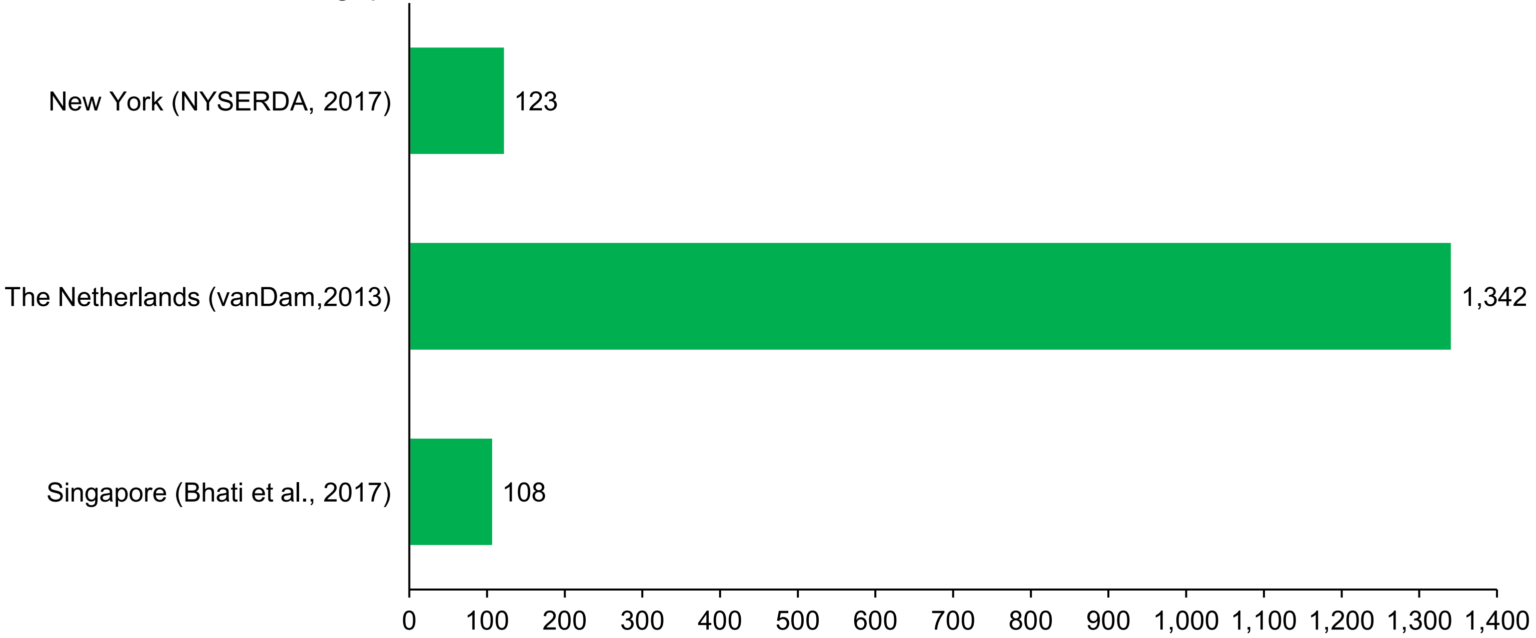
1. Aside from the energy-saving effect of smart refrigerators, all other information comes from the Energy Efficient End-Use Equipment (4E) report by IEA.
2. Smart thermostat: Heating and cooling can be switched on and off remotely and the temperature adjusted up and down.
3. Smart refrigerator: The smart refrigerator is a refrigerator equipped with functions that use internet connectivity and sensor technology to efficiently manage cooling and energy consumption. The energy reduction rate for the entire home from smart refrigerators is calculated by multiplying the energy efficiency improvement of the refrigerator (9-10%), by its share of household electricity consumption (10%).
4. Smart lighting: Smart lighting that can be controlled remotely, automated, reacts to occupancy.
5. Home energy monitoring system: Provides insights into home energy use and encourages reduction.
6. Home energy monitoring system(display) plus dynamic pricing: Offers incentives for reduction through DR linked to electricity tariffs.
7. Home energy management system: HEMS comprises smart connected devices that can provide information on, and dynamically adjust, energy use within a home.
8. Energy savings range for overall home energy use as stated in the source.

Source: IEA, under 4E Programme, with contributions from EDNA (2018), NEEP (2015) , EPA (n.d.), Malysheva, A.A., B. Rawat, N. Singh, P.C. Jena, and Kapil (2024)

(5) Affordability – Considering the HEMS installation cost and its lifespan, the abatement cost is estimated at USD108-1,342/tCO_2

Abatement costs per CO_2 reduction, USD/tCO_2-eq

Abatement cost by HEMS varies significantly over varies depending on regional climate, environment, and differences in the concept and average floor area of detached houses etc. Therefore, this page provides case studies of New York, the Netherlands and Singapore using the same cost of HEMS shown in the table the right side. Floor areas of a "detached house" are different in those countries: approximately 200m^2 in NY and Singapore, and 100m^2 in the Netherlands.



Example of cost breakdown for HEMS for average home

Type	Quantity	Unit cost(USD)
Hub	1	99.99
Smart Lights	10	14.99
Smart Switches[5]	3	54.99
Smart Outlets[6]	5	53.50
Whole Home Power Meter	1	53.23
Occupancy Sensors	5	39.99
Geo-fencing Sensors	4	29.00
Smart Thermostat	1	199.00
	Total count	Total sensor cost
Sensors Total (per Home)	30	1,250.54
Labour Total (per Home)	1	600
Total Installed Cost (per Home)		1,850.54

Source: IEA, under 4E Programme, with contributions from EDNA (2018), NYSERDA (2017), van Dam, S.(2013), Bhati, A., M. Hansen, and C.M. Chan (2017), MSE (2021), Statista (2024), EMA (2024a), UNFCCC (2022)

[Reference] Methodologies: Affordability

Methodology: Abatement costs per CO_2 reduction

1. HEMS installation cost (USD/unit) : In calculating the CO_2 reduction costs for the Netherlands and Singapore, the data on installation costs and the lifespan of HEMS from NYSERDA were used.
2. Average electricity use in landed residential households(kWh/year) : For the Netherlands, the data is based on the baseline consumption used in the experiment, while for Singapore, it represents the 2020 average electricity use in landed residential households.
3. CO_2 emission factor(kgCO_2/kWh) : 2021 CO_2 Emission Factors in the Netherlands and Singapore.

Items	New York	Netherlands	Singapore
①HEMS installation cost (USD/unit)	1,850	1,850	1,850
②Estimated useful life of HEMS (year)	15	15	15
③Average electricity use in landed residential households(kWh/year)	—	3,615	15,084
④Energy savings potential (%)	16	7.8	20
⑤CO_2 emission factor(kgCO_2/kWh)	—	0.33	0.38
⑥Annual energy saving(kWh/year): ③×④÷100	—	282	3,017
⑦Annual CO_2 reduction(t-CO_2/year): ⑥×(⑤÷1,000)	1	0.09	1.14
Abatement costs per CO_2 reduction(USD/tCO_2-eq) : (①÷②)÷⑦	123	1,342	108

Example of cost breakdown for HEMS for average home

1. Example of cost breakdown for HEMS for average home: The total cost breakdown for HEMS for an average home was calculated from NYSERDA's unit cost and quantity.
2. Smart switches: Devices that plug into standard outlets to allow remote control of connected appliances via smartphone or voice assistant, enabling scheduled on/off times and improving energy efficiency.
3. Smart outlets: Wall switches that replace traditional switches, allowing remote control of lights via smartphone or voice assistant, with options for scheduling and dimming.

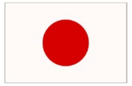
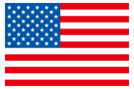
Source: IEA, under 4E Programme, with contributions from EDNA (2018), NYSERDA (2017), van Dam, S.(2013), Bhati, A., M. Hansen, and C.M. Chan (2017), MSE (2021), Statista (2024), EMA (2024a), UNFCCC (2022)

(6) Reliability – Japan and the U.S. are implementing projects utilising HEMS to improve household and regional energy efficiency

Estimated commercialisation status

- TRL 9: HEMS is already being sold and utilised as a product

Recent project examples

	Details
Niseko Mirai in Hokkaido 	• This demonstration project started in July 2024 and will evaluate the effectiveness of HEMS in multi-dwelling units. It aims to optimise energy management through collaboration with local governments and energy companies. • The annual electricity expenditure per unit is expected to be around 50% of a typical electric house in Hokkaido.
Open HEMS 	• In 2019, the U.S. Department of Energy (DOE)'s Oak Ridge Lab collaborated with partners to create an open-source HEMS platform connecting home devices for efficient energy use. • In 2021, ASEAN Centre for Energy (ACE) IoT[1] developed a mobile app for Tennessee Valley Authority's pilot to enhance Open HEMS technology, improving residential energy management.

Note:
1. IoT (Internet of Things): A system where devices are connected to the internet to collect, share, and manage data for improved efficiency and automation.

Source: Hokkaido Electric Power Company (2024), TVA (n.d.)

(7)(8)(9) Lock-in prevention/DNSH/social considerations – HEMS integration with renewable energy, DR, and smart grids is key to achieving zero emission

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for a technology to be zero or near-zero emissions?**	• HEMS provides pathways to transition to low or zero carbon emission systems by integrating with renewable energy sources such as solar and wind, DR management, smart grids, and energy storage systems like batteries.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions?	• Dependence on fossil fuel infrastructure, lack of policy support, and high initial investment costs can hinder the transition to low or zero emissions. • Additionally, technical challenges with smart grids and energy storage, along with low awareness of renewable energy and HEMS benefits, may slow the transition.
DNSH considerations	**Protection of healthy ecosystem and diversity**	• No direct negative impact on ecosystem and biodiversity is expected.
	Promotion of transition to circular economy	• By ensuring that HEMS equipment and replaced appliances are properly recycled after use and that waste is not released into the natural environment, resource reuse and the promotion of a circular economy can be achieved.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• The cost of the system and services, uncertainty about the effectiveness of energy consumption reduction, cyber security concerns, data privacy concerns and lack of incentives are the factors that hinder adoption. • Lack of standards and communication protocols that enable devices from different manufacturers to interact, might require external assistance to set up the systems, use of technologies from different manufacturers may lead to problems getting technical support.

Source : REI (2023), IEA, under 4E Programme, with contributions from EDNA (2018)

[Reference] Potential use of HEMS in ASEAN

Potential of HEMS in ASEAN

HEMS technology has primarily been piloted and implemented in higher latitude regions, such as Europe, North America, and Japan, where household electricity is predominantly used for heating. Consequently, studies on HEMS effectiveness in reducing electricity consumption for cooling are limited. Findings from these regions suggest that HEMS contributes more significantly to reducing heating-related electricity consumption, given the higher demand for heating in these areas. In ASEAN, where cooling constitutes the largest portion of household electricity usage, it is anticipated that HEMS could achieve a comparable reduction rate for cooling-demand to that observed for heating in higher latitude regions.

Role of HEMS for grid stabilisation

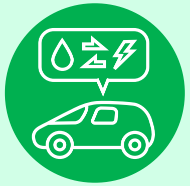
In regions where electricity prices are relatively low, homeowners have limited incentives to reduce their consumption, leading to minimal motivation for adopting HEMS. However, HEMS can play a vital role in stabilising the grid, especially with the increasing integration of variable renewable energy sources (VRE), which can challenge grid stability. Modern HEMS technology is evolving to include advanced two-way communication between consumers and providers, allowing users to dynamically adjust their energy consumption in response to real-time price signals. This capability not only enables consumers to reduce costs but also assists providers in alleviating grid stress during peak demand periods. In 2023, IEA published a report entitled “Efficient Grid-Interactive Buildings, Future of buildings in ASEAN”, which examines suitability of such system for each ASEAN members state.

Potential policy instrument

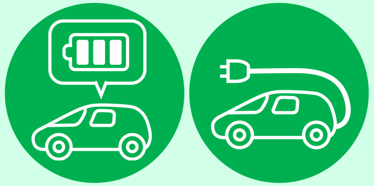
One potential policy instrument to accelerate HEMS adoption is the distribution of smart meters. In Thailand, smart meters are becoming more common as the country modernises its energy infrastructure aiming to reduce energy waste. In the UK approximately 85% of households will have a smart meter by 2024 as the government mandated energy suppliers to offer smart meters to all households and small businesses[1].

Source : Expert interview, Spencer Jones, J. (2021) Smart energy international, IEA (2023c)

Six potential transition technologies for the transport sub-sector



Hydrogen Fuel Cell Vehicles (HFCV)

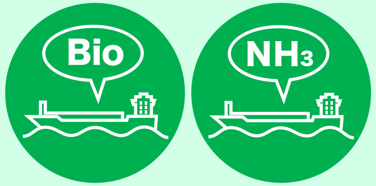


Battery Electric Vehicles (BEV), Plug-in Hybrid Vehicles (PHEV)

Hybrid Vehicles (HEV)

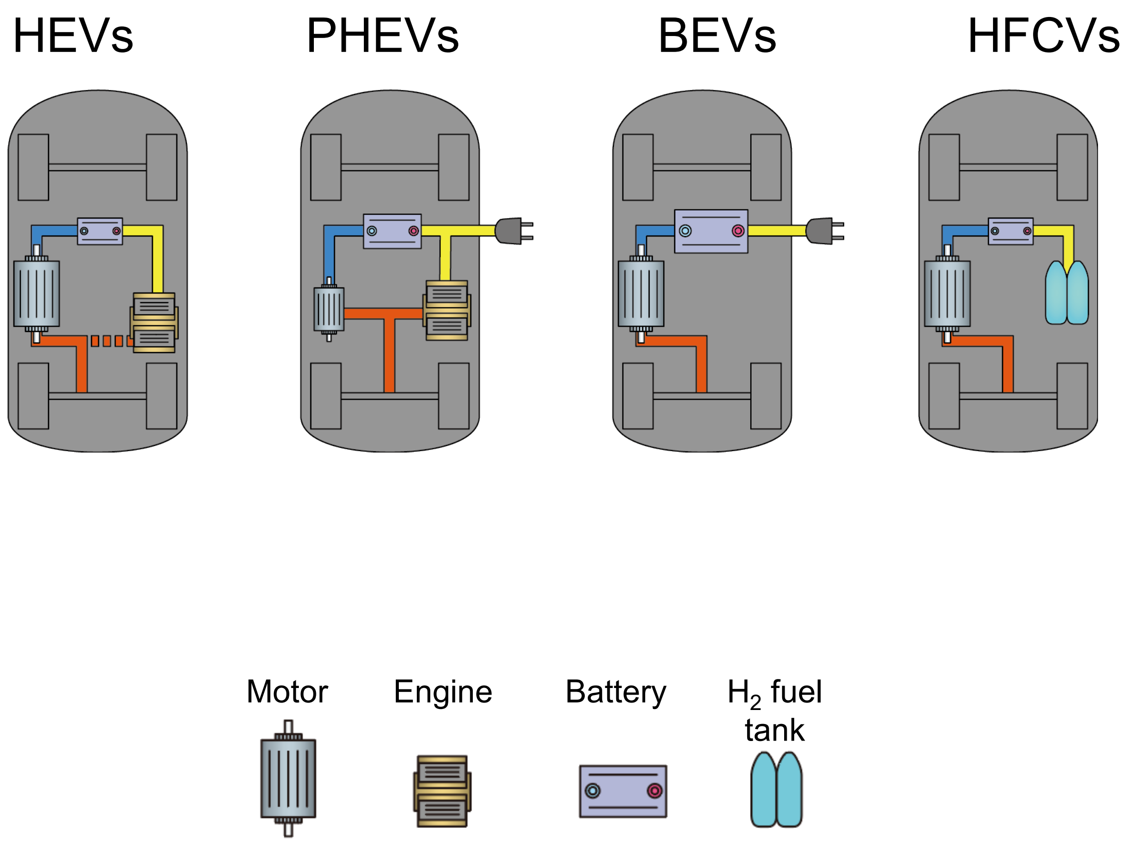
Flex Fuel Vehicles (FFV)

LNG-fuelled Ship



Biofuel-fuelled Ship (Methanol & Ethanol)
Ammonia-fuelled Ship

[Reference] Overview of different approaches to vehicle electrification



Source: Author created based on various literature

There are various approaches to vehicle electrification.

Although all vehicles using electricity as a power source fall under the "electric vehicle" category, this includes more than just battery electric vehicles (BEVs). It also comprises hybrid electric vehicles (HEVs), which combine gasoline and electric power; plug-in hybrid electric vehicles (PHEVs), which can operate on electricity for shorter trips and switch to gasoline for extended range; and hydrogen fuel cell electric vehicles (HFCVs), which generate electricity using H_2.

Each type offers distinct benefits and trade-offs in fuel efficiency, emissions reduction, and driving range, enabling consumers to choose the option that best aligns with their driving requirements and environmental priorities.

Source: ANRE (2022)

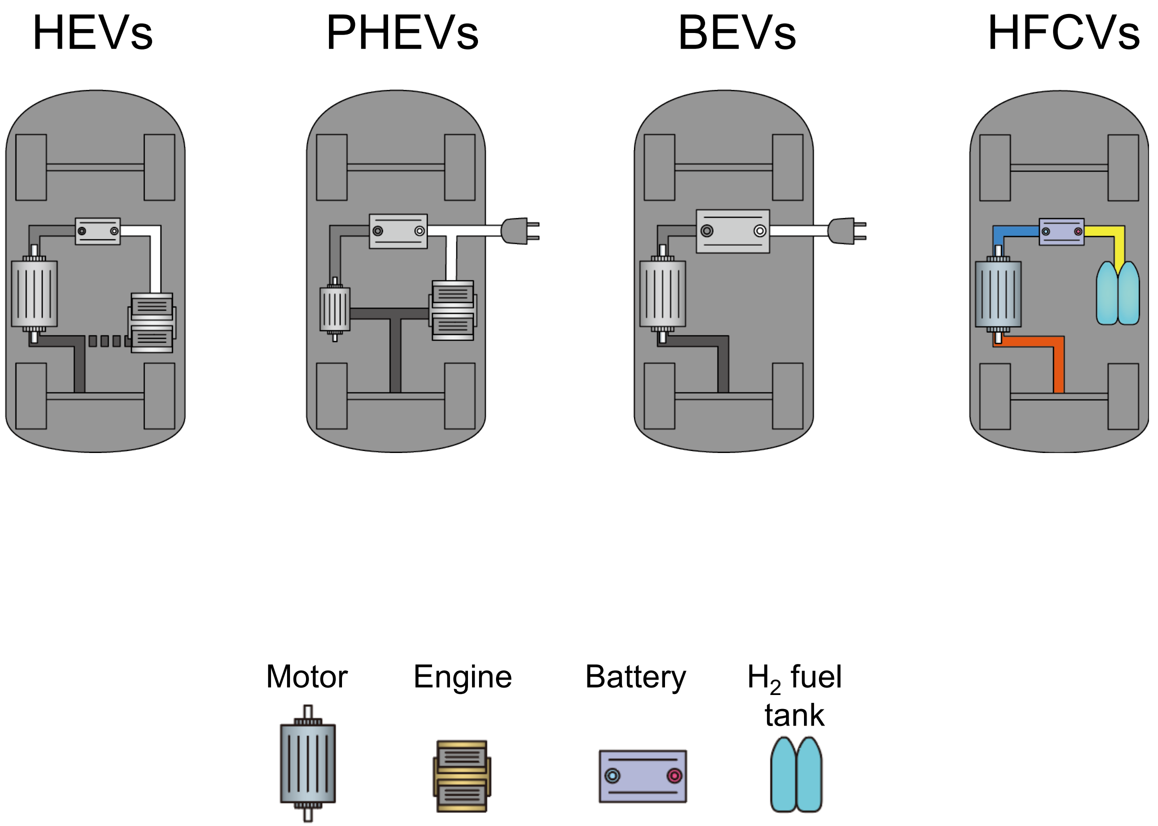
[Perspective] The road transport technologies during the transition towards carbon neutrality

Realistic approach towards carbon neutrality

To achieve carbon neutrality in the mobility sector, a comprehensive approach that integrates various options, including a lifecycle perspective, is essential. This requires offering a full line-up of electrified and alternative fuel vehicles suited to practical use, such as flex-fuel vehicles (FFVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs).Rather than waiting for all technologies to be fully developed, promoting multiple decarbonisation technologies in parallel allows for immediate impact while leveraging economies of scale. The application of electrification technologies is influenced by each country's energy mix and progress in energy transition plans. To achieve a realistic and sustainable pathway to carbon neutrality, it is crucial to introduce electrified and alternative fuel vehicles in a manner that aligns with each country's specific circumstances and needs.

Source: EPA (2024)

(1) HFCVs – Technology schematics and overview



Source: Author created based on various literature

HFCV technology uses H_2 as a fuel to generate electricity through a chemical process in a fuel cell. The fuel cell combines H_2 from the vehicle's tank with oxygen from the air to produce electricity, which powers an electric motor that drives the vehicle. They emit only water vapour and offer fast refueling and long range.

HFCVs are similar to BEVs in that they both use electric motors, but unlike BEVs that store energy in batteries, HFCVs generate electricity on-demand in the fuel cell.

Source: ANRE (2022), JADA (2024)

(2) HFCVs – Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• HFCVs offer significant emission reductions but depend on clean H_2 production for environmental benefits.
Affordability	• HFCV prices remain high due to limited production, needs to establish H_2 refuelling infrastructure. However, as production scales up and the supply chain matures, prices are expected to decrease.
Reliability	• HFCV sales remain low primarily due to factors such as the high cost of ownership and the limited availability of H_2 refuelling infrastructure. TRL 9.
Lock-in prevention considerations	• Path 1: Use of green H_2 which has essentially zero full fuel-cycle GHG emissions • Path 2: Capture substantial amounts of CO_2 from H_2 production processes via CCUS
DNSH considerations	• Green H_2 production requires significant water and renewable energy, posing risks of water shortages and environmental harm if unsustainably sourced. For example, in water-scarce regions, this can exacerbate water stress, potentially impacting local ecosystems and communities reliant on these water resources. In addition, if renewables are not sufficient, the demand for energy could lead to indirect reliance on non-renewable sources, resulting in associated emissions and undermining the “green” aspect of H_2. • H_2 production from non-renewable energy sources typically involves processes like steam methane reforming (SMR), coal gasification, or the electrolysis of water using electricity from fossil fuels. These methods rely on resources that are extracted through mining and drilling, leading to various environmental impacts, including biodiversity loss.
Social considerations	• Adopting circular economy principles for HFCVs and their components is essential to minimise waste and environmental impact. • Reskilling workers in traditional automotive sectors is necessary to address job losses from the transition to HFCVs.

(3) ASEAN Taxonomy – Relevant technical screening criteria

Urban and suburban transport, road passenger transport

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	1. The activity complies with one or all of the following criteria: a. The activity provides urban or suburban passenger transport, and its direct (tailpipe) CO_2 emissions are zero; AND b. Until 31 December 2030, the Activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD and comply with the latest EURO VI Standard.
Excludes	**Tier 2 (Amber T2)**	1. The activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD; AND 2. Until 31 December 2030, comply with the latest EURO V Standard.
	Tier 3 (Amber T3)	1. The activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD; AND 2. Until 31 December 2030, comply with the latest EURO IV Standard.

Note:
M2: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass ("technically permissible maximum laden mass") not exceeding 5 tons, M3: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tons
CA: Single-deck vehicle; CB: Double-deck vehicle; CC: Single-deck articulated vehicle; CD: Double-deck articulated vehicle
As defined by European Emissions Standards. Note that these standards do not define GHG limits per se. However, these are intended to set minimum standards for M2 and M3 vehicles (i.e., buses), which are deemed to be low emission in terms of gCO^2e/pkm.

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Transport by motorbikes, passenger cars and light commercial vehicles

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	1. The activity compiles with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2025, direct emissions of CO_2 are < 50 gCO_2-eq/v-km ii. From 1 January 2026, direct emissions of CO_2 are 0gCO_2-eq/v-km; b. For vehicles of category L, tailpipe CO_2 emissions are 0gCO_2-eq/v-km
Excludes -	**Tier 2 (Amber T2)**	1. The activity compiles with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2030, direct emissions of CO_2 are < 50 gCO_2-eq/v-km
	Tier 3 (Amber T3)	1. The activity complies with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2030, direct emissions of CO_2 are < 100 gCO_2-eq/v-km

Note:
- M1: Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat, and having a maximum mass ("technically permissible maximum laden mass") not exceeding 3.5 tons; N1: Vehicles for the carriage
- of goods and having a maximum mass not exceeding 3.5 tonnes
- vkm: Vehicle-kilometre
- L: Mopeds, Motorcycles, Motor Tricycles and Quadricycles

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Freight transport services by road

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	1. The activity complies with one of the following criteria: a. vehicles of category N1 have zero direct (tailpipe) CO_2 emissions; b. vehicles of category N2 and N3[1] with a technically permissible maximum laden mass not exceeding 7.5 tonnes are 'zero-emission heavy-duty vehicles'; c. vehicles of category N2 and N3 with a technically permissible maximum laden mass exceeding 7.5 tonnes are one of the following: i. Zero-emission heavy-duty vehicle; OR ii. where technologically and economically not feasible to comply with the criterion in point (i), until 31 December 2030 have direct (tailpipe) CO_2 emissions less than 21 gCO_2/t-km[2]; AND 2. Vehicles are not dedicated to the transport of fossil fuels.
Excludes -	**Tier 2 (Amber T2)**	1. The activity complies with one of the following criteria: a. vehicles of category N2 and N3 with a technically permissible maximum laden mass exceeding 7.5 tonnes are one of the following: i. where technologically and economically not feasible to achieve zero emissions, until 31 December 2030, have direct (tailpipe) CO_2 emissions less than 42 gCO_2-eq/t-km, and 1 January 2031 onwards, less than 21 gCO_2-eq/t-km; AND 2. Vehicles are not dedicated to the transport of fossil fuels.
	Tier 3 (Amber T3)	• No TSC available.

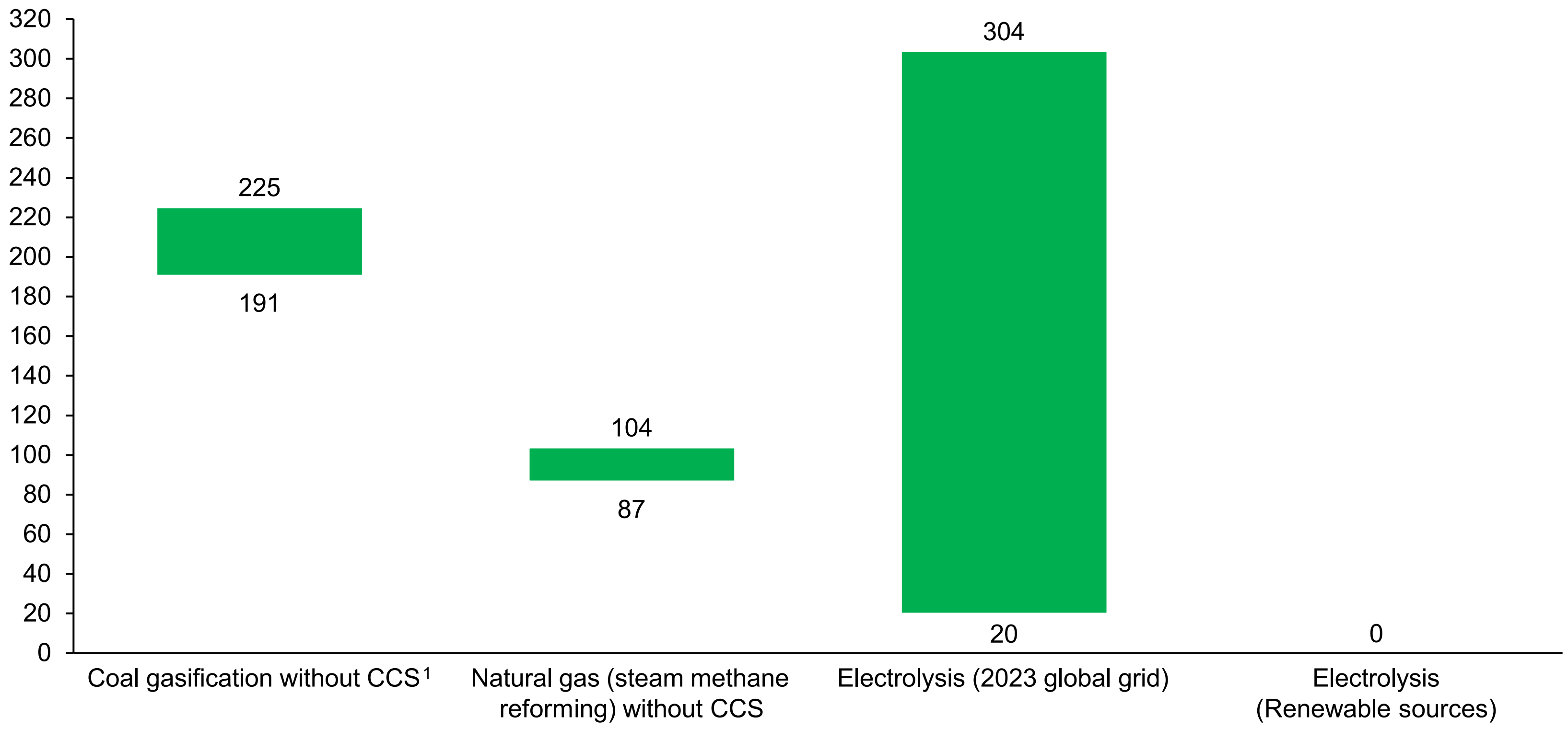
Notes:

1. N1: Vehicles for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes; N2: Vehicles for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes; N3: Vehicles for the carriage of goods and having a maximum mass exceeding 12 tonnes
2. Based on the current difference between emissions projections for freight activity by the CBI (18gCO_2-eq/t-km by 2050) and IEA NZE (18gCO_2-eq/t-km by 2040), it is proposed to have a forward outlook with a horizon date of 2030; indicative of reviewing the TSC at the period and potentially amending the threshold based on new emissions data in the future.

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition – HFCVs themself do not emit CO_2, but H_2 used as a fuel may cause emissions depending on production routes

Emissions intensity (lifecycle), g CO_2-eq/km



Note:
1. Carbon capture and storage

Comparison with ASEAN Taxonomy

There are three TSCs which are potentially applicable to HFCVs.

All of them set threshold on direct (tailpipe) emissions, and NOT lifecycle emissions. Therefore, all the HFCVs will be labelled as "Green" by the ASEAN Taxonomy.

The left graph shows lifecycle GHG emissions of H_2 of different production pathways for a reference purpose only.

Source: IEA (2024e), H2 MOBILITY Deutschland (n.d.), NEDO (2014), DOE (n.d. e)

[Reference] Methodologies: Contribution to Energy Transition

Methodology: Emissions intensities

1. The figures were calculated by multiplying emission intensities of different hydrogen production routes (g CO_2-eq/g H_2) with the average amount of fuel consumption of HFCVs (g H_2/km). The average amount of fuel consumption, which is 8.7 g H_2/km, is calculated by averaging multiple data of different types of HFCVs.
2. The range of emission intensities was basically impacted by several regional factors, including available technologies and upstream and midstream emissions. The wide range of emissions from electrolysis (2023 global grid) is due primarily to the grid electricity intensity across countries.
3. The emissions occurring during the production of renewable electricity facilities (so-called embedded emissions) are not included in the emissions of 'Electrolysis (Renewable sources).'

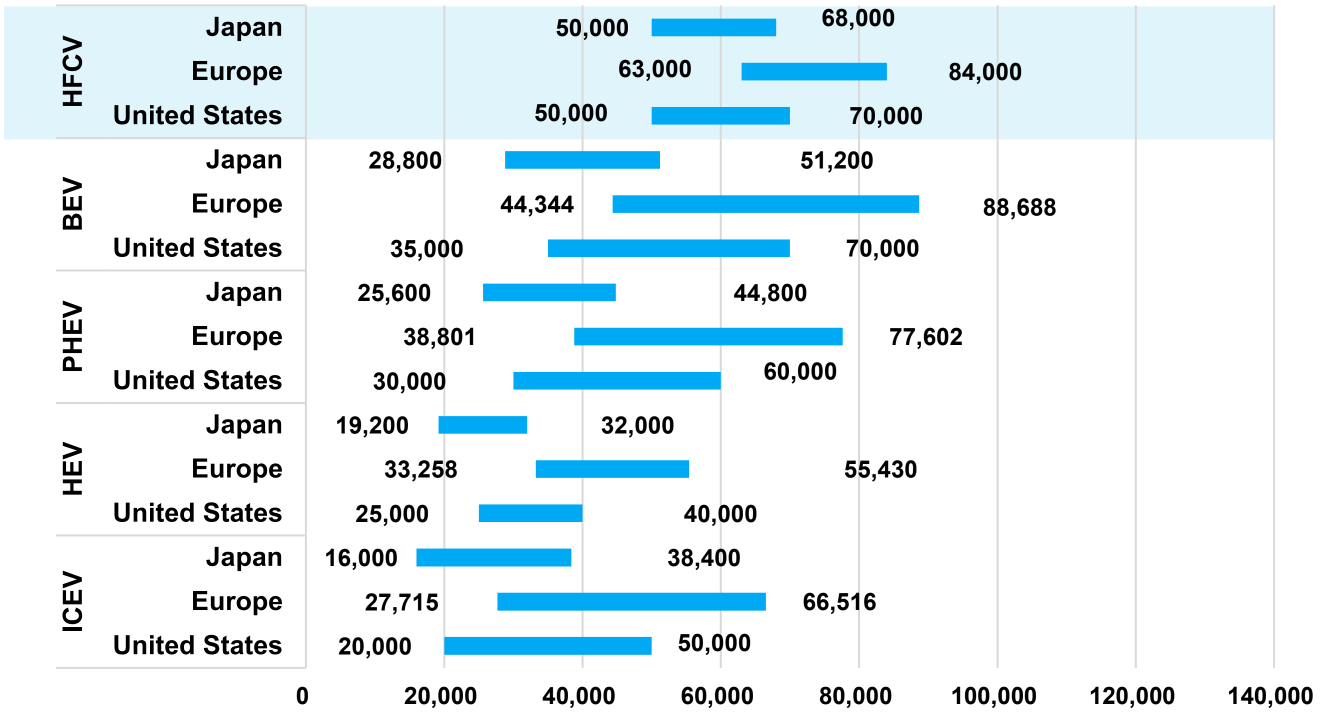
Note

- HFCVs basically do not cause emissions during its operation. Yet, emissions occur during the production process of hydrogen that HFCVs rely on as fuels. Thus, the emission levels depend on how hydrogen is produced.
- The graph on the left shows the range of emissions of HFCVs by different ways of hydrogen production as below.
  - Coal gasification without CCS
  - Natural gas (SMR) without CCS. SMR is used here since most commonly-used and mature way for hydrogen production today is via SMR.
  - Electrolysis using grid electricity.
  - Electrolysis using renewable sources, specifically onshore wind and solar power
- When hydrogen is produced from fossil fuels, such as coal and natural gas, the associated emissions tend to be much higher compared to those produced via electrolysis using renewable energies. It should be noted that when using grid electricity in the electrolysis process for hydrogen production, emission intensities might become even higher than when using fossil fuels, depending on regions.
- Since HFCVs do not produce emissions directly during the operation, they are categorised into Tier 1 (Green) in Climate Change Mitigation TSC.

(5) Affordability – HFCV prices remain high due to limited production, infrastructure needs, and technology maturity, but are expected to lower over time

Vehicle cost, USD/vehicle

Price range for HFCVs in comparison with BEVs, PHEVs, HEVs, ICEVs

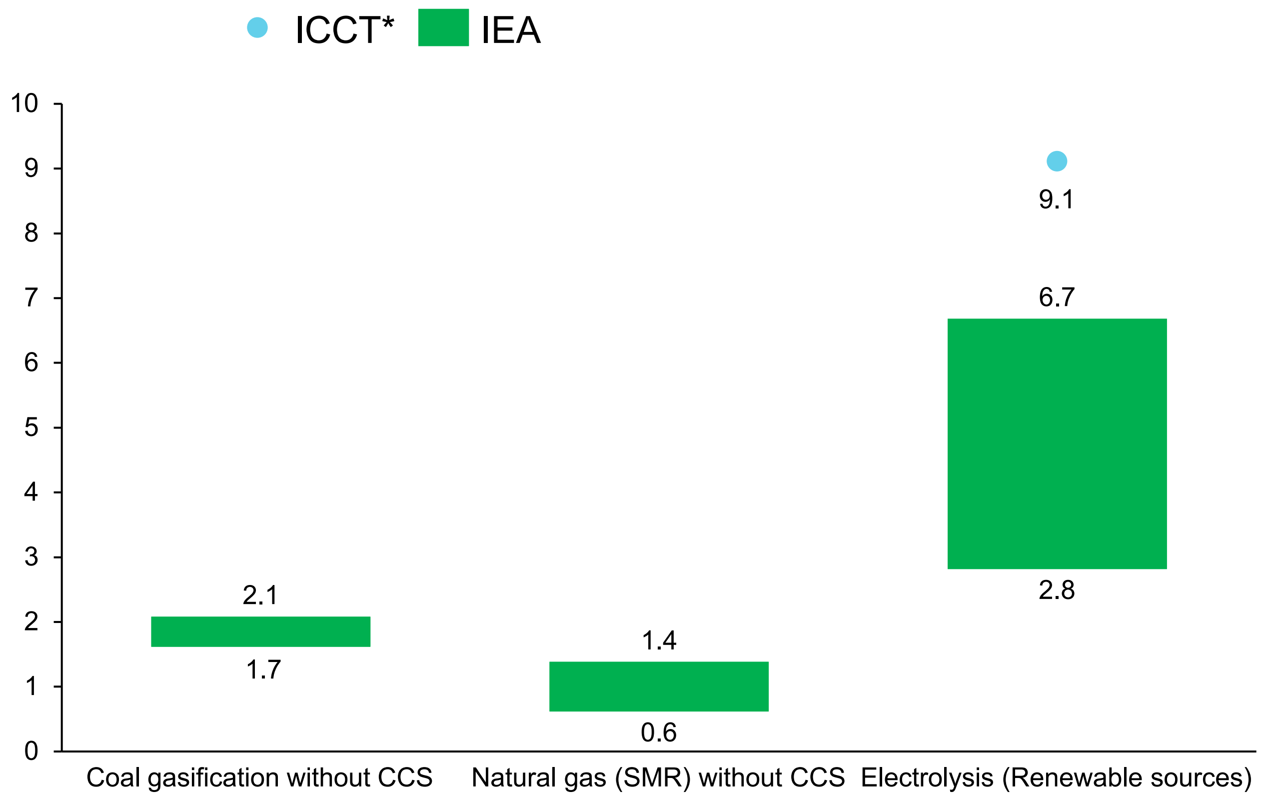


- The price range for HFCVs varies significantly across regions due to factors such as local taxes, subsidies, and market demand. Typically, the prices shown left reflect the base models, with higher-end models featuring additional options being more expensive.
- In general, HFCVs are significantly more costly than internal combustion engine vehicles (ICEV) and even more expensive than PHEVs and BEVs. This is largely due to factors such as the technology's maturity, limited production scale, and high research and development costs.
- As technology advances and production scales increase, HFCV prices are expected to decrease, potentially making them more competitive with other vehicle types. However, as of 2024, making HFCVs affordable remains a significant challenge.

Sources: IEA (2024d), Toyota Motor (2024), Saunders, M. (2021) Autocar, Car and Driver (2024b), Car and Driver (2024a), Mitsubishi Motors (n.d.), etc.

(5) Affordability – Fuel costs of HFCV vary over different ways of H_2 production

Cost of fuel, USD/100km



- The graph on the left shows the range of costs (fuel) in USD required for HFCVs to run 100 km. Each cost value is estimated through the cost calculations of fuel, which is hydrogen, by different ways of hydrogen production as below.
  - Coal gasification without CCS
  - Natural gas (SMR) without CCS.
  - Electrolysis using renewable electricity
- There exists wide cost ranges in each hydrogen production pathways due to regional differences in fossil fuel prices, CO_2 prices, renewable costs, CAPEX and OPEX.
- The cost when consuming hydrogen produced via electrolysis which uses renewable sources is the highest. Meanwhile, in the case of using hydrogen produced with fossil fuels, the costs are kept relatively low.

Source: IEA (2020b), H2 MOBILITY Deutschland (n.d.), Basma, H., Y. Zhou and F. Rodríguez (2022)

[Reference] Methodologies: Affordability

Methodology: Vehicle cost, USD/vehicle

1. The calculation made was based on prices for medium-sized vehicles, using the following exchange rates at 13/9/2024: JPY1 = USD0.0064, and EUR1 = USD1.1086. These prices are exclusive of any local taxes and subsidies.

Methodology: Cost of fuel, USD/100km

1. ICCT stands for International Council on Clean Transportation. The ICCT figure was the average of France, Germany, Italy, Netherlands, Poland, Spain, and the United Kingdom.
2. The figures are calculated by multiplying costs during different hydrogen production routes (USD/g H_2) with the average amount of fuel consumption of HFCVs (g H_2/100 km). The average amount of fuel consumption, which is 870 g H_2/100 km, is calculated by averaging multiple data of different types of HFCVs.

Source: IEA (2020b), H2 MOBILITY Deutschland (n.d.), Basma, H., Y. Zhou and F. Rodríguez (2022)

(6) Reliability – HFCV sales remain small primarily due to factors such as the high cost of ownership and the limited availability of H_2 refuelling infrastructure

Estimated commercialisation status

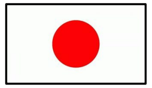
- TRL 9: HFCVs are already at the commercial stage.

Recent utilisation examples

Global

- Although global sales of HFCVs have increased year by year, they remain significantly lower than sales of BEVs and PHEVs.
- In 2023, HFCVs accounted for only about 0.6% of the combined sales of BEVs and PHEVs.

Japan



- In Japan, one of the countries where HFCVs were introduced early on, annual sales have been limited to fewer than 1,000 units in recent years.

Source: IEA (2024d), JADA (2024)

(7) Lock-in prevention – Green H_2 and blue H_2 with CCUS offer low-emission alternatives but face high costs and technological challenges

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Two paths exist for HFCVs to be zero or near-zero emissions; – Path 1: Use of green H_2 which has essentially zero full fuel-cycle GHG emissions Green H_2 is produced using renewable energy sources to electrolyse water, separating H_2 from oxygen. Since the energy used is renewable, this method does not emit any GHG, making it the most environmentally friendly option. – Path 2: Capture substantial amounts of CO_2 from H_2 production processes via CCUS As emissions from blue H_2 production is a challenge, capturing substantial amounts of carbon dioxide from H_2 production processes via CCUS can be considered a proactive approach towards mitigating that negative effect.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Use of green H_2 which has essentially zero GHG emissions – Green H_2 is produced through electrolysis using renewable energy sources. This process is currently more expensive than producing H_2 from fossil fuels due to the high costs of renewable energy and electrolysis technology. • Path 2: Capture substantial amounts of CO_2 from H_2 production processes via CCUS – Blue H_2 is produced through a process where natural gas is heated with steam to produce H_2 and CO_2 as byproducts. Producing blue H_2 involves capturing and storing this CO_2 emission, which adds significant costs. This makes blue H_2 more expensive compared to traditional fossil fuels and even green H_2 in some cases. – The technology for capturing and storing carbon emissions from blue H_2 production is still developing. Ensuring that CCUS is effective and economically feasible is crucial for the viability of blue H_2.

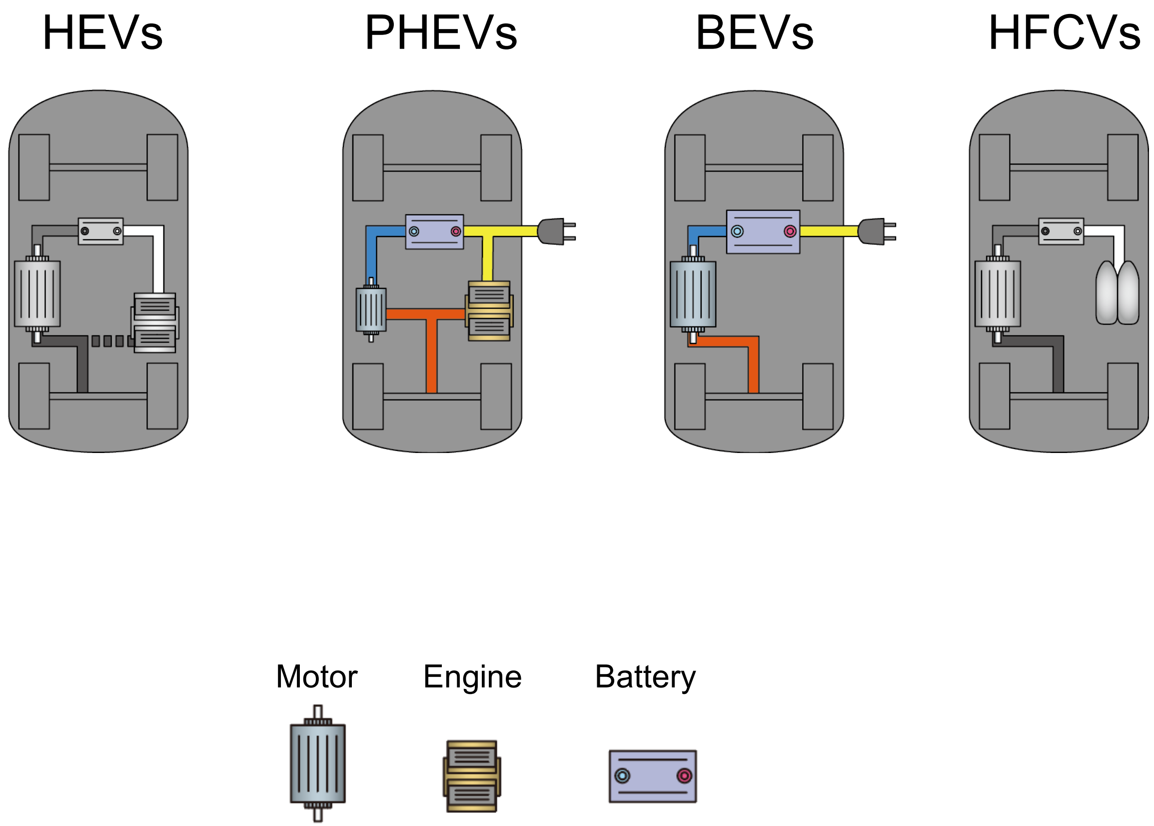
Source: Maka, A.O. and M. Mehmood (2024), Bauer, C. et al. (2021))

(8)(9) DNSH/social considerations – Sustainable H_2 production requires careful resource management and reskilling to minimise environmental and social impacts

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• To produce green H_2, substantial amounts of water and renewable energy are needed. If not managed sustainably, this could lead to water conflicts and environmental degradation. • H_2 production from non-renewable energy sources typically involves processes like SMR, coal gasification, or the electrolysis of water using electricity from fossil fuels. These methods rely on resources that are extracted through mining and drilling, leading to various environmental impacts, including biodiversity loss.
	Transition to circular economy	• Ensuring that the production and disposal of HFCVs and their components, such as fuel cells, adhere to circular economy principles is essential to minimise waste and environmental impact. • Fuel cell technology relies on rare metals, such as platinum, as catalysts to facilitate the necessary chemical reactions for power generation. However, the increasing demand for these metals could lead to over-extraction, potentially harming ecosystems and disturbing the balance of natural habitats.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• The transition from traditional automotive manufacturing to HFCV production could result in job losses in sectors tied to internal combustion engines (ICE), affecting workers and communities dependent on these industries. Therefore, it is essential to plan for reskilling these workers. • Additionally, the mining processes for rare metals such as platinum are often associated with human rights concerns, including the risk of forced labour, which raises significant ethical and social issues within the supply chain. • On the other hand, new job opportunities would be created in fuel cell production, electric operation parts, fuel cell recycling, H_2 charging stations, and related fields. • Since HFCVs generate electricity through an electrochemical reaction and only produce water as a byproduct, they can contribute to a significant reduction in air pollutants, including PM2.5. • Since HFCVs produce less noise during an electric operation, it may contribute to reducing noise pollution.

Source: Fladvad, B. (2023), Lucien Duclos, Maria Lupsea, Guillaume Mandil, Lenka Svecova, Pierre-Xavier Thivel, et al. (2018), Horizon Educational (n.d.), Energy Voice (2023)

(1) PHEVs & BEVs – Technology schematics and overview



Source: Author created based on various literature

PHEVs combine an electric motor and a gasoline engine. They run on electricity for short trips and switch to fuel when the battery runs out, offering flexibility and reduced emissions.

BEVs refer to electric vehicles powered solely by electricity stored in a battery pack. BEVs do not use any form of ICEs or fossil fuels. Instead, they rely on electric motors for propulsion.

Source: ANRE (2022)

(2) PHEVs & BEVs – Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• A BEV sold in 2023 would emit 50%, and a PHEV 30% less than an ICEV over its lifetime globally.
Affordability	• The cost of purchasing a medium-sized BEV tends to be higher than that of ICEV. • BEVs are usually the most expensive due to their more complex structure and the high cost of battery production. They are followed by PHEVs, HEVs, and ICEVs, in that order.
Reliability	• In 2023, global sales of EVs, including both BEVs and PHEVs, continued to grow, reflecting the advancing technological maturity of BEVs and PHEVs, with some countries reaching notable levels of adoption. (TRL 11)
Lock-in prevention considerations	• Path 1: Transitioning the grid to clean energy and developing advanced batteries which cause zero emission during production. • Path 2: For PHEV, replace traditional gasoline with alternative fuels that are considered green such as biodiesel etc. • Path 3: Achieve net-zero emissions by using e-fuel to eliminate CO_2 emissions during operation.
DNSH considerations	• Production of batteries required in BEVs and PHEVs can be an environmental concern as it requires rare metal. • Depending on the electricity sources, BEV and PHEV can adversely contribute to climate change.
Social considerations	• The shift to BEVs significantly impacts the employment due to their design, which excludes traditional ICE components like engines, transmissions, and exhaust systems. BEV adoption may displace workers in traditional automotive manufacturing sectors, especially those involved in ICE component production (e.g., engine assembly, exhaust systems). Workers in these areas may require retraining for roles in BEV production. • PHEVs, which still retain some ICE parts, have a less pronounced impact on jobs and supply change as compared to BEVs.

(3) ASEAN Taxonomy – Relevant technical screening criteria

Urban and suburban transport, road passenger transport

Eligibility	Climate Change Mitigation TSC	Details
Includes - **Excludes**	**Tier 1 (Green)**	1. The activity complies with one or all of the following criteria: a. The activity provides urban or suburban passenger transport, and its direct (tailpipe) CO_2 emissions are zero; AND b. Until 31 December 2030, the Activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD and comply with the latest EURO VI Standard.
	Tier 2 (Amber T2)	1. The activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD; AND 2. Until 31 December 2030, comply with the latest EURO V Standard.
	Tier 3 (Amber T3)	1. The activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD; AND 2. Until 31 December 2030, comply with the latest EURO IV Standard.

Note:
M2: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass ("technically permissible maximum laden mass") not exceeding 5 tons, M3: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tons
CA: Single-deck vehicle; CB: Double-deck vehicle; CC: Single-deck articulated vehicle; CD: Double-deck articulated vehicle
As defined by European Emissions Standards. Note that these standards do not define GHG limits per se. However, these are intended to set minimum standards for M2 and M3 vehicles (i.e., buses), which are deemed to be low emission in terms of gCO^2e/pkm.

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Transport by motorbikes, passenger cars and light commercial vehicles

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	1. The activity compiles with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2025, direct emissions of CO_2 are < 50 gCO_2-eq/v-km ii. From 1 January 2026, direct emissions of CO_2 are 0gCO_2-eq/v-km; b. For vehicles of category L, tailpipe CO_2 emissions are 0gCO_2-eq/v-km
Excludes	**Tier 2 (Amber T2)**	1. The activity compiles with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2030, direct emissions of CO_2 are < 50 gCO_2-eq/v-km
	Tier 3 (Amber T3)	1. The activity complies with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2030, direct emissions of CO_2 are < 100 gCO_2-eq/v-km

Note:
- M1: Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat, and having a maximum mass ("technically permissible maximum laden mass") not exceeding 3.5 tons; N1: Vehicles for the carriage
- of goods and having a maximum mass not exceeding 3.5 tonnes
- vkm: Vehicle-kilometre
- L: Mopeds, Motorcycles, Motor Tricycles and Quadricycles

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Freight transport services by road

Eligibility	Climate Change Mitigation TSC	Details
Includes - **Excludes**	**Tier 1 (Green)**	1. The activity complies with one of the following criteria: a. vehicles of category N1 have zero direct (tailpipe) CO_2 emissions; b. vehicles of category N2 and N3[1] with a technically permissible maximum laden mass not exceeding 7.5 tonnes are ‘zero-emission heavy-duty vehicles’; c. vehicles of category N2 and N3 with a technically permissible maximum laden mass exceeding 7.5 tonnes are one of the following: i. Zero-emission heavy-duty vehicle; OR ii. where technologically and economically not feasible to comply with the criterion in point (i), until 31 December 2030 have direct (tailpipe) CO_2 emissions less than 21 gCO_2/t-km[2]; AND 2. Vehicles are not dedicated to the transport of fossil fuels.
	Tier 2 (Amber T2)	1. The activity complies with one of the following criteria: a. vehicles of category N2 and N3 with a technically permissible maximum laden mass exceeding 7.5 tonnes are one of the following: i. where technologically and economically not feasible to achieve zero emissions, until 31 December 2030, have direct (tailpipe) CO_2 emissions less than 42 gCO_2-eq/t-km, and 1 January 2031 onwards, less than 21 gCO_2-eq/t-km; AND 2. Vehicles are not dedicated to the transport of fossil fuels.
	Tier 3 (Amber T3)	• No TSC available.

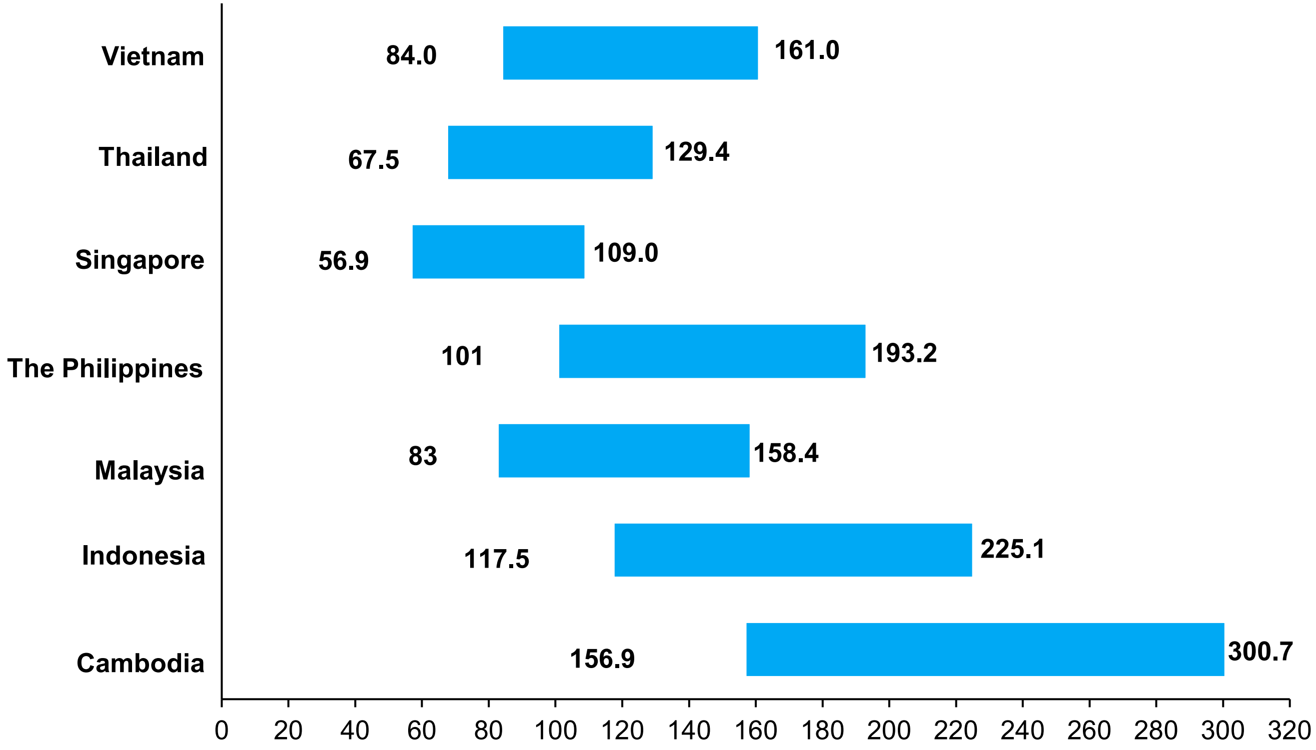
Notes:

1. N1: Vehicles for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes; N2: Vehicles for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes; N3: Vehicles for the carriage of goods and having a maximum mass exceeding 12 tonnes
2. Based on the current difference between emissions projections for freight activity by the CBI (18gCO_2-eq/t-km by 2050) and IEA NZE (18gCO_2-eq/t-km by 2040), it is proposed to have a forward outlook with a horizon date of 2030; indicative of reviewing the TSC at the period and potentially amending the threshold based on new emissions data in the future.

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition – CO_2 emissions of BEVs depend on grid emission factors; All the BEVs will be lablled as "Green" by the ASEAN Taxonomy

Indirect CO_2 emissions of BEV from km travelled, gCO_2/km



Comparison with ASEAN Taxonomy

There are three TSCs which are potentially applicable to BEVs.

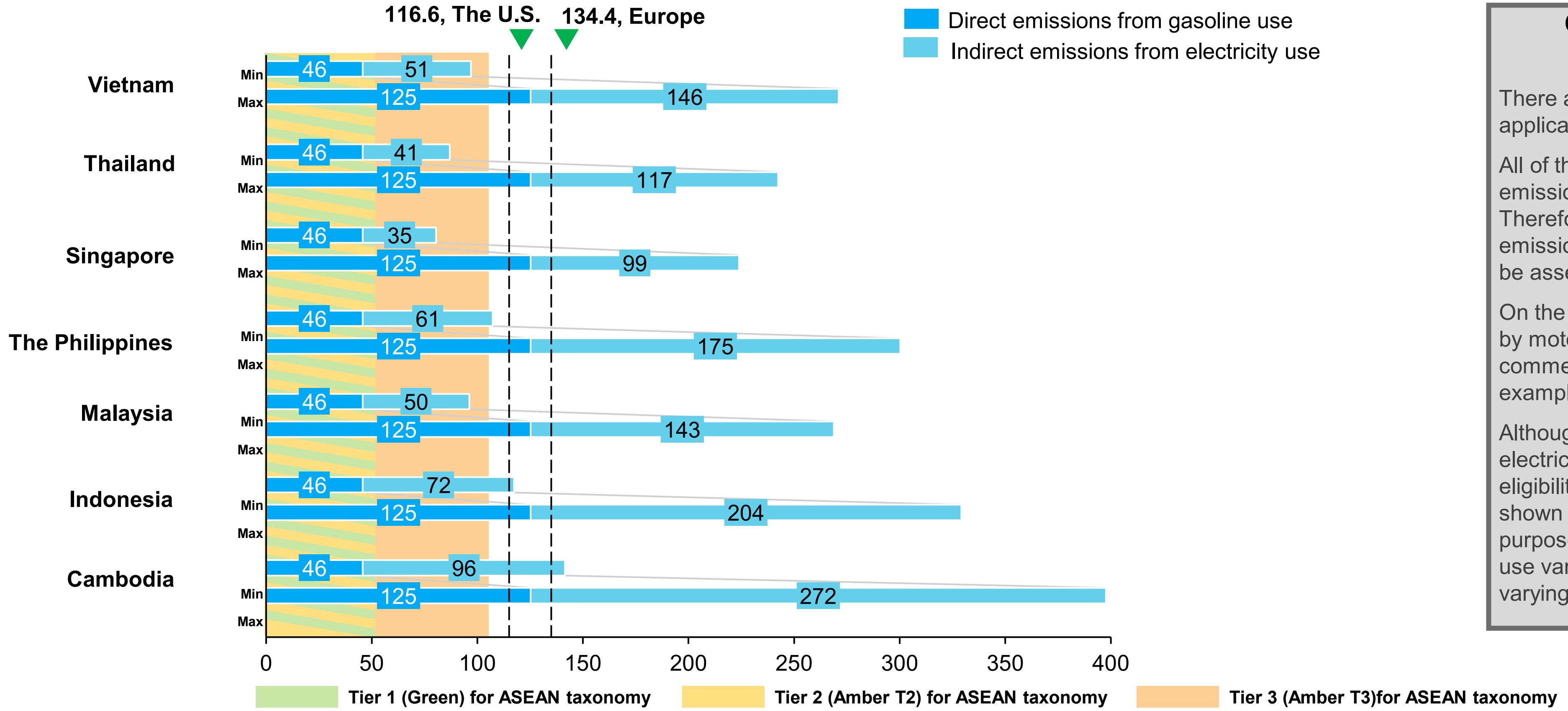
All of them set thresholds on direct (tailpipe) emissions, and NOT lifecycle emissions. Therefore, all the BEVs will be labelled as "Green" by the ASEAN Taxonomy.

The left graph shows GHG emissions derived from electricity usage to drive a BEV. The figures vary over different countries due to the varying power mix.

Sources: DOE and EPA (2024b), DOE (n.d. d), IFI TWG (2019), Steinmetz, M.,E. van Eijk, and N. Ligterink (2023)

(4) Contribution to Energy Transition –Only the emissions from gasoline combustion would be counted for assessment against the ASEAN Taxonomy

CO_2 emissions of PHEV from km travelled, gCO_2/km



Comparison with ASEAN Taxonomy

There are three TSCs which are potentially applicable to PHEVs.

All of them set thresholds on direct (tailpipe) emissions, and NOT lifecycle emissions. Therefore, in the case of PHEVs, only the emissions derived from gasoline use should be assessed against TSCs.

On the left graph, only the TSC of "transport by motorbikes, passenger cars and light commercial vehicles" is shown as an example.

Although the emissions derived from electricity use are not counted towards eligibility of the ASEAN Taxonomy, those are shown in the left graph for a reference purpose. Emissions derived from electricity use vary over different countries due to varying grid emission factors.

Tier1 to Tier3 here refer to the TSC of "transport by motorbikes, passenger cars and light commercial vehicles" of the ASEAN Taxonomy. Direct emissions of < $50gCO_2$-eq/v-km. are classified as Tier 1 until 31 December 2025, but after 1 January 2026, it will be deemed as Tier 2 (Amber T2). After 1 January 2026 direct emissions of < $0gCO_2$-eq/v-k will be deemed as Tier 1.

Sources: DOE and EPA (2024b), DOE (n.d. d), IFI TWG (2019), Steinmetz, M.,E. van Eijk, and N. Ligterink (2023

[Reference] Methodologies: Contribution to Energy Transition

Methodology: CO_2 emissions of BEV from km travelled

1. The figures were calculated by multiplying the fuel economies of midsize BEVs sold in the U.S. in 2024 by the grid emission factors of ASEAN. The grid emission factors referred to the harmonised grid emission factor data set publicised by the United Nations Framework Convention on Climate Change.

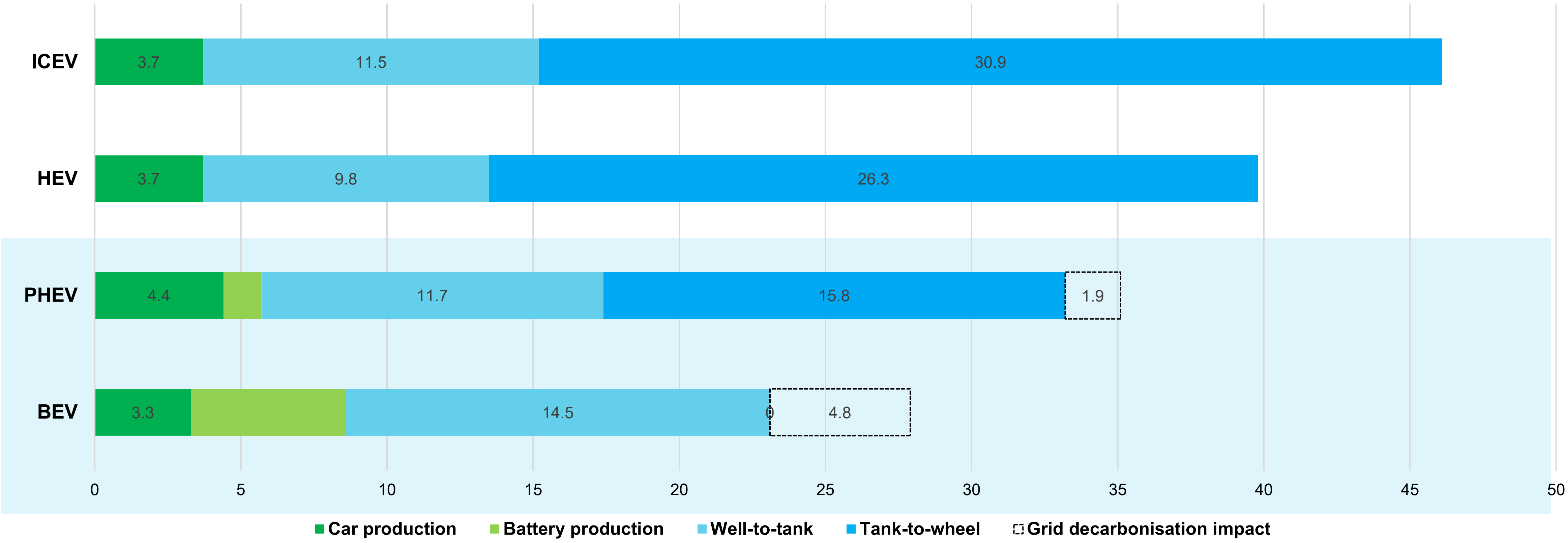
Methodology: CO_2 emissions of PHEV from km travelled

1. The figures were calculated by multiplying the fuel economies of midsize PHEVs sold in the U.S. in 2023 and 2024 by the grid emission factors of ASEAN. The electricity driving mode share was assumed to be 56.3% which is the US utility factor set by SAE J2841 in 2010. The grid emission factors referred to the harmonized grid emission factor dataset publicised by the United Nations Framework Convention on Climate Change.
2. CO_2 emissions of PHEVs are highly influenced by the share of electric deriving which varies over ways of driving.

Sources: DOE and EPA (2024b), DOE (n.d. d), IFI TWG (2019), Steinmetz, M.,E. van Eijk, and N. Ligterink (2023

[Reference] Lifecycle CO_2 emissions of BEVs and PHEVs

Lifecycle CO_2 emission[1,2], tCO_2-eq/vehicle

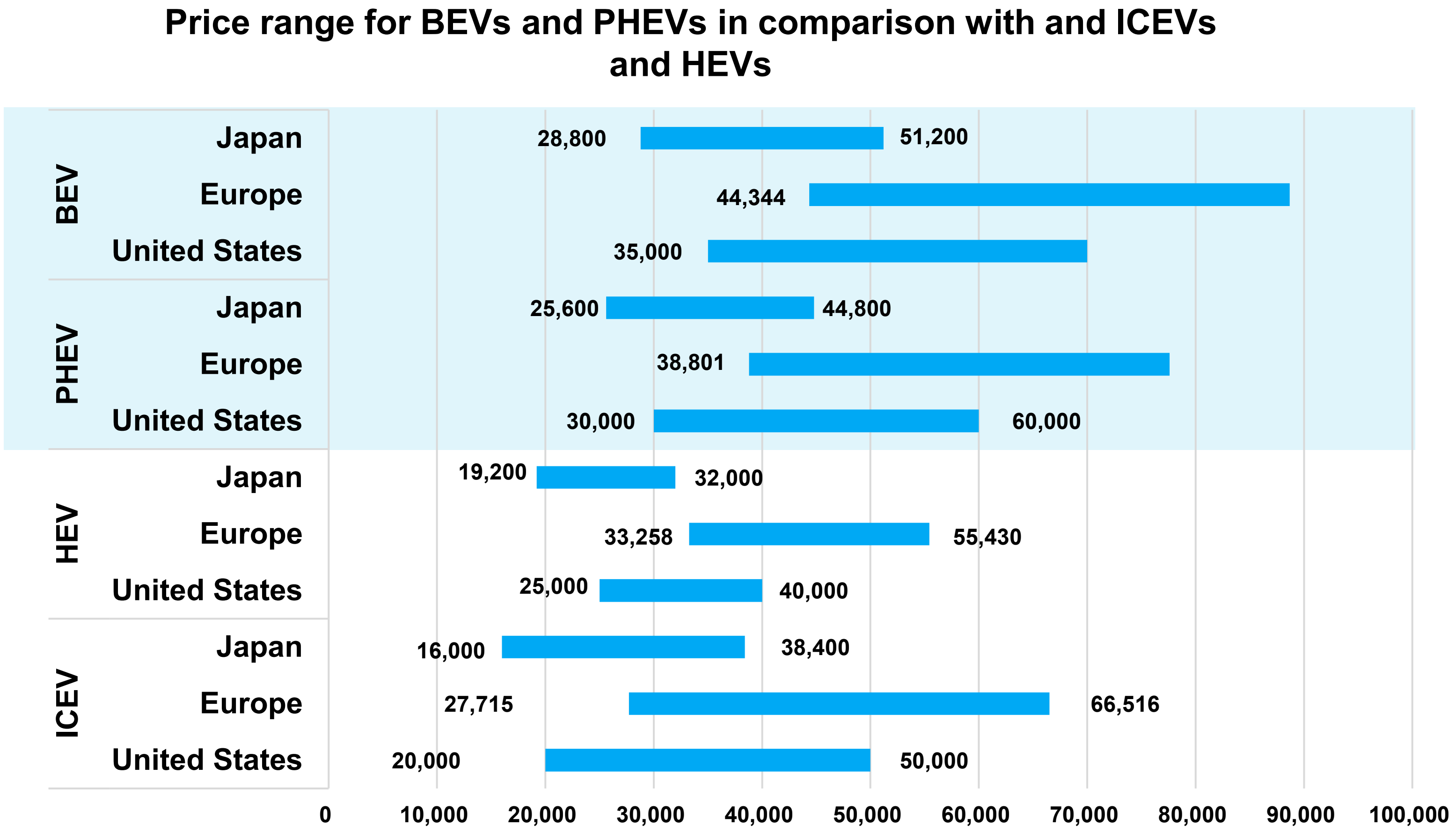


Notes:
1. The numbers are the global average lifecycle emissions by powertrain produced in 2023
2. "Grid decarbonisation impact" refers to the effect of electricity emissions intensity improvements over the lifetime of the vehicle. The years 2023 refer to the first year of use of the vehicle. For further details on the assumptions behind this lifecycle analysis, please see refer to "Global EV Outlook 2024" by IEA.

Source: IEA (2024d)

(5) Affordability – The costs of a medium-sized BEV and PHEV tend to be higher than that of ICEV counterpart

Vehicle Cost, USD/vehicle



- The price range for PHEVs, HEVs, BEVs, and ICEVs varies significantly by region, depending on factors such as local taxes, subsidies, and market demand. Typically, these prices (see figure below) refer to base models, while higher-end models with additional features tend to be more expensive.
- These price ranges typically derives from base models, while higher-end models with additional features are generally more expensive. In general, BEVs are usually the most expensive due to their more complex structure and the high cost of battery production. They are followed by PHEVs, HEVs, and ICEVs, in that order.

Sources: IEA (2024d), Toyota Motor (2024) , Saunders, M. (2021) Autocar, Car and Driver (2024b), Car and Driver (2024a), Mitsubishi Motors (n.d.), etc.

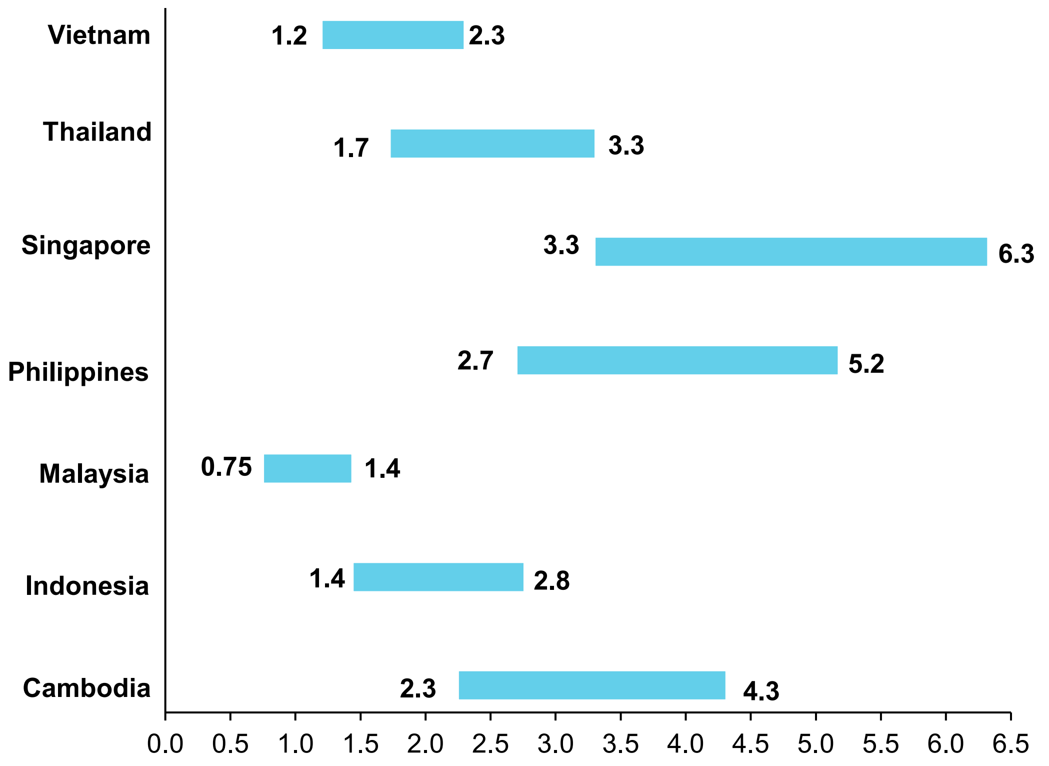
[Reference] Methodologies: Affordability

Methodology: Price range for BEVs and PHEVs in comparison with and ICEVs and HEVs

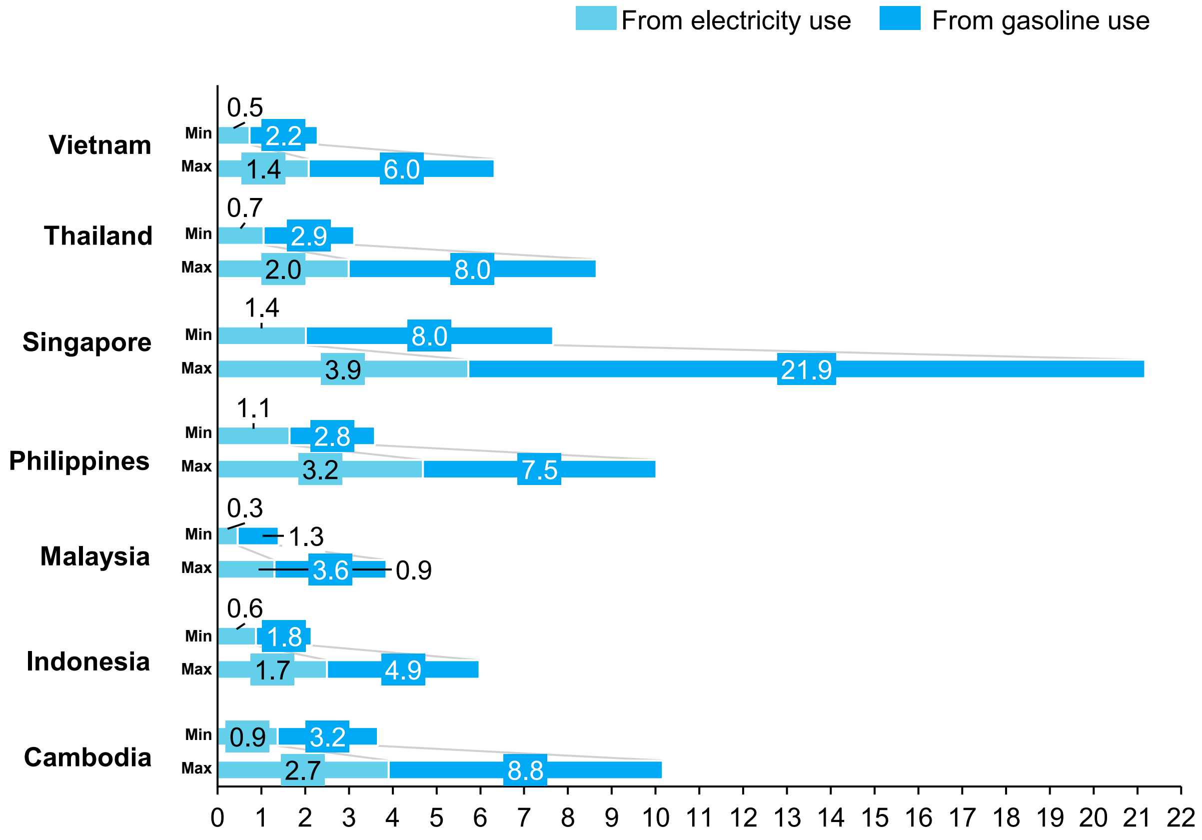
1. The calculation is based on prices for medium-sized vehicles, using the following exchange rates on 13/9/2024: JPY100 = USD0.64 , and EUR 1= USD1.1086. These prices are exclusive of any local taxes and subsidies.

(5) Affordability – The cost of a medium-sized BEV tends to be higher than that of ICEV

Cost of electricity for BEV, USD/100km



Cost of fuel and electricity for PHEV, USD/100km



Sources: DOE and EPA (2024b), DOE (n.d. d), DOE and EPA (2024a), OECD (2024), Trading Economics (2024)

[Reference] Methodologies: Affordability

Methodology: Cost of electricity for BEV

1. The figures were calculated by multiplying the fuel (electricity) economies of midsize BEVs sold in the U.S. in 2024 by the household electricity prices of ASEAN as of 2022.

Methodology: Cost of fuel and electricity for PHEV

1. The figures were calculated by multiplying the fuel economies of midsize PHEVs sold in the U.S. in 2023 and 2024 by the household electricity prices as of 2022 and the gasoline prices of ASEAN as of October 2024 respectively. The electricity driving mode share was assumed to 56.3% which is the US utility factor set by SAE J2841 in 2010.
2. Cost of fuel and electricity of PHEVs are highly influenced by the share of electric deriving which varies over ways of driving.

Sources: DOE and EPA (2024b), DOE (n.d. d), DOE and EPA (2024a), OECD (2024), Trading Economics (2024)

(6) Reliability – In Southeast Asia, the sales of PHEVs and BEVs have seen a significant growth in 2023

Estimated commercialisation status

- TRL 11: PHEVs and BEVs are already at the commercial stage

Recent utilisation examples

Thailand

- In Thailand, PHEV and BEV registrations surged more than fourfold from 2022 to 2023 to 87,000, reaching 10% of new vehicle sales.
- This growth was driven by new subsidies, lower import and excise taxes, and the increasing presence of Chinese carmakers, such as BYD.

Vietnam

- Electric car sales grew significantly, from under 100 in 2021 to over 30,000 in 2023, capturing 15% of new vehicle sales.
- VinFast, the domestic leader, dominated the market and also expanded internationally.

Malaysia

- Electric car registrations more than tripled between 2022 and 2023 to 10,000, boosted by tax breaks and the entry of major brands such as BYD, Tesla, and Mercedes-Benz, with a focus on expanding charging infrastructure.

Source: Nishino, K. (2024), IEA (2024d)

(7) Lock-in prevention – Transitioning to clean energy and green fuel is essential for achieving net zero; Cost and infrastructure challenges need to be addressed

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Three paths exist for BEVs and PHEVs to be zero or near-zero emissions; – Path 1: Transitioning the grid to clean energy and developing advanced batteries which cause zero emission during production. – Path 2: For PHEV, replace traditional gasoline with alternative fuels that are considered green such as biodiesel etc. – Path 3: Achieve net-zero emissions by using e-fuel to eliminate CO_2 emissions during operation.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• **Path 1: Transition to clean energy and develop zero-emission advanced batteries during production.** – The cost of EVs remains a barrier for many consumers. While prices have decreased over time, they are still higher than traditional ICEVs. – Achieving net zero requires transitioning to renewable energy sources. However, the share of primary energy produced by renewables is still relatively low. Accelerating the shift to clean energy is vital. – Additionally, focus on developing advanced batteries that produce zero emissions during their production process. • **Path 2: Replace traditional gasoline with alternative fuels that are considered green** – The production and infrastructure for green fuels often require significant upfront investment. For example, hydrogen production through electrolysis is currently more expensive than traditional methods. Biodiesel technology is more mature, but it still faces challenges in terms of efficiency and scalability. – For biodiesel, sourcing sustainable feedstock (like used cooking oil or algae) can be challenging. Competing uses for these materials can drive up costs.

Source: IEA (2024d), IRENA (2020) , Interview with Dr. Dr Nana O Bonsu, Birmingham Business School, University of Birmingham on 27/9/2024.

(7) Lock-in prevention – Transitioning to clean energy and green fuel is essential for achieving net zero; Cost and infrastructure challenges need to be addressed

Framework dimensions	Considerations/ Key questions	Details
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• **Path 3: Achieve net-zero emissions by using e-fuel to eliminate CO_2 emissions during operation.** – E-fuel, or synthetic fuel, is produced by combining H_2 generated through water electrolysis using renewable energy with CO_2 captured from the air or industrial processes to create liquid fuels. – While e-fuels offer a promising path towards reducing CO_2 emissions, their energy-intensive production, high costs mainly due to the cost of H_2, infrastructure challenges, and competition from other technologies could hinder their role in achieving net-zero emissions.

Source: Ellis, T., R. Gerrish, and G. Michel (2024) , Fladvad, B. (2023), Lucien Duclos, Maria Lupsea, Guillaume Mandil, Lenka Svecova, Pierre-Xavier Thivel, et al. (2018)

(8)(9) DNSH/social considerations – The use of rare materials mainly for batteries in BEVs and PHEVs can be an environmental concern and needs to be addressed

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	Protection of healthy ecosystems and biodiversity	• Due to the extensive use of rare materials such as lithium, nickel, cobalt, and copper required for the production of lithium-ion batteries, the mineral resource deployment related to the BEVs and PHEVs results abundantly higher than the impact caused the ICEVs. • Regarding PHEVs, gasoline spills during extraction, transport, or use can contaminate soil and water, leading to the death of aquatic life, poisoning of wildlife, and degradation of natural habitats. Over time, these effects reduce biodiversity and weaken ecosystem resilience. • Depending on the electricity sources, BEVs and PHEVs can harm the environment in the way the electricity is generated.
	Transition to circular economy	• **Battery Recycling and Second Life**: Efficient recycling processes for lithium-ion batteries are crucial. Repurposing used batteries for energy storage systems can extend their lifespan. • **End-of-Life Management**: Proper vehicle disposal and recycling are essential at the end of their life cycle. Consumers should be encouraged to return vehicles to authorised centres for responsible recycling. Extracting valuable materials, such as rare earth metals, from old components is important. • **Circular Supply Chains**: Manufacturers should focus on sustainable material sourcing, minimising production waste, and adopting closed-loop supply chains. Recycled materials should be incorporated into vehicle production.

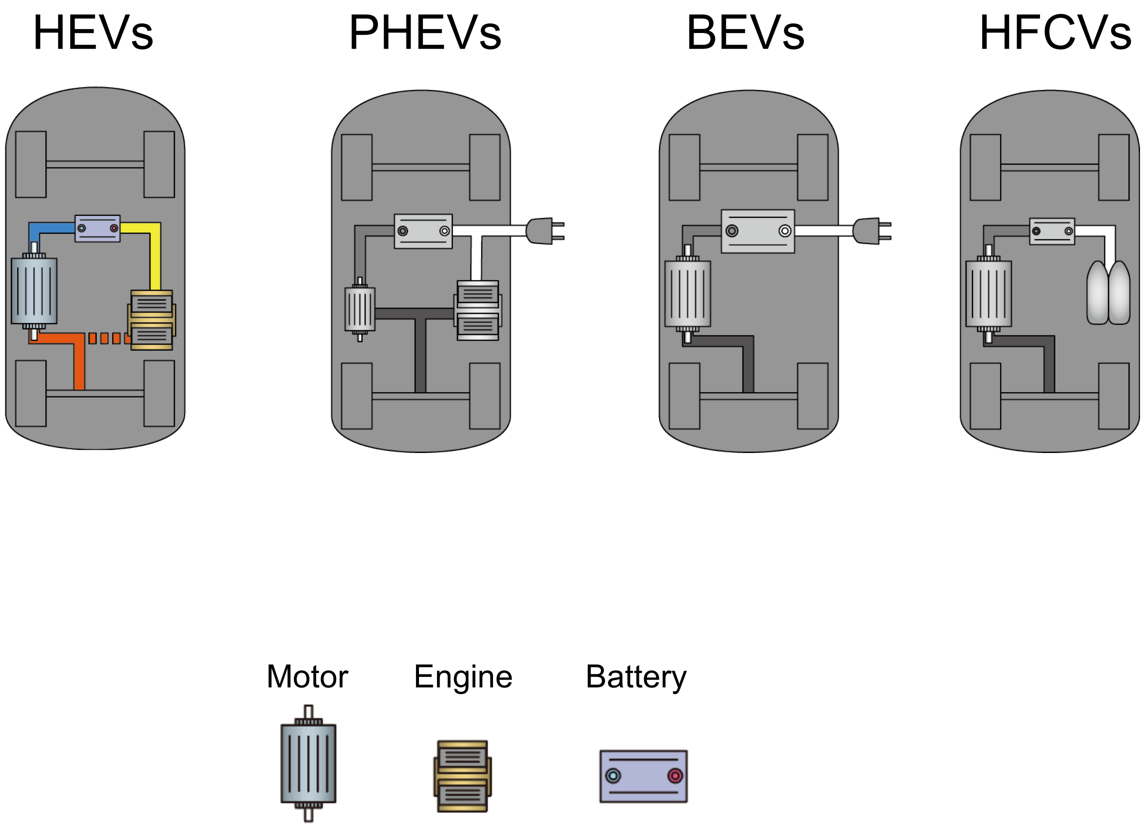
Source: Pipitone, E.; Caltabellotta, S.; Occhipinti (2021), Patel AN, Lander L, Ahuja J, Bulman J, Lum JKH, Pople JOD, Hales A, Patel Y and Edge JS (2024)

(9) Social considerations – The shift to BEVs may reduce employment temporarily, but would create a new supply chain around battery and charging infrastructure

Framework dimensions	Considerations/ Key questions	Details
Social considerations	**Plans to mitigate the negative social impact of the technology**	• The shift to BEVs significantly impacts employment due to their design, which excludes traditional ICEV components like engines, transmissions, and exhaust systems. BEVs adoption may displace workers in traditional automotive manufacturing sectors, especially those involved in ICEV component production (e.g., engine assembly, exhaust systems). Workers in these areas may require retraining for roles in BEV production. • The production of BEVs introduces a new supply chain, centred around battery materials and charging infrastructure. This shift leads to the emergence of new suppliers while existing suppliers adapt to meet the demands of BEV components. As a result, the automotive supply chain and logistics sectors undergo significant changes. PHEVs, which still retain some ICEV parts, have a less pronounced impact on jobs and supply change as compared to BEVs. • Since BEVs and PHEVs do not combust fuels during electric operation, they can contribute to a significant reduction in air pollutants, including PM2.5 and NOx. • Since BEVs and PHEVs produce less noise during an electric operation mode, they may contribute to reducing noise pollution.

Source: IEA (2022a), Campagnol, N., A. Pfeiffer, and C. Tryggestad (2022) McKinsey & Company, Economic Policy Institute (2021)

(1) HEVs – Technology schematics and overview



Source: Author created based on various literature

HEVs technology combines an ICEV with an electric motor to improve fuel efficiency and reduce emissions. The electric motor assists during acceleration and low-speed driving, while regenerative braking recharges the battery without needing external charging.

Source: ANRE (2022)

(2) HEVs – Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• Compared to ICEVs, HEVs have about 13% lower emissions. However, the emission levels are higher than those of BEVs and PHEVs.
Affordability	• Generally, HEVs are more expensive than ICEVs but remain more affordable than PHEVs and BEVs, primarily because HEVs have smaller batteries compared to the latter two types of vehicles.
Reliability	• Global sales of HEVs are rising in tandem with the broader shift toward electrification, highlighting the growing reliability and trust in this technology. (TRL 11) • In Japan, HEVs have surpassed ICEVs as the top-selling vehicle type in Japan in recent years.
Lock-in prevention considerations	• Path 1: Replace traditional gasoline with alternative fuels that are considered green such as biodiesel etc. • Path 2: Achieve net-zero emissions by using e-fuel to eliminate CO_2 emissions during operation.
DNSH considerations	• The production of batteries can lead to environmental concerns because it requires a significant amount of natural resources.
Social considerations	• Resource demand for battery production can be an environmental concern. • Although the impact on employment is less significant compared to BEVs as many existing automotive jobs related to ICEV production and maintenance remain relevant, however, new roles are emerging in hybrid technology integration and maintenance, which will require specialised training.

(3) ASEAN Taxonomy – Relevant technical screening criteria

Urban and suburban transport, road passenger transport

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	1. The activity complies with one or all of the following criteria: a. The activity provides urban or suburban passenger transport, and its direct (tailpipe) CO_2 emissions are zero; AND b. Until 31 December 2030, the Activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD and comply with the latest EURO VI Standard.
Excludes	**Tier 2 (Amber T2)**	1. The activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD; AND 2. Until 31 December 2030, comply with the latest EURO V Standard.
	Tier 3 (Amber T3)	1. The activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD; AND 2. Until 31 December 2030, comply with the latest EURO IV Standard.

Note:
M2: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver’s seat, and having a maximum mass (“technically permissible maximum laden mass”) not exceeding 5 tons, M3: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver’s seat, and having a maximum mass exceeding 5 tons
CA: Single-deck vehicle; CB: Double-deck vehicle; CC: Single-deck articulated vehicle; CD: Double-deck articulated vehicle
As defined by European Emissions Standards. Note that these standards do not define GHG limits per se. However, these are intended to set minimum standards for M2 and M3 vehicles (i.e., buses), which are deemed to be low emission in terms of gCO^2e/pkm.

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Transport by motorbikes, passenger cars and light commercial vehicles

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	1. The activity compiles with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2025, direct emissions of CO_2 are < 50 gCO_2-eq/v-km ii. From 1 January 2026, direct emissions of CO_2 are 0gCO_2-eq/v-km; b. For vehicles of category L, tailpipe CO_2 emissions are 0gCO_2-eq/v-km
	Tier 2 (Amber T2)	1. The activity compiles with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2030, direct emissions of CO_2 are < 50 gCO_2-eq/v-km
Excludes	**Tier 3 (Amber T3)**	1. The activity complies with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2030, direct emissions of CO_2 are < 100 gCO_2-eq/v-km

Note:
- M1: Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat, and having a maximum mass ("technically permissible maximum laden mass") not exceeding 3.5 tons; N1: Vehicles for the carriage
- of goods and having a maximum mass not exceeding 3.5 tonnes
- vkm: Vehicle-kilometre
- L: Mopeds, Motorcycles, Motor Tricycles and Quadricycles

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Freight transport services by road

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	1. The activity complies with one of the following criteria: a. vehicles of category N1 have zero direct (tailpipe) CO_2 emissions; b. vehicles of category N2 and N3[1] with a technically permissible maximum laden mass not exceeding 7.5 tonnes are 'zero-emission heavy-duty vehicles'; c. vehicles of category N2 and N3 with a technically permissible maximum laden mass exceeding 7.5 tonnes are one of the following: i. Zero-emission heavy-duty vehicle; OR ii. where technologically and economically not feasible to comply with the criterion in point (i), until 31 December 2030 have direct (tailpipe) CO_2 emissions less than 21 gCO_2/t-km[2]; AND 2. Vehicles are not dedicated to the transport of fossil fuels.
Excludes	**Tier 2 (Amber T2)**	1. The activity complies with one of the following criteria: a. vehicles of category N2 and N3 with a technically permissible maximum laden mass exceeding 7.5 tonnes are one of the following: i. where technologically and economically not feasible to achieve zero emissions, until 31 December 2030, have direct (tailpipe) CO_2 emissions less than 42 gCO_2-eq/t-km, and 1 January 2031 onwards, less than 21 gCO_2-eq/t-km; AND 2. Vehicles are not dedicated to the transport of fossil fuels.
	Tier 3 (Amber T3)	• No TSC available.

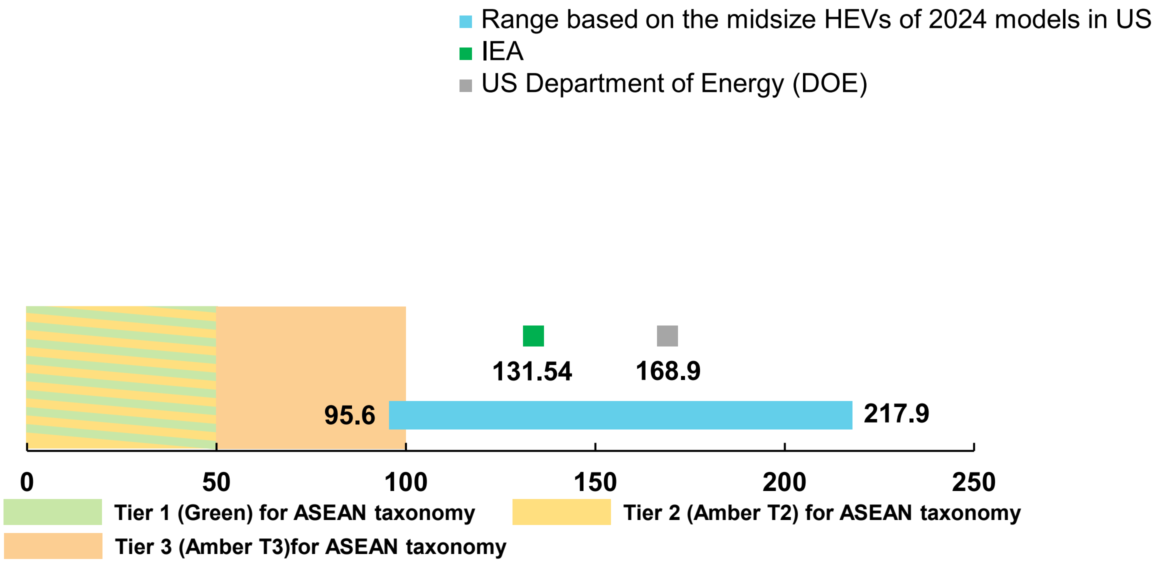
Notes:

1. N1: Vehicles for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes; N2: Vehicles for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes; N3: Vehicles for the carriage of goods and having a maximum mass exceeding 12 tonnes
2. Based on the current difference between emissions projections for freight activity by the CBI (18gCO_2-eq/t-km by 2050) and IEA NZE (18gCO_2-eq/t-km by 2040), it is proposed to have a forward outlook with a horizon date of 2030; indicative of reviewing the TSC at the period and potentially amending the threshold based on new emissions data in the future.

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition – HEVs emission levels differ over different models

CO_2 emission from km travelled, gCO_2-eq/km



Tier1 to Tier3 here refer to the TSC of “transport by motorbikes, passenger cars and light commercial vehicles” of the ASEAN Taxonomy. Direct emissions of < 50gCO_2-eq/v-km. are classified as Tier 1 until 31 December 2025, but after 1 January 2026, it will be deemed as Tier 2 (Amber T2). . After 1 January 2026 direct emissions of < 0gCO_2-eq/v-k will be deemed as Tier 1.

Comparison with ASEAN Taxonomy

There are three TSCs which are potentially applicable to HEVs.

All of them set thresholds on direct (tailpipe) emissions, and NOT lifecycle emissions.

The left graph shows GHG emissions derived from gasoline combustion and those emissions are counted towards eligibility of the ASEAN Taxonomy labelling.

As the graph shows, most of the HEVs would not be labelled as either Green or Amber (T2 or T3).

Source: IEA (2024d), DOE and EPA (2024b), IPCC (2006b), DOE (n.d. d)

[Reference] Methodologies: Contribution to Energy Transition

Methodology: CO_2 emission from km travelled

1. Range based on the midsize HEVs of 2024 models in US: The figures were calculated by multiplying fuel economies of the midsize HEVs of 2024 models sold in the U.S. by the default CO_2 emission factor of motor gasoline set in 2006 Intergovernmental Panel on Climate Change (IPCC) Guideline. Other GHG types are not taken into account.
2. IEA: The figure was calculated by dividing the global average lifecycle tank-to-wheel (TTW) emissions by powertrain produced in 2023 by 200,000km of lifecycle distance travelled.
3. DOE: The figure was calculated based on the 2022 data. The detailed assumptions and calculation are available on the DOE website.

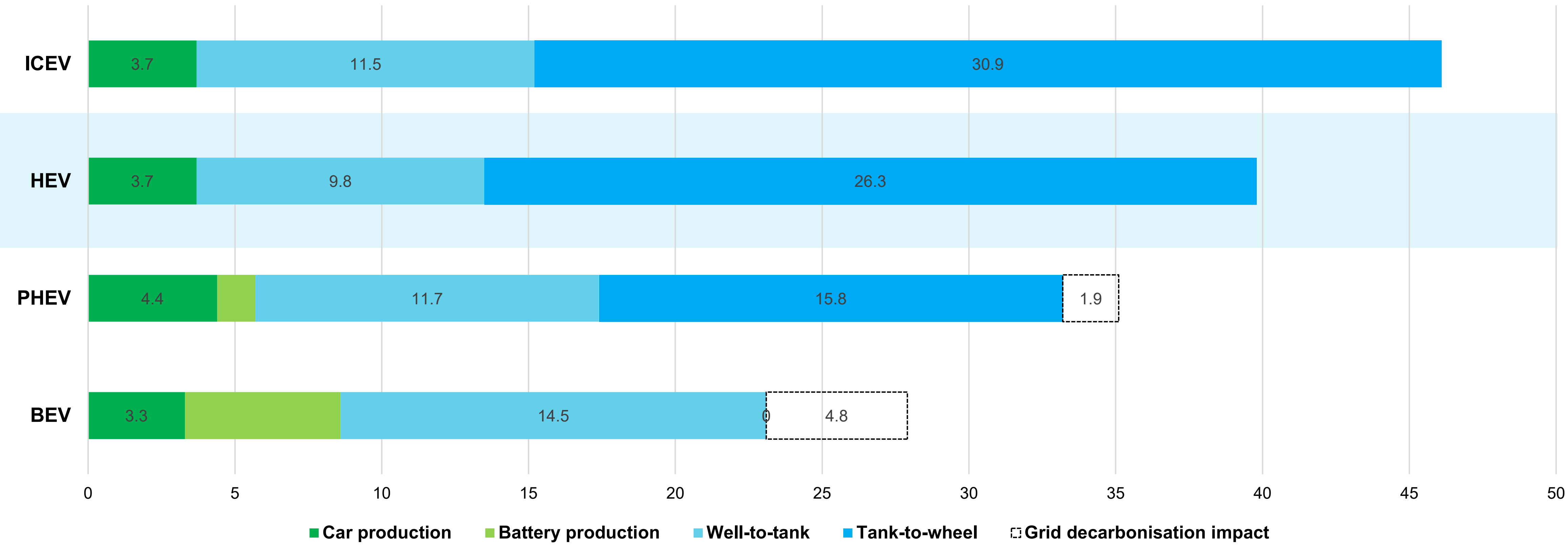
Note

- Fuel efficiency varies widely among HEV models depending on the size of their batteries and electric motors. Models with larger batteries and motors, often called "full" or "strong" hybrids, can store more electricity and deliver greater assistance to the gasoline engine, with some capable of running solely on electricity for short distances. On the other hand, "mild" hybrids, equipped with smaller batteries and motors, have a more limited impact on fuel economy. For the range shown based on the midsize HEVs of 2024 models in the U.S. only include full hybrids.

Source: IEA (2024d), DOE and EPA (2024b), IPCC (2006b), DOE (n.d. d)

[Reference] Lifecycle CO_2 emissions of HEVs

Lifecycle CO_2 emission, tCO_2-eq/vehicle

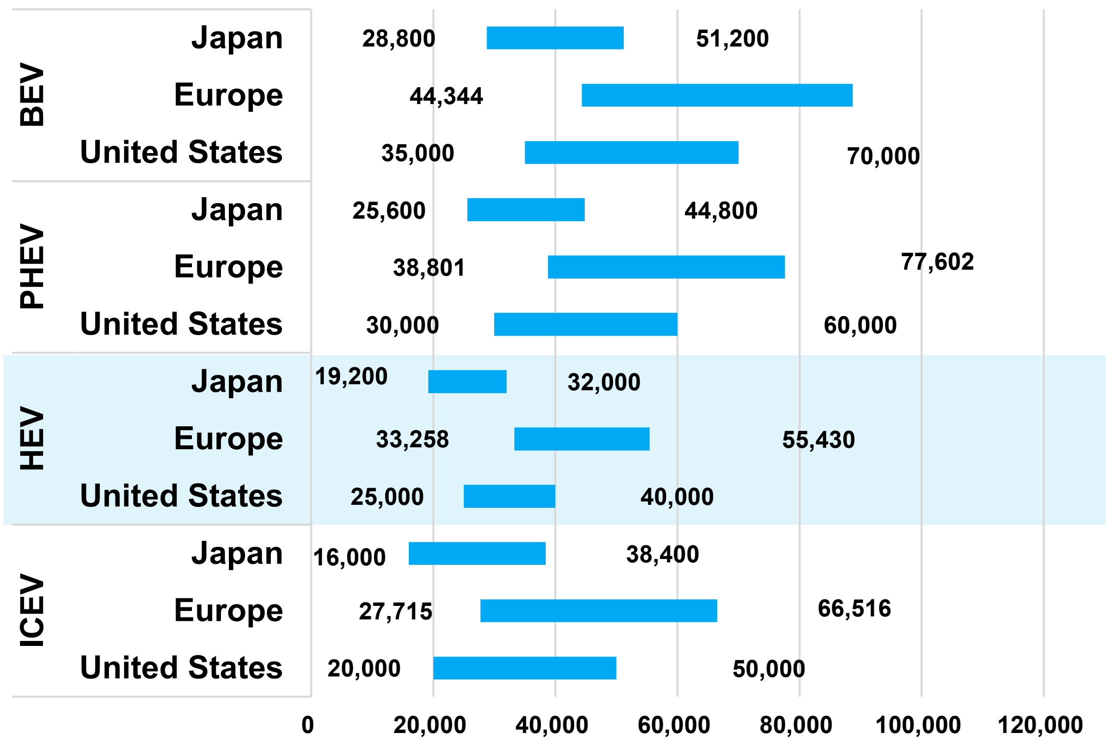


Notes:
1. The numbers are the global average lifecycle emissions by powertrain produced in 2023
2. "Grid decarbonisation impact" refers to the effect of electricity emissions intensity improvements over the lifetime of the vehicle. The years 2023 refer to the first year of use of the vehicle. For further details on the assumptions behind this lifecycle analysis, please see refer to "Global EV Outlook 2024" by IEA.

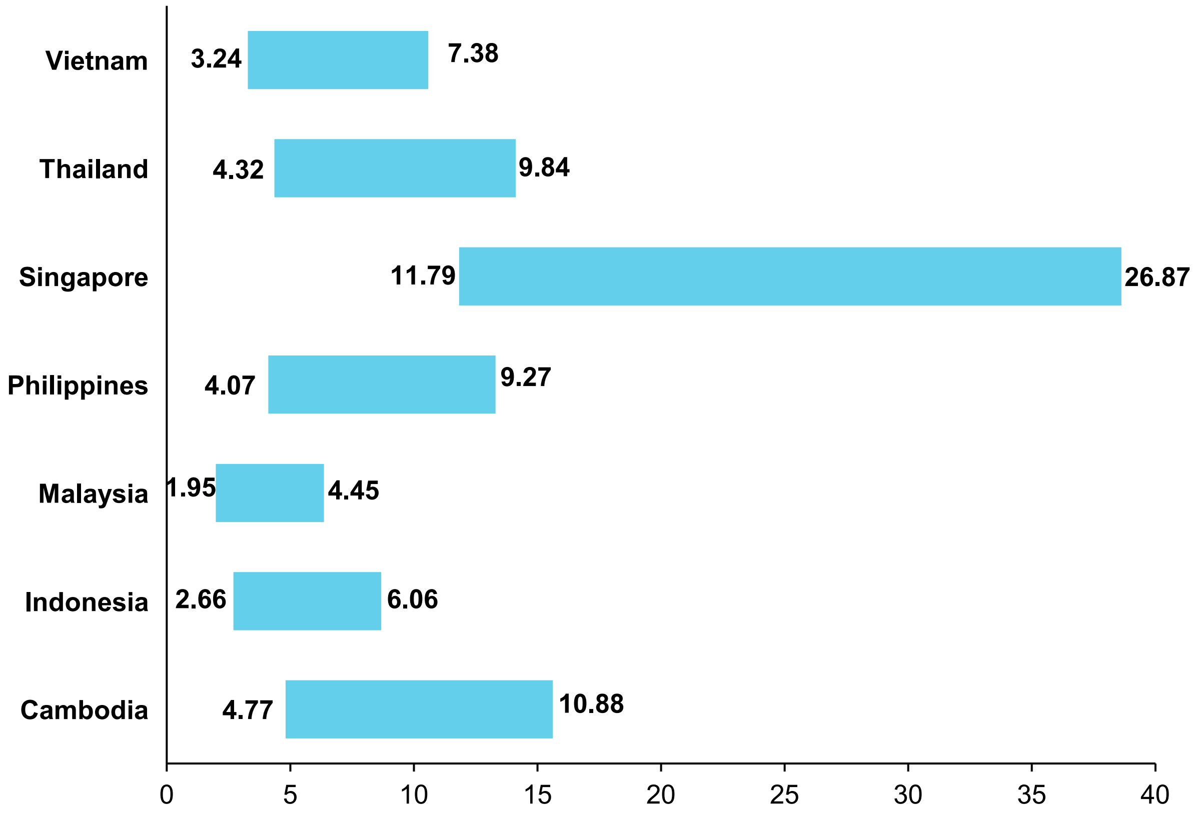
Source: IEA (2024d)

(5) Affordability – The cost of a medium-sized HEV tends to be more affordable than other electric alternatives, i.e. BEVs and PHEVs

Vehicle cost, USD/vehicle



Cost of fuel (gasoline), USD/100km



Sources: IEA (2024d), Toyota Motor (2024), Saunders, M. (2021) Autocar, Car and Driver (2024b), Mitsubishi Motors (n.d.) , Car and Driver (2024a), Trading Economics (2024), DOE and EPA (2024b)

[Reference] Methodologies: Affordability

Methodology: Vehicle cost

1. The calculation is based on prices for medium-sized vehicles, using the following exchange rates at 13/9/2024: JPY100 = USD0.64, and EUR1= USD1.1086. These prices are exclusive of any local taxes and subsidies.

Methodology: Cost of fuel (gasoline)

1. Fuel cost was calculated based on fuel economies of the midsize HEVs of 2024 models in the U.S. and gasoline prices of different ASEAN countries in Oct 2024 (USD/liter).

Sources: IEA (2024d), Toyota Motor (2024), Saunders, M. (2021) Autocar, Car and Driver (2024b), Mitsubishi Motors (n.d.) , Ca r and Driver (2024a), Trading Economics (2024), DOE and EPA (2024b)

(6) Reliability – Global sales of HEVs are increasing alongside the general trend of electrification

Estimated commercialisation status

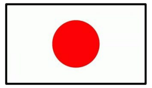
- TRL 11: HEVs are already at the commercial stage.

Recent utilisation examples

Global

- Driven by stringent environmental regulations in various countries, the electrification of powertrains is advancing in the automotive industry. Along with the expansion of the BEV market, HEVs and Mild Hybrid Electric Vehicles (MHEVs) are also seeing growth. Global sales in 2022 amounted to approx. 3.5 million units for HEVs, or almost 5.5 million units if MHEVs are also included.

Japan



- HEVs have become very popular, as evidenced by their rising sales in recent years. Prior to 2021, gasoline cars were the top-selling vehicles, but from 2022 onward, HEVs have surpassed them to become the most popular type of car by fuel type in Japan.

Source: MarkLines (2022), JADA (2024)

(7) Lock-in prevention – Transitioning to green fuel or e-fuel is essential for achieving net zero, but faces cost and infrastructure challenges

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Two paths exist for HEVs to achieve zero or near-zero emissions; – Path 1: Replace traditional gasoline with alternative fuels that are considered green such as biodiesel etc. – Path 2: Achieve net-zero emissions by using e-fuel to eliminate CO_2 emissions during operation.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• **Path 1: Replace traditional gasoline with alternative fuels that are considered green** – The production and infrastructure for green fuels often require significant upfront investment. For example, H_2 production through electrolysis is currently more expensive than traditional methods. Biodiesel technology is more mature, but it still faces challenges in terms of efficiency and scalability. – For biodiesel, sourcing sustainable feedstock (like used cooking oil or algae) can be challenging. Competing uses for these materials can drive up costs. • **Path 2: Achieve net-zero emissions by using e-fuel to eliminate CO_2 emissions during operation.** – E-fuel, or synthetic fuel, is produced by combining H_2 generated through water electrolysis using renewable energy with CO_2 captured from the air or industrial processes to create liquid fuels. – While e-fuels offer a promising path towards reducing CO_2 emissions, their energy-intensive production, high costs mainly due to the cost of H_2, infrastructure challenges, and competition from other technologies could hinder their role in achieving net-zero emissions.

Source: IEA (2019c), IRENA (2020), Ellis, T., R. Gerrish, and G. Michel (2024)

(8) DNSH considerations – The use of rare materials mainly for batteries can be an environmental concern and needs to be addressed

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• The production of lithium-ion batteries for HEVs requires extensive use of rare materials such as lithium, nickel, cobalt, and copper, leading to a higher impact on mineral resource consumption compared to ICEVs.
	Transition to circular economy	• **Battery Recycling and Second Life**: Efficient recycling processes for lithium-ion batteries are crucial. Repurposing used batteries for energy storage systems can extend their lifespan. • **End-of-Life Management**: Proper vehicle disposal and recycling are essential at the end of their life cycle. Consumers should be encouraged to return vehicles to authorised centres for responsible recycling. Extracting valuable materials, such as rare earth metals, from old components is important. • **Circular Supply Chains**: Manufacturers should focus on sustainable material sourcing, minimising production waste, and adopting closed-loop supply chains. Recycled materials should be incorporated into vehicle production.

Source: Pipitone, E.; Caltabellotta, S.; Occhipinti (2021), Patel AN, Lander L, Ahuja J, Bulman J, Lum JKH, Pople JOD, Hales A, Patel Y and Edge JS (2024)

(9) Social considerations – Impacts on employment are expected to be small

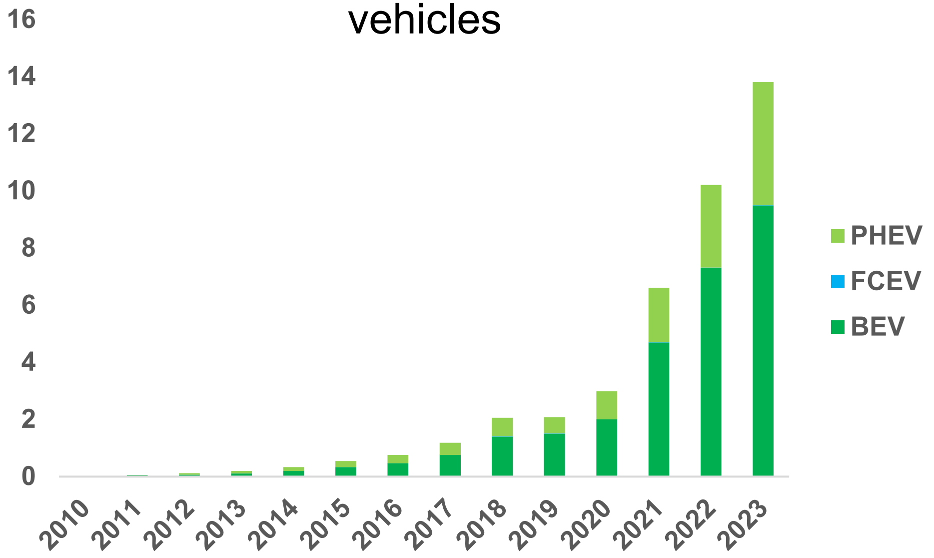
Framework dimensions	Considerations/ Key questions	Details
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Since HEVs retain most of the components of ICEVs, the impact on employment is less significant compared to BEVs. • Many existing automotive jobs related to ICEV production and maintenance remain relevant. • However, new roles are emerging in hybrid technology integration and maintenance, which will require specialised training. • HEVs produce less noise during an electric operation mode, it may contribute to reducing the noise pollution.

Source: Reuters (2024)

[Reference] Globally, sales of PHEVs and BEVs have increased, with some countries reaching very high shares of EV adoption

- In 2023, almost 14 million new electric cars were sold globally, with a 35% increase compared to 2022. BEVs represented 70% of these sales, with the remaining 30% being PHEVs and HFCVs.
- Sales of electric cars started from a low base but are growing quickly in many markets. Globally, around 1-in-4 new cars sold were electric in 2023. This share was almost 40% in China while it was approximately 20% in Europe.

Numbers of electric cars sold from 2010 to 2023, million vehicles

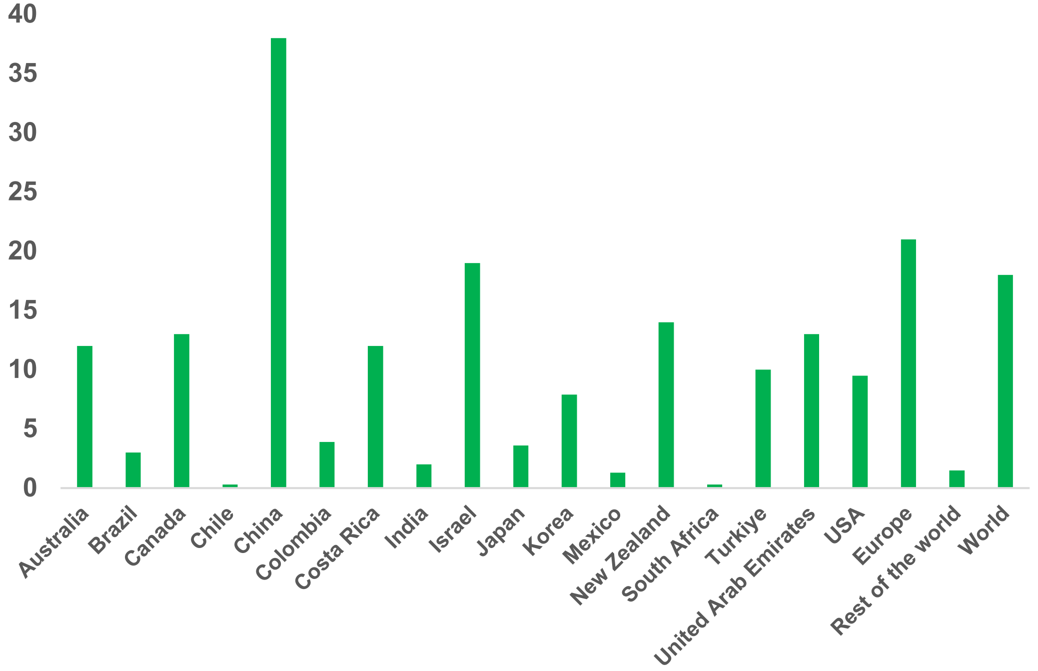


Notes:

1. Electric cars include BEVs and PHEVs.

Source: IEA (2024)

Shares of electric cars sold in 2023, %

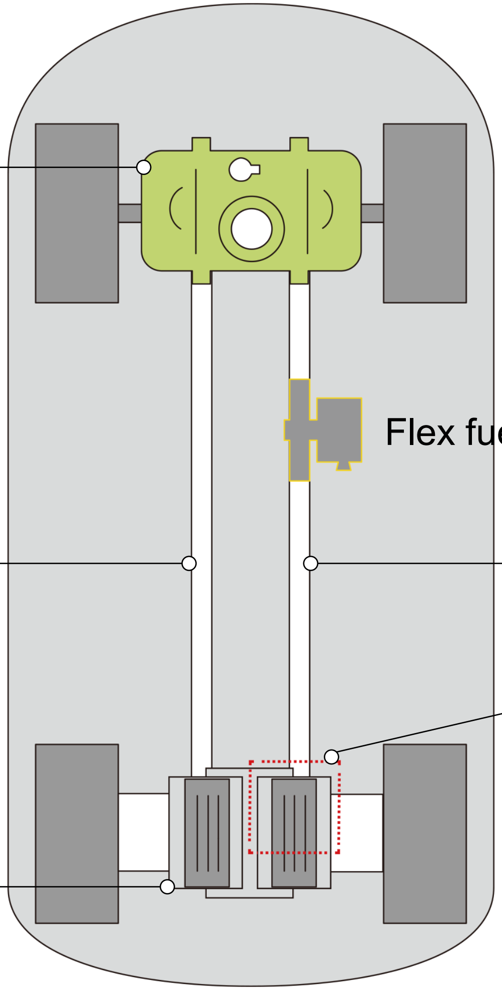


2. Electric cars include BEVs and PHEVs.

Source : IEA (2024)

Source: IEA (2024c)

(1) FFVs – Technology schematics and overview



Source: Author created based on various literature

FFV can operate on multiple fuels, primarily gasoline and ethanol blends. A key feature of FFV is their ability to use high-ethanol fuels like E85, which consists of 85% ethanol and 15% gasoline, making it a more environmentally friendly biofuel.

The main advantage of FFV is their contribution to reducing emissions. Using ethanol helps lower CO_2 emissions and reduces reliance on fossil fuels, as ethanol is produced from renewable sources. However, ethanol has a lower energy density than gasoline, meaning more fuel is needed to cover the same distance.

FFV also offer flexibility in handling various fuel mix ratios, enabling users to select the most cost-effective or accessible fuel depending on market conditions.

Source: DOE (n.d. c), DOE (n.d. a)

(2) FFVs – Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• When flex fuel vehicles (FFV) use E85, i.e., a fuel blend containing 85% ethanol and 15% gasoline, ethanol-blended fuel, they can reduce CO_2 emissions by up to around 68% compared to conventional vehicles. • However, in cold or cool conditions, they may be less efficient than petrol vehicles because they use energy to heat the fuel. Additionally, due to lower fuel efficiency compared to petrol, refueling may be required more frequently.
Affordability	• FFV has a CO_2 reduction cost of USD 158-227/ tCO_2 when using E85 ethanol-blended fuel, compared to a conventional petrol-powered vehicle.
Reliability	• FFV are already at the commercial stage, their TRL is assumed to be 9. • Brazil has introduced FFVs since 2003 and achieved a cumulative reduction of 630 million tCO_2 emissions by 2022. • In Indonesia, Pertamina and Toyota tested 100% bioethanol fuel from sorghum.
Lock-in prevention considerations	• Path 1: Utilise low-emission bioethanol production methods, such as biomass or waste-based bioethanol production and bioenergy with carbon capture and storage (BECCS) technology, to minimise CO_2 emissions. • Path 2: Shift away from fossil fuel by adopting renewable energy and efficient manufacturing in vehicle production. • Path 3: Reduce the ratio of gasoline in the blended fuel and increase the proportion of CO_2-free bioethanol.
DNSH considerations	• The expansion of large-scale sugarcane, palm oil, and corn production for cultivation may lead to the destruction of rainforests or grassland ecosystems and result in the conversion of forest areas into farmland. • To develop sustainable biofuel sources, ethanol production from agricultural waste or non-food biomass is essential.
Social considerations	• E85 increases acetaldehyde emissions. To prevent people from absorbing acetaldehyde and becoming ill, improvements in technology and stricter emission regulations are necessary. • Biofuel production involving rural communities creates jobs and boosts the local economy, as seen in Brazil with over 1.5 million jobs in 2019.

(3) ASEAN Taxonomy – Relevant technical screening criteria

Urban and suburban transport, road passenger transport

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	1. The activity complies with one or all of the following criteria: a. The activity provides urban or suburban passenger transport, and its direct (tailpipe) CO_2 emissions are zero; AND b. Until 31 December 2030, the Activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD and comply with the latest EURO VI Standard.
	Tier 2 (Amber T2)	1. The activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD; AND 2. Until 31 December 2030, comply with the latest EURO V Standard.
Excludes -	**Tier 3 (Amber T3)**	1. The activity provides interurban passenger road transport using vehicles designated as categories M2 and M3 that have a type of bodywork classified as CA, CB, CC, CD; AND 2. Until 31 December 2030, comply with the latest EURO IV Standard.

Source: ASEAN Taxonomy Body (2024), “ASEAN taxonomy for sustainable finance”, https://www.sfinstitute.asia/wp-content/uploads/2024/07/ASEAN_Taxonomy_Version_3.pdf (Last accessed 15/11/2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Transport by motorbikes, passenger cars and light commercial vehicles

Eligibility	Climate Change Mitigation TSC	Details
Includes - **Excludes** -	**Tier 1 (Green)**	1. The activity compiles with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2025, direct emissions of CO_2 are < 50 gCO_2-eq/v-km ii. From 1 January 2026, direct emissions of CO_2 are 0 gCO_2-eq/v-km; b. For vehicles of category L, tailpipe CO_2 emissions are 0 gCO_2-eq/v-km
	Tier 2 (Amber T2)	1. The activity compiles with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2030, direct emissions of CO_2 are < 50 gCO_2-eq/v-km
	Tier 3 (Amber T3)	1. The activity complies with the following criteria: a. For vehicles of category M1 and N1: i. Until 31 December 2030, direct emissions of CO_2 are < 100 gCO_2-eq/v-km

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Freight transport services by road

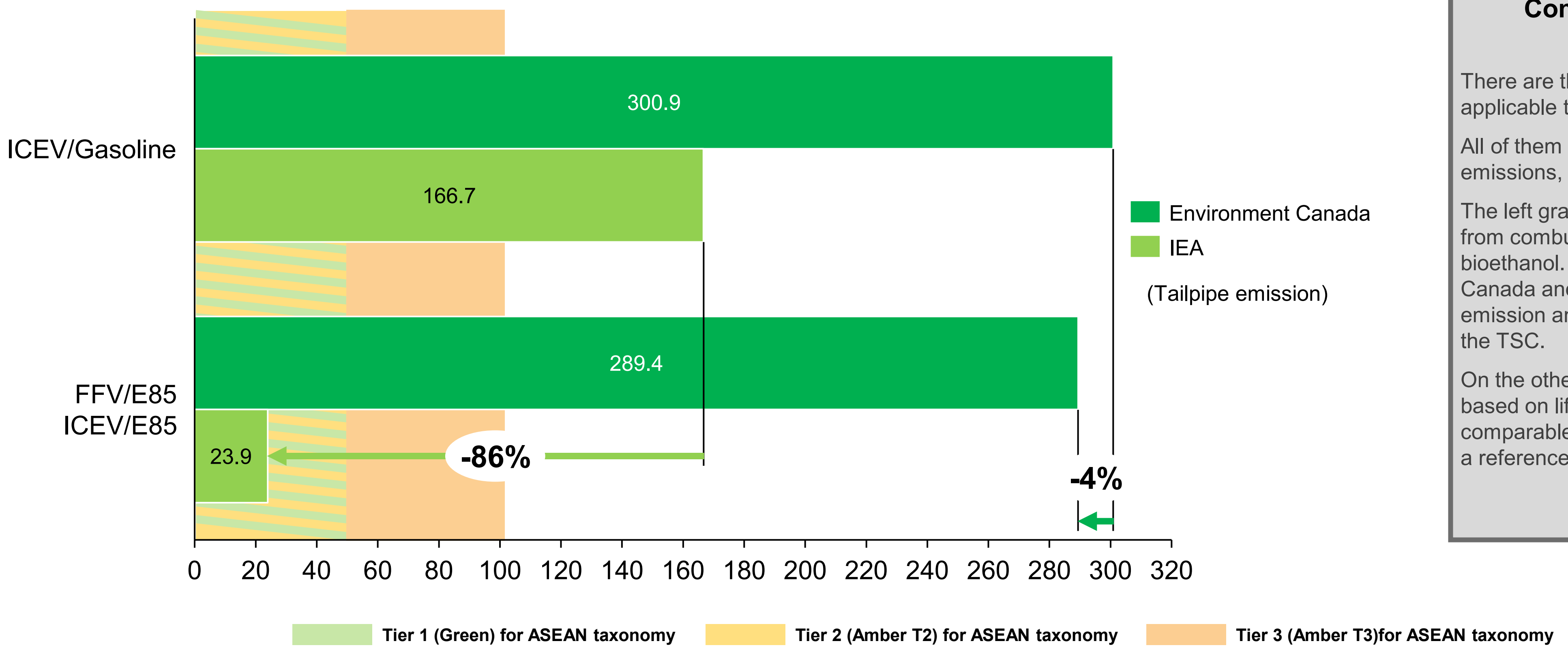
Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	1. The activity complies with one of the following criteria: a. vehicles of category N1 have zero direct (tailpipe) CO_2 emissions; b. vehicles of category N2 and N3[1] with a technically permissible maximum laden mass not exceeding 7.5 tonnes are 'zero-emission heavy-duty vehicles'; c. vehicles of category N2 and N3 with a technically permissible maximum laden mass exceeding 7.5 tonnes are one of the following: i. Zero-emission heavy-duty vehicle; OR ii. where technologically and economically not feasible to comply with the criterion in point (i), until 31 December 2030 have direct (tailpipe) CO_2 emissions less than 21 gCO_2/t-km[2]; AND 2. Vehicles are not dedicated to the transport of fossil fuels.
Excludes	**Tier 2 (Amber T2)**	1. The activity complies with one of the following criteria: a. vehicles of category N2 and N3 with a technically permissible maximum laden mass exceeding 7.5 tonnes are one of the following: i. where technologically and economically not feasible to achieve zero emissions, until 31 December 2030, have direct (tailpipe) CO_2 emissions less than 42 gCO_2-eq/t-km, and 1 January 2031 onwards, less than 21 gCO_2-eq/t-km; AND 2. Vehicles are not dedicated to the transport of fossil fuels.
	Tier 3 (Amber T3)	• No TSC available.

Notes:
1. N1: Vehicles for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes; N2: Vehicles for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes; N3: Vehicles for the carriage of goods and having a maximum mass exceeding 12 tonnes
2. Based on the current difference between emissions projections for freight activity by the CBI (18gCO_2-eq/t-km by 2050) and IEA NZE (18gCO_2-eq/t-km by 2040), it is proposed to have a forward outlook with a horizon date of 2030; indicative of reviewing the TSC at the period and potentially amending the threshold based on new emissions data in the future.

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition –FFV/E85 can reduce CO_2 emissions by up to 86% compared to conventional vehicles

Emissions, gCO_2 -eq/km



Tier1 to Tier3 refers to Climate Change Mitigation TSC for Production of Transport by motorbikes, passenger cars and light commercial vehicles. Tier 1 applies in two stages: until 31 December 2025, direct CO2 emissions must be less than 50 gCO2-eq/v-km; from 1 January 2026, the requirement becomes stricter, allowing only 0 gCO2-eq/v-km.

Comparison with ASEAN Taxonomy

There are three TSCs which are potentially applicable to FFVs.

All of them set thresholds on direct (tailpipe) emissions, and NOT lifecycle emissions.

The left graph shows GHG emissions derived from combustion of a fuel mix of gasoline and bioethanol. Data from the Environment Canada and IEA are based on tailpipe emission and thus those are comparable to the TSC.

On the other hand, the data from ePURE are based on lifecycle emissions and are not comparable to the TSC. Those are shown for a reference purpose only.

Source: Environment Canada (2005), IEA (2010), Bunse, M., L. Mulder, E. van den Heuvel, L. Knotter and C. Hamelinck (2022), Greenhouse Gas Protocol (n.d.)

[Reference] Methodologies: Contribution to Energy Transition

Methodology: Emissions

1. CO_2 emissions for Environment Canada are based on Composite data, which is calculated by combining phases 1 to 3.
   →Phase1(cold engine start) , Phase3(hot engine start) : average speed 41.1 km/h, maximum speed 91.1 km/h, Distance covered 5.8 km in 505 seconds
   →Phase2(stabilised operation) : average speed 25.8 km/h, maximum speed 55.1 km/h, Distance covered 6.2 km in 865 seconds
2. To convert to the same gCO_2-eq/km as other document, CH_4[1] and N_2O[2] emissions were converted to CO_2 and added to the CO_2 emissions.
3. The WTW (Well-to-Wheel) values were used to account for emissions generated during fuel production, but Environment Canada's data is based on driving test data, so it follows the TTW (Tank-to-Wheel) standard.
4. The CO_2 emissions data from the IEA is based on medium-size cars. Although the CO_2 reduction rates differ significantly among the three documents, the definition of vehicle class is unclear across them.
5. E85 is a gasoline blend with 85% bioethanol by volume.
6. Calculated from Base Energy Consumption (Liter/km) and GHG emissions of WTW (gCO_2-eq/km) for comparison with other documents.
7. Greenhouse gas impacts (gCO_2-eq/ MJ) is converted to gCO_2-eq/Liter for comparison with other documents.

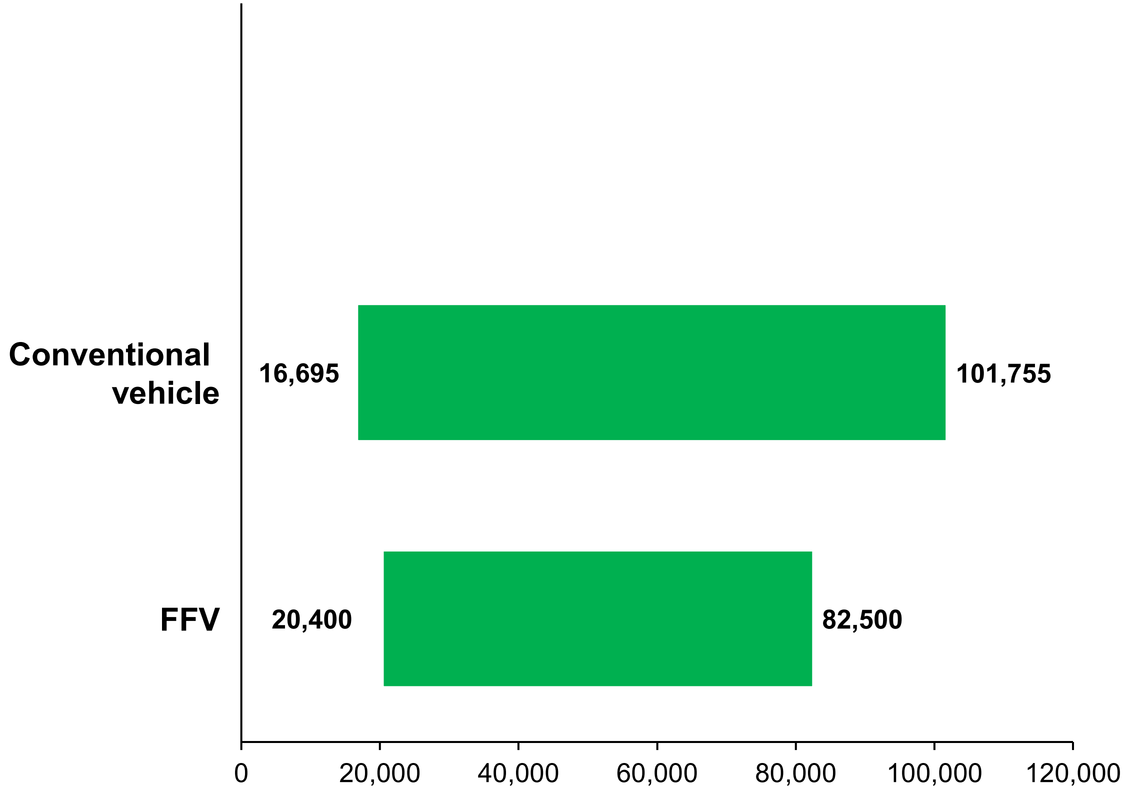
Reference values for CO_2 emissions	Environment Canada	IEA
Energy consumption of ICEV fuelled by gasoline only (Medium cars) (Litre/km)	0.13	0.072
Energy consumption of FFV (Medium cars) (Litre/km)	0.17	0.105
Gasoline GHG impacts (gCO_2-eq/Litre)	2,391.9	2,315.3
E85 (E20, E10) GHG impacts (gCO_2-eq/Litre)	1,697.8	227.6

Notes:
1. CH_4 = Methane
2. N_2O = Nitrous oxide

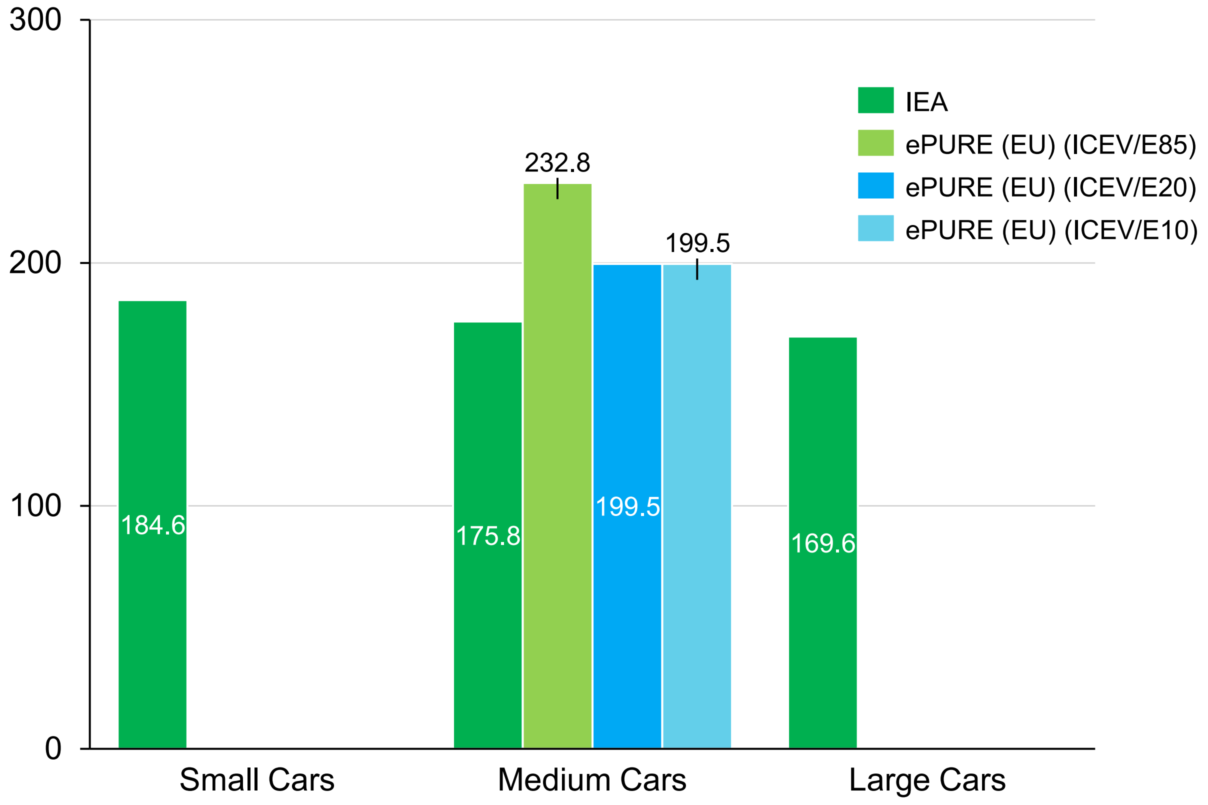
Source: Environment Canada (2005), IEA (2010), Bunse, M., L. Mulder, E. van den Heuvel, L. Knotter and C. Hamelinck (2022), Greenhouse Gas Protocol (n.d.)

(5) Affordability – FFV/E85 has a CO_2 reduction cost of USD158-227/ tCO_2

Initial cost, USD/vehicle



Abatement costs per CO_2 reduction, USD/tCO_2-eq



Source: IEA (2010), Bunse, M., L. Mulder, E. van den Heuvel, L. Knotter and C. Hamelinck (2022), USDA Foreign Agricultural Service (2024), Google Finance (2024), Praiwan, Y. (2024) Bangkok Post, Oak Ridge National Laboratory, on behalf of DOE and EPA (n.d.), Thai Driver License Service (n.d.)

[Reference] Methodologies: Affordability

Methodology: Vehicle cost

		MSRP(manufacturer's suggested retail price, USD)	Registration fee(USD)	Initial cost(USD)
Conventional vehicle	min	16,695	30.1	16,725
	max	101,755	210.7	101,966
FFV	min	20,400	30.1	20,430
	max	82,500	210.7	82,711

1. The ePURE (EU) E10 and E20 use ICEVs. E85 is also calculated assuming a vehicle with a flex fuel sensor added to the ICEV, not an FFV.
2. Exchange rate = USD1.1086/EUR
3. The initial cost includes the vehicle price and registration fees.= Extra costs compared to conventional vehicle / lifecycle CO_2 saving compared to conventional vehicle.

Methodology: Abatement cost per CO_2 reduction

Reference values for comparison of abatement cost per CO_2 reduction in Medium Cars	IEA	ePURE (EU)
Energy costs of gasoline (USD/Liter)	1.45	0.56
Energy costs of E85 (E10, E20) (USD/Liter)	1.14	E85：0.65 E20：0.58 E10：0.57
Energy consumption of conventional vehicle (Medium Cars) (Liter/km)	0.072	0.054
Energy consumption of FFV (Medium Cars) (Liter/km)	0.105	0.072
CO_2 and other GHG emissions of conventional vehicle (Medium Cars, WTW) (gCO_2-eq/km)	196.4	159.6
CO_2 and other GHG emissions of FFV/E85 (ICEV/E10, E20) (Medium Cars, WTW) (gCO_2-eq/km)	108.1	E85：50.3 E20：134.2 E10：146.9

1. Abatement costs were calculated by using Thai fuel price as of September 2024. Biofuels are cheaper than gasoline in Thailand due to subsidy support from the Oil Fuel Fund Office(OFFO). The programme was originally scheduled to end in 2019 but was extended due to the pandemic, and it will be extended until 2026.
2. The IEA's extra costs only include fuel costs (energy costs × energy consumption), since capital costs and O&M costs are equivalent to those for conventional vehicles.
3. The cost of ePURE (EU) includes vehicle purchase, fuel, maintenance, and insurance.
4. The ePURE (EU) E10 and E20 use ICEVs. E85 is also calculated assuming a vehicle with a flex fuel sensor added to the ICEV, not an FFV.

Source: IEA (2010), Bunse, M., L. Mulder, E. van den Heuvel, L. Knotter and C. Hamelinck (2022), USDA Foreign Agricultural Service (2024), Google Finance (2024), Praiwan, Y. (2024) Bangkok Post, Oak Ridge National Laboratory, on behalf of DOE and EPA (n.d.), Thai Driver License Service (n.d.)

[Reference] Price Structure of Gasoline and Gasohol in Bangkok (2023 & 2024)

April 19, 2023(USD/Liter)	Premium Gasoline (octane 95)	Gasohol			
		E10 Octane 95	E10 Octane 91	E20	E85
Ex-Refinery Factory Price	0.6731	0.6769	0.6640	0.6870	0.8157
Excise Tax	0.1957	0.1761	0.1761	0.1565	0.0293
Municipal Tax	0.0196	0.0176	0.0176	0.0157	0.0029
State Oil Fund	0.2583	0.0602	0.0602	0.0003	0.0003
Conservation Fund	0.0015	0.0015	0.0015	0.0015	0.0015
Wholesale Price (WS)	1.1481	0.9323	0.9194	0.8613	0.8498
Value Added Tax (VAT)	0.0804	0.0653	0.0643	0.0603	0.0595
WS+VAT	1.2285	0.9976	0.9838	0.9213	0.9093
Marketing Margin	0.1194	0.1156	0.1208	0.1219	0.1457
VAT	0.0084	0.0081	0.0085	0.0085	0.0102
Retail Price	1.3563	1.1212	1.1131	1.0517	1.0652

Note: 1. Exchange rate = USD0.0301/baht
Source : Petroleum Division, Energy Policy and Planing Office, Ministry of Energy

April 19, 2024(USD/Liter)	Premium Gasoline (octane 95)	Gasohol			
		E10 Octane 95	E10 Octane 91	E20	E85
Ex-Refinery Factory Price	0.7540	0.7509	0.7372	0.7593	0.8832
Excise Tax	0.1957	0.1761	0.1761	0.1565	0.0293
Municipal Tax	0.0196	0.0176	0.0176	0.0157	0.0029
State Oil Fund	0.2823	0.0843	0.0527	0.0244	0.0048
Conservation Fund	0.0015	0.0015	0.0015	0.0015	0.0015
Wholesale Price (WS)	1.2530	1.0304	0.9851	0.9574	0.9218
Value Added Tax (VAT)	0.0877	0.0721	0.0690	0.0670	0.0645
WS+VAT	1.3408	1.1025	1.0540	1.0244	0.9863
Marketing Margin	0.1040	0.1047	0.1087	0.1184	0.1469
VAT	0.0073	0.0073	0.0076	0.0083	0.0103
Retail Price	1.4520	1.2145	1.1703	1.1510	1.1435

Note: 1. Exchange rate = USD0.0301/baht

The ex-refinery factory price of gasohol is higher than that of gasoline, but due to tax incentives and subsidies, the retail price is reversed.

Source: USDA Foreign Agricultural Service (2024)

[Reference] Conversion systems available for an affordable price in the U.S.

Conversion systems in the U.S.

In the U.S., the EPA has established a certification programme for conversion systems that enable ICEVs to operate on alternative fuels not originally intended by their design. The EPA maintains and publicly shares a list of these certified conversion systems on its website, promoting the adoption of lower-emission fuel options among vehicle owners. Expert insights gathered during our research suggest that the installation cost of a certified conversion system is approximately USD 500 per unit, presenting an accessible and cost-effective solution for vehicle owners interested in reducing their carbon footprint.

Source: EPA (2024)

(6) Reliability – Brazil and Indonesia plan to promote the widespread use of bioethanol fuel

Estimated commercialisation status

- TRL 9: FFV are already at the commercial stage.

Recent project examples

Details

Brazil introduced FFVs in 2003

- Brazil, the world's largest producer of bioethanol made from sugar cane, has introduced FFVs since 2003, and as of 2023, 97% of Toyota's domestically produced vehicles will be FFVs.
- The introduction of FFVs has reduced gasoline use in the transportation sector by 41.7% and CO_2 emissions by 630 million tons by 2022.

Pertamina and Toyota test 100% bioethanol fuel from sorghum

- Pertamina and Toyota tested 100% bioethanol (E100) fuel, produced from sorghum, at GIIAS(Gaikindo Indonesia International Auto Show) 2024. The test involved Toyota's FFV and demonstrated significantly reduced emissions compared to fossil fuels.
- Meanwhile, in Indonesia, Pertamina is also implementing an FFV with 5% bioethanol content (E5) which brings the potential to lower annual CO_2 emissions by 2.8 million tonnes, equivalent to 1.9% of Indonesia's total emissions.
- This trial supports Indonesia's carbon neutrality goal by 2060, aligning with Pertamina's efforts to expand bioethanol production and promote sustainable energy solutions.

Source: Toyota Motor (2023), Pertamina (2024)

(7) Lock-in prevention –Low-cost bioethanol and its manufacturing process offer a low-emission alternative but face high initial costs and technological challenges

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	There are three paths exist for FFV to achieve zero or near-zero emissions. • Path 1: Utilise low-emission bioethanol production methods, such as biomass or waste-based bioethanol production and BECCS technology, to minimise CO_2 emissions. • Path 2: Shift away from fossil fuel by adopting renewable energy and efficient manufacturing in vehicle production. • Path 3: Reduce the ratio of gasoline in the blended fuel and increase the proportion of CO_2 -free bioethanol.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path1: Utilise low-emission bioethanol production methods, such as biomass or waste-based bioethanol production and BECCS technology, to minimise CO_2 emissions. – High initial development costs and low technological maturity could hinder this transition. If commercialisation proves difficult, there is also a risk that sustained investment may not materialise. – BECCS also requires significant installation costs, lacks large-scale commercialisation examples, and requires careful consideration of the sustainability of feedstock supply. • Path2: Shift away from fossil fuel by adopting renewable energy and efficient manufacturing in vehicle production. – Replacing energy sources with renewables may face resource and supply stability challenges. If the related technologies are not sufficiently mature, the implementation could be delayed. • Path3: Reduce the ratio of gasoline in the blended fuel and increase the proportion of CO_2 -free bioethanol. – Production and distribution costs must decrease to lower the cost of bioethanol-blended fuel make it more competitive as compared with gasoline and diesel. Technological maturity and supply chain agreements play a crucial role in achieving this.

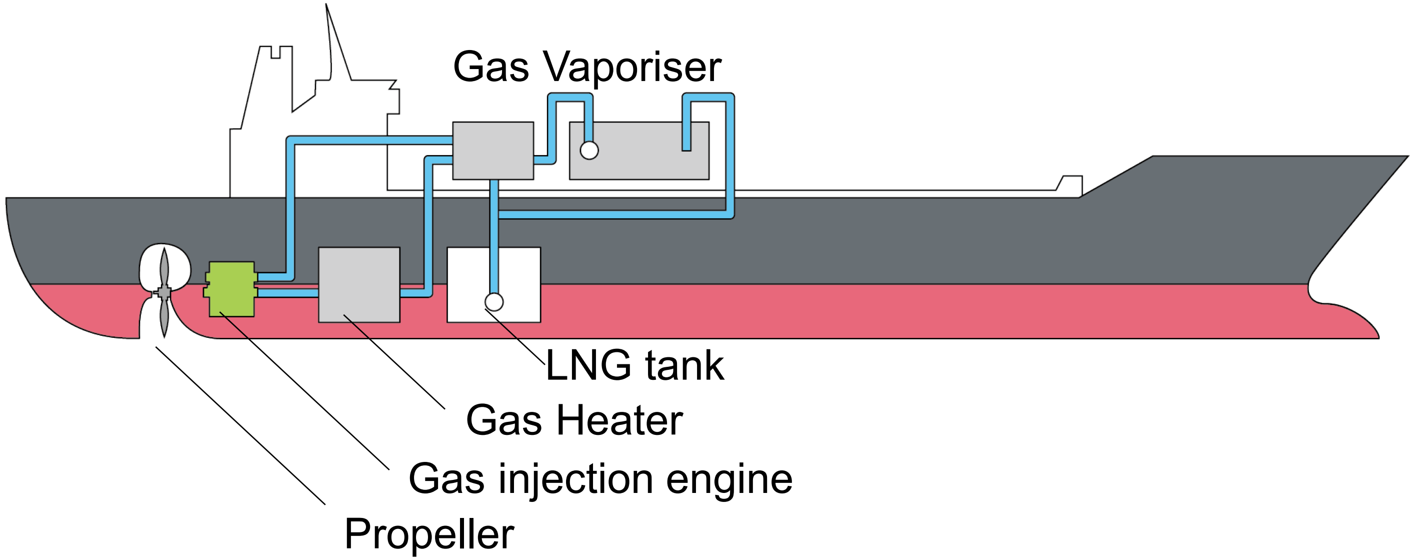
Source: Sarisky-Reed, V. (2022) DOE, ASEAN (2019), Interview with Mr. Giorgio Martini, Deputy Head of Unit of Sustainable, Smart and Safe Mobility Unit Directorate for Energy, Mobility and Climate, Joint Research Centre of the European Commission on 11/11/2024.

(8)(9) DNSH/social considerations – Producing ethanol from agricultural waste or non-food biomass minimises environmental impact and contributes to job creation

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• The expansion of sugarcane, palm oil, and corn production may lead to large-scale deforestation and conversion of forest areas into farmland. This process reduces the number of forests that naturally absorb carbon, leading to increased GHG emissions. Therefore, sustainable farming methods should be adopted, and habitats should be restored to ensure that ecosystems are managed without causing harm. • The use of ethanol as fuel can lead to increased emissions of specific pollutants, such as acetaldehyde and formaldehyde. However, this issue can be significantly mitigated with the use of efficient catalysts.
	Promotion of transition to circular economy	• Bioethanol should be produced from sustainable resources such as waste, agricultural residues, or non-food crops (e.g., switchgrass). This minimises waste, reduces environmental impact, and promotes the recycling of resources, helping to prevent the depletion of natural resources. • It is also necessary to make efforts to recycle or convert discarded vehicle parts into fuel.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• The combustion of ethanol increases acetaldehyde emissions, a substance classified as 'reasonably anticipated to be a human carcinogen.' While the overall risk is relatively small, reducing health impacts requires improvements in fuel composition, catalytic converters, engine technology, and stricter emission regulations. • Acetaldehyde also contributes to ground-level ozone formation, which can worsen air pollution and respiratory issues. To address this, advancements in emissions control and air quality management are needed. • Involving rural residents in the biofuel production process helps create jobs and revitalise the rural economy. In Brazil, as of 2019, over 1.5 million direct and indirect jobs were created, contributing to the improvement of residents' living standards.

Source: DOE (n.d. b), Forslund, T. (2022) WEF, Graciosa, E. (2024) AgriBrasilis, IEA Bioenergy (2021), Interview with Mr. Giorgio Martini, Deputy Head of Unit of Sustainable, Smart and Safe Mobiiity Unit Directorate for Energy, Mobility and Climate, Joint Research Centre of the European Commission on 11/11/2024.

(1) LNG Fuelled ship – Technology schematics and overview



Source: Author created based on various literature

LNG-fuelled ships use liquefied natural gas (LNG) as their primary fuel. LNG consists mainly of methane (CH_4), a hydrocarbon with the lowest carbon content, offering significant potential for CO_2 emission reduction.

Compared to conventional heavy oil fuelled ship, LNG fuelled ships are structurally different in that their engines are designed for LNG and they are equipped with a methane gas reliquefication device.

When using LNG fuelled ships, facilities for bunkering LNG fuel to the ships are required, and the introduction of bunkering facilities is progressing in major transport hubs.

Source: Burke, J. (2017) Power Progress

(2) LNG Fuelled ship – Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• LNG fuelled ships can reduce CO_2 emissions by more than 20% compared to diesel and heavy oil.
Affordability	• LNG fuelled ship is more expensive to build than conventionally fuelled ships, but cheaper to operate.
Reliability	• LNG fuelled ship: TRL 9-10, In 2024 there were more than 2,400 vessels equipped to operate on LNG globally.
Lock-in prevention considerations	• Path 1: Shift to carbon-free fuels and add decarbonised technologies.
DNSH considerations	• LNG fuelled ships release much less NO_x and sulfur oxide (SO_x) compared to ships using heavy oil. • NO_x and SO_x can cause acid rain, harming ecosystems, but LNG fuelled ships help reduce these emissions. • International agreements, such as the Hong Kong Convention, require banning harmful substances such as asbestos and polychlorinated biphenyls (PCBs), and setting up recycling systems for ships.
Social considerations	• It is necessary to provide education and training on the handling of natural gas, a gaseous fuel, to operators who have been using liquid fossil fuels.

(3) ASEAN Taxonomy – Relevant technical screening criteria

Sea and coastal freight water transport, vessels for port operations and auxiliary activities (1/2)

Eligibility	Climate Change Mitigation TSC	Details
Includes - **Excludes** -	**Tier 1 (Green)**	1. The activity complies with one of the following criteria: a. the vessels have zero direct (tailpipe) CO_2 emissions; OR b. b. until 31 December 2027, hybrid and dual fuel vessels derive at least 25% of their energy from zero direct (tailpipe) CO_2 emission fuels or plug-in power for their normal operation at sea and in ports; OR c. where technologically and economically not feasible to comply with the criterion in point (a), until 31 December 2027, and only where it can be proved that the vessels are used exclusively for operating coastal and short sea services designed to enable modal shift of freight currently transported by land to sea, the vessels have direct (tailpipe) CO_2 emissions 13% below the AER[1] trajectories from IMO2023; OR d. where technologically and economically not feasible to comply with the criterion in point (a), until 31 December 2027, the vessels have an attained EEDI[2] /EEXI[3] value 10% below the EEDI/EEXI requirements applicable on 1 January 2023 if the vessels are able to run on zero direct (tailpipe) CO_2 emission fuels or on fuels from renewable sources; AND 2. Vessels are not dedicated to the transport of fossil fuels.

Notes:
1. AER: Annual Efficiency Ratio
2. EEDI: Energy Efficiency Design Index
3. EEXI: Energy Efficiency Existing Ship Index

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

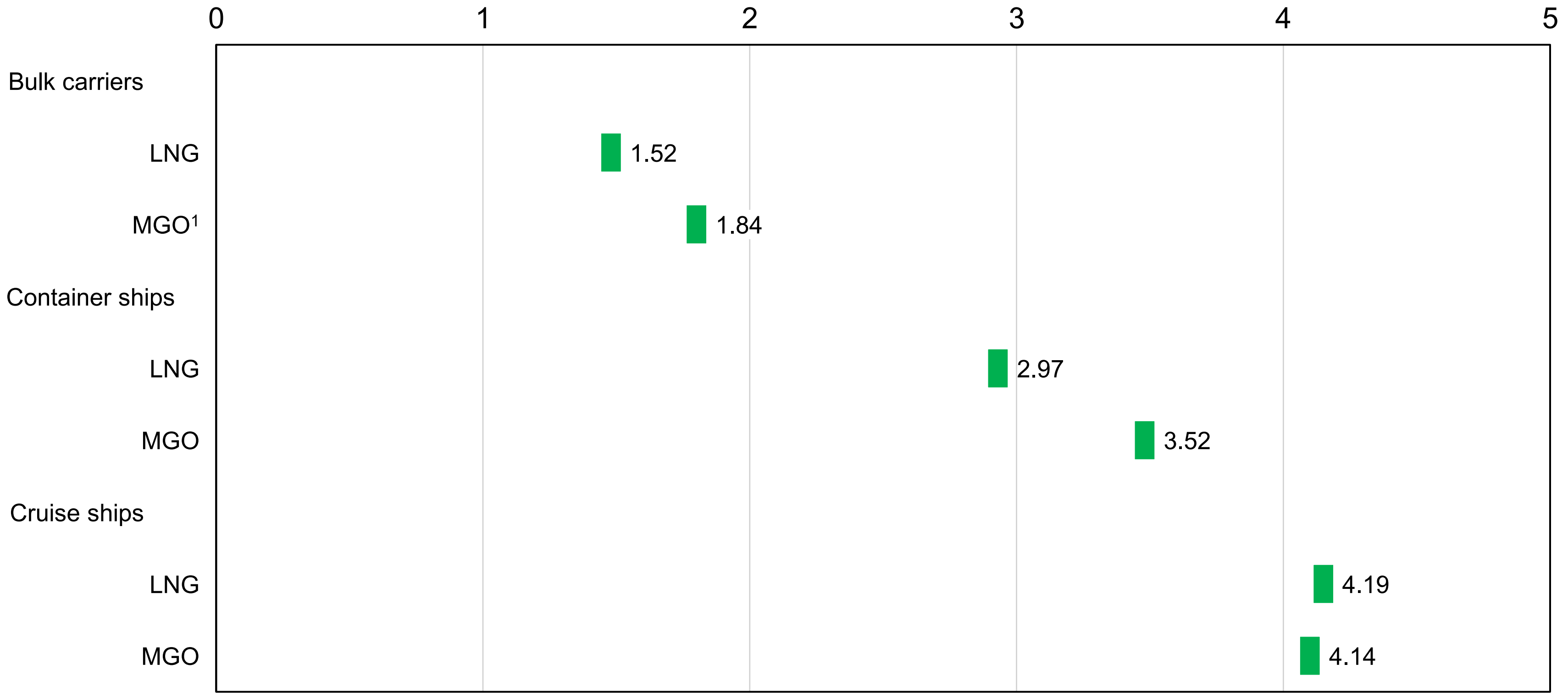
Sea and coastal freight water transport, vessels for port operations and auxiliary activities (2/2)

Eligibility	Climate Change Mitigation TSC	Details
Includes - **Excludes** -	**Tier 2 (Amber T2)**	1. The activity complies with one of the following criteria: a. a. Until 1 January 2030, vessels must be capable of using zero direct CO_2 tailpipe emission fuels; AND will derive at least 50% of their energy from renewable fuels; OR b. b. Until 31 December 2030, vessels meet the same TSC as Green criterion 1.c. or criterion 1.d.; AND 2. Vessels are not dedicated to the transport of fossil fuels
	Tier 3 (Amber T3)	• No TSC available.

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition - LNG fuelled ship can reduce CO_2 emissions by 20% compared to a diesel fuelled ship

Lifecycle CO_2 emissions, $kgCO_2$-eq/tonne-km



Comparison with ASEAN Taxonomy

There is one TSC which is potentially applicable to LNG fuelled ships.

The TSC for sea and coastal freight water transport, vessels for port operations and auxiliary activities sets thresholds on tailpipe emission, which has to be zero to be labelled as "Green", or a percentage of zero-emission fuels/ plug-in power in a fuel mix to be labelled as "Amber". A percentage of zero emission fuel or plug-in power in a fuel mix depends on operation and not ship technology itself. Therefore the direct comparison with TSC is not available for this technology. When assessing an LNG-ship project, a financial institution would have to look at an operation plan of each ship to see how much zero emission fuel would be mixed. Therefore the TSC was not applied to the left graph.

Notes:

1. MGO: Marine Gas Oil

Source: Kanchiralla, F.M., S. Brynolf, and A. Mjelde (2024)

[Reference] Methodologies: Contribution to Energy Transition

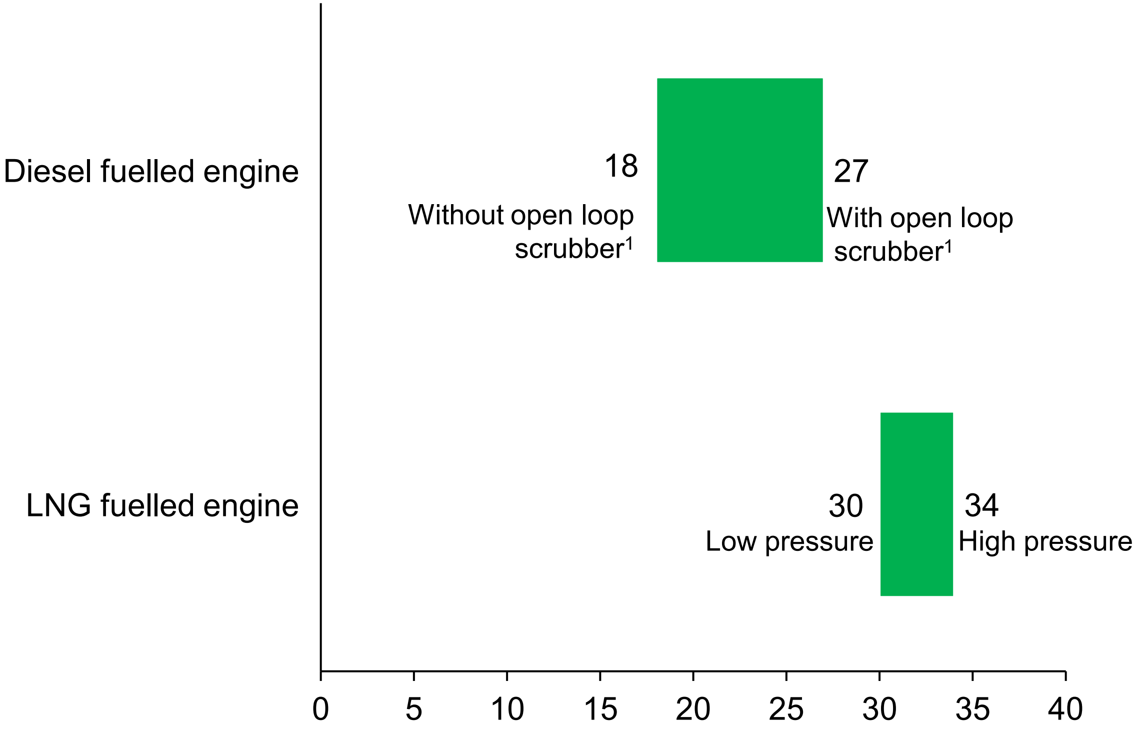
Methodology: Lifecycle CO_2 emissions

1. The level of CO_2 emission reduction depends on the type of ship, operating conditions, type of engine selected, and other factors.
2. The graph compares the lifecycle CO_2 emissions for three types of ships. The lifecycle CO_2 emissions include ship building emission, ship operation emission, fuel consumption and fuel product emission.
3. The CO_2 emissions are calculated for three ship types based on operational data and ship-specific build data. "Tonne" of "kgCO_2 -eq/tonne-km" refers to DWT (Deadweight Tonnage) for bulk carriers and container ships, and GT (Gross Tonnage) for cruise ships. The maximum values for each fuel type assume the use of ICEs, while the minimum values are based on ships equipped with fuel cells.
4. MGO: A type of diesel oil primarily used in ships, powering engines and boilers.

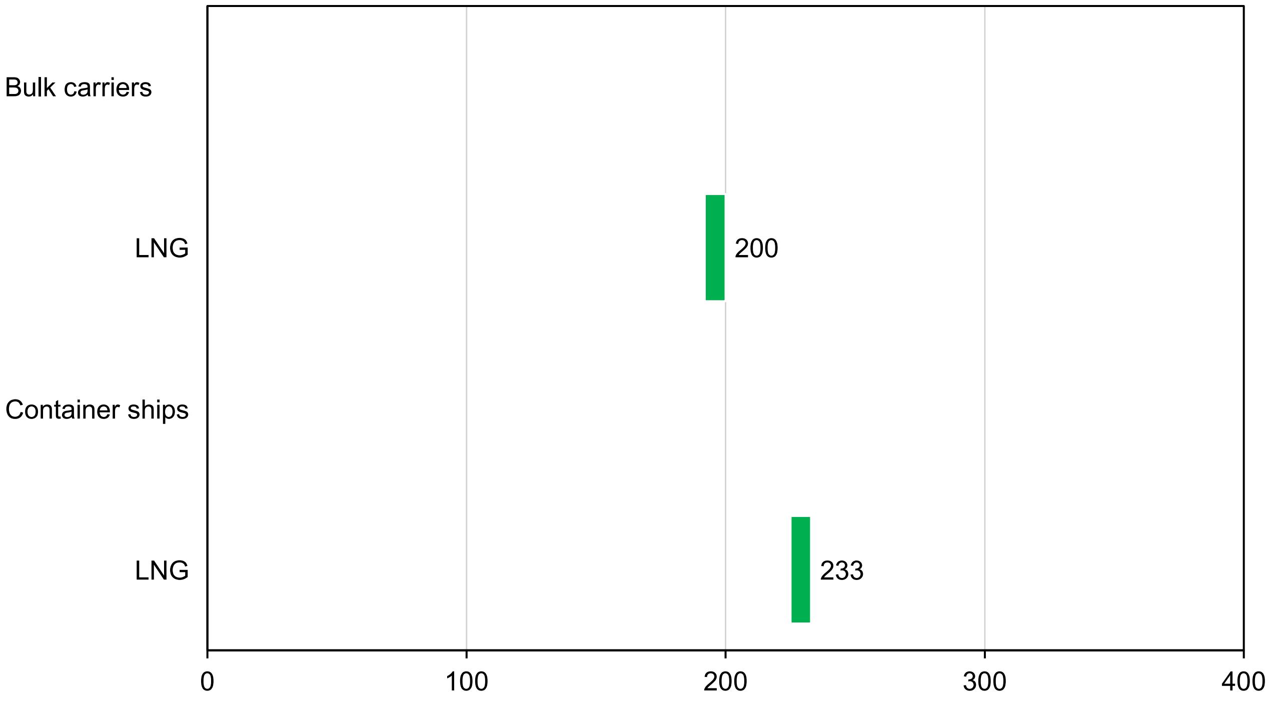
Source: Kanchiralla, F.M., S. Brynolf, and A. Mjelde (2024)

(5) Affordability – LNG fuelled ship is more expensive to build than conventionally fuelled ships, but cheaper to operate

Installation cost, million USD



Abatement costs per emission reduction, USD/tCO_2-eq



Note:
1. An open loop scrubber is an exhaust gas cleaning device used to remove SO_x from ship exhaust gases.

Source: 1) SEA-LNG (2019)

Source: 2) Kanchiralla, F.M., S. Brynolf, and A. Mjelde (2024)

[Reference] Methodologies: Affordability

Methodology: Installation cost

- In the estimation case, the CAPEX for a 14,000 TEU[1] container LNG fuelled ship is around USD 30-34 million, depending on the type of engine (high-pressure or low-pressure).

*LNG fuelled ships have higher introduction costs than conventional ships due to factors such as the cost of the fuel tank.

Note:
1. TEU: Twenty-foot equivalent unit

Source: 1) SEA-LNG (2019)

Methodology: Abatement costs per emission reduction

- The abatement cost for LNG fuelled ships varies depending on the assumed unit price of LNG supplied, the time spent at sea and the type of ship.

Source: 2) Kanchiralla, F.M., S. Brynolf, and A. Mjelde (2024)

(6) Reliability – LNG fuelled ship has been operating in Singapore, Japan and South Korea

Estimated commercialisation status

- LNG Ship: TRL 9-10, The introduction of LNG fuelled ships is progressing in Singapore, Japan, South Korea

Recent project examples

	Details
Singapore is refuelling LNG fuelled ships sailing along the coast of Southeast Asia.[1)] 	• Singapore-based LNG bunkering company FueLNG Pte Ltd. provides ship-to-ship LNG bunkering services and as of July 2024, it has provided over 200 bunkering services. • The company launched the Singapore's first LNG-fueled LNG supply ship in 2020.
Major shipping companies and shipbuilders are developing LNG fuelled ships together. 	• Mitsui O.S.K. Lines, Ltd. (MOL), Nippon Yusen Kaisha (NYK Line) and Kawasaki Kisen Kaisha Ltd. (K Line) have been operating car carriers by LNG fuelled ship from 2020. Each company is gradually introducing LNG fuelled ship with the cooperation of shipbuilder.
H-Line has started operating LNG-fuelled bulk carriers 	• H-Line Shipping Co., Ltd. has started operating LNG fuelled bulk carriers. The company has 19 more ships on order, predominantly car carriers and large LNG carriers.

Source: Čučuk, A. (2024) Offshore Energy, "K"Line (2019a), MOL (2022), NYK Line (2021), "K"Line (2019b), Ovcina Mandra, J. (2024) Offshore Energy

(7) Lock-in prevention –The utilisation of lower-emission fuels is essential for LNG-fuelled ships to achieve zero or near-zero emissions.

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• There is one path exists for LNG fuelled ship to be zero or near-zero emissions; • Path 1 : Shift to lower-emission fuels and add decarbonising technologies
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1 : Shift to lower-emission fuels and add decarbonising technologies. – Fuel should gradually shift from LNG to lower-emission fuels, e.g. biomass-derived methane fuels or synthetic methane fuels derived from captured CO_2. However, as of 2024, synthetic methane and other decarbonised fuels to replace LNG are still in the development phase. – Decarbonised fuel systems such as ammonia and H_2 are still in the early stages of development. – The price needs to fall to a level where decarbonised fuels can be used. – A supply chain that provides sufficient amounts of decarbonised fuel is needed. – Decarbonising technologies, such as carbon capture, can be retrofitted to an LNG fuelled ship, but it’s still in the research and pilot stage, with limited commercial deployment.

Note:
1. Methane slips used to be thought as one of the causes of increasing GHG emissions from a ship. However, expert interviews revealed that technological advancement has minimised methane slips. Thus methane slips were not considered for lock-in prevention considerations.

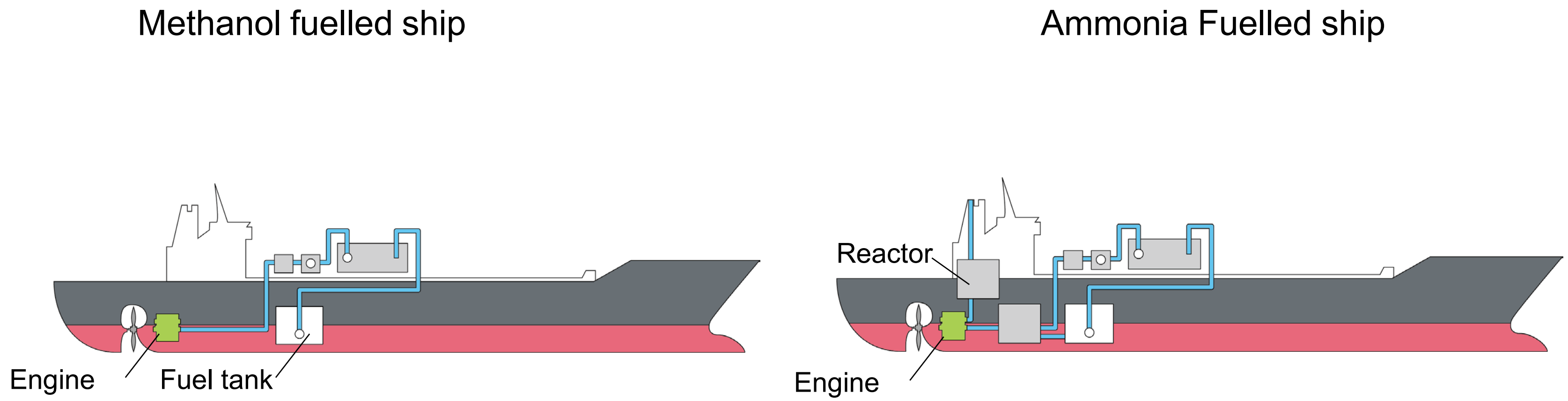
Source: Murphy, J. (2023) Natural Gas World

(8)(9) DNSH/social considerations – LNG fuelled ships can reduce NOx and SOx emissions resulting in positive impacts on ecosystems

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• LNG fuelled ships emit far less air pollutants such as NO_x and SO_x than heavy oil fuelled ships. • NO_x and SO_x can cause acid rain, which can damage the ecosystem, but LNG fuelled ships can reduce emissions of these substances more than heavy oil fuelled ships.
	Transition to circular economy	• There is a need to prohibit the use of hazardous substances such as asbestos and PCBs, and to establish a recycling system, as stipulated in international agreements such as the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• It is necessary to provide education and training on the handling of natural gas, a gaseous fuel, to operators who have been using liquid fossil fuels for improvement the occupational safety of seafarers.

Source: IMO (n.d.)

(1) Biofuel fuelled ship (methanol fuelled ship) and Ammonia fuelled ship – Technology schematics and overview



Source: Author created based on various literature

Biofuel fuelled ships

Biofuel fuelled ships use biomass-derived fuels, such as methanol, ethanol, or fuel oils. Those fuels are often blended with fossil fuels to power conventional engines.

Among biomass-derived fuels used in shipping, bio-methanol stands out as a key option more than bio-ethanol.

Ammonia fuelled ships

Ammonia fuelled ships rely on ammonia as a primary fuel, requiring specialised engines and supply systems. These vessels also require reactors with catalysts to prevent ammonia slip, unburned ammonia emissions, ensuring safer and more efficient fuel usage.

Source: DNV (2023), Methanex (n.d.), Sustainable Ships (2024), Sánchez, A., M.A. Martín Rengel, and M. Martín (2023)

(2) Biofuel fuelled ship and Ammonia fuelled ship– Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• Compared to LNG and MGO, biomass-derived fuel and ammonia fuel offer significantly lower CO_2 emissions on a Well-to-Propeller basis. • CO_2 emissions per tonne-nautical mile of transport can be reduced to about one-fourth of the levels seen with fossil fuels such as LNG and MGO when biomass-derived fuels are used.
Affordability	• The abatement costs for bio-methanol and ammonia-fueled ships vary by ship type and production method, ranging from USD 122–389/tCO_2 and USD 311–633/tCO_2, respectively.
Reliability	• Methanol fuelled ship, which can take both bio-derived and non-bio derived methanol, is commercialised (**TRL 8-9**) and new construction orders for methanol fuelled ship are increasing in 2024. • Ammonia fuelled ship is tested (**TRL 6**) and ammonia fuelled ships are being tested or operated in Japan and Singapore in 2024.
Lock-in prevention considerations	• Path 1: Reduce the ratio of fossil fuels in the mix. • Path 2: Minimise N_2O emissions from ammonia combustion and capture NOx emissions. • Path 3: Retrofit GHG capture technology to bio fuelled and ammonia fuelled ship.
DNSH considerations	• Incomplete ammonia combustion emits NO_x, which can lead to acid rain and harm ecosystems. • Measures must be taken to ensure that producing biomass for biofuel does not negatively affect existing ecosystems. • International agreements, such as the Hong Kong Convention, require banning harmful substances (e.g., asbestos, PCBs) and setting up recycling systems for ships.
Social considerations	• Ammonia slip is highly toxic, presenting a safety risk for crew and passengers on board the vessel. • Proper education and training are essential for users handling new fuels like ammonia and methanol during operations and bunkering.

Note:
1. "CO_2 emissions per tonne-nautical mile" indicates the amount of CO2 emissions per tonne of ship and per nautical mile (1.853 kilometre).

(3) ASEAN Taxonomy – Relevant technical screening criteria

Sea and coastal freight water transport, vessels for port operations and auxiliary activities (1/2)

Eligibility	Climate Change Mitigation TSC	Details
Includes - **Excludes** -	**Tier 1 (Green)**	1. The activity complies with one of the following criteria: a. the vessels have zero direct (tailpipe) CO_2 emissions; OR b. b. until 31 December 2027, hybrid and dual fuel vessels derive at least 25% of their energy from zero direct (tailpipe) CO_2 emission fuels or plug-in power for their normal operation at sea and in ports;OR c. where technologically and economically not feasible to comply with the criterion in point (a), until 31 December 2027, and only where it can be proved that the vessels are used exclusively for operating coastal and short sea services designed to enable modal shift of freight currently transported by land to sea, the vessels have direct (tailpipe) CO_2 emissions 13% below the AER[1] trajectories from IMO2023; OR d. where technologically and economically not feasible to comply with the criterion in point (a), until 31 December 2027, the vessels have an attained EEDI[2] /EEXI[3] value 10% below the EEDI/EEXI requirements applicable on 1 January 2023 if the vessels are able to run on zero direct (tailpipe) CO_2 emission fuels or on fuels from renewable sources; AND 2. Vessels are not dedicated to the transport of fossil fuels.

Notes:
1. AER: Annual Efficiency Ratio
2. EEDI: Energy Efficiency Design Index
3. EEXI: Energy Efficiency Existing Ship Index

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

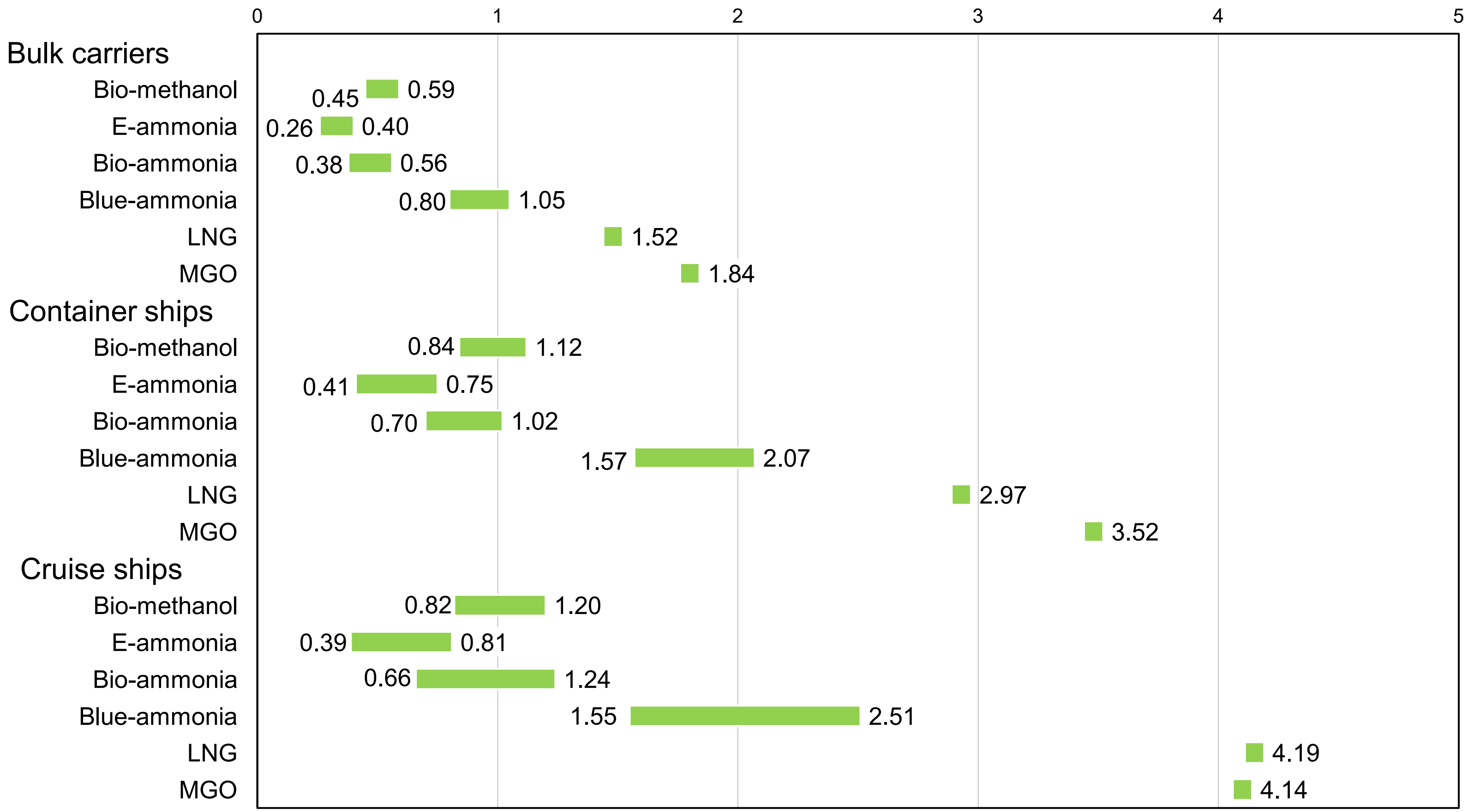
Sea and coastal freight water transport, vessels for port operations and auxiliary activities (2/2)

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 2 (Amber T2)**	1. The activity complies with one of the following criteria: a. a. Until 1 January 2030, vessels must be capable of using zero direct CO_2 tailpipe emission fuels; AND will derive at least 50% of their energy from renewable fuels; OR b. b. Until 31 December 2030, vessels meet the same TSC as Green criterion 1.c. or criterion 1.d.; AND 2. Vessels are not dedicated to the transport of fossil fuels
	Tier 3 (Amber T3)	• No TSC available.
Excludes -		

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition - Biomass-derived fuel and ammonia fuel can offer significantly lower CO_2 emissions on a Well-to-Propeller basis

Lifecycle CO_2 emissions, kgCO_2-eq/tonne-km



Comparison with ASEAN Taxonomy

There is one TSC which is potentially applicable to LNG fuelled ships.

The TSC for "sea and coastal freight water transport, vessels for port operations and auxiliary activities" sets thresholds on tailpipe emission, which has to be zero to labelled as "Green", or a percentage of zero-emission fuels/ plug-in power in a fuel mix to be labelled as "Amber". A percentage of zero emission fuel or plug-in power in a fuel mix depends on operation and not ship technology itself. Therefore, a direct comparison with TSC is not available for this technology. When assessing an LNG-ship project, a financial institution would have to look at an operation plan of each ship to see how much zero emission fuel would be mixed. Therefore the TSC was not applied to the left graph.

Source: Kanchiralla, F.M., S. Brynolf, and A. Mjelde (2024)

[Reference] Methodologies: Contribution to Energy Transition

Methodology: Lifecycle CO_2 emissions

1. The CO_2 emissions are calculated for three ship types based on operational data and ship-specific build data. "Tonne" of "kgCO_2 -eq/tonne-km" refers to different measurements based on the type of ship: bulk carriers and container ships use DWT, while cruise ships use GT.The maximum values for each fuel type assume the use of ICEs, while the minimum values are based on ships equipped with fuel cells.
2. Bio-methanol: Methanol produced from biomass sources.
3. E-Ammonia: Synthetic ammonia generated using renewable energy.
4. Bio-ammonia: Ammonia produced from biomass
5. Blue ammonia: Ammonia produced from fossil fuels, made carbon-neutral through CCS during the manufacturing process.
6. Grey ammonia: Ammonia produced from fossil fuels without CCS, resulting in higher carbon emissions.
7. MGO: A type of diesel oil primarily used in ships, powering engines and boilers. The values for LNG-fuelled and MGO-fuelled ships are the same as those for LNG-fuelled ships.
8. Well-to-Propeller fuel emissions refer to the process from production to consumption on board the ship.

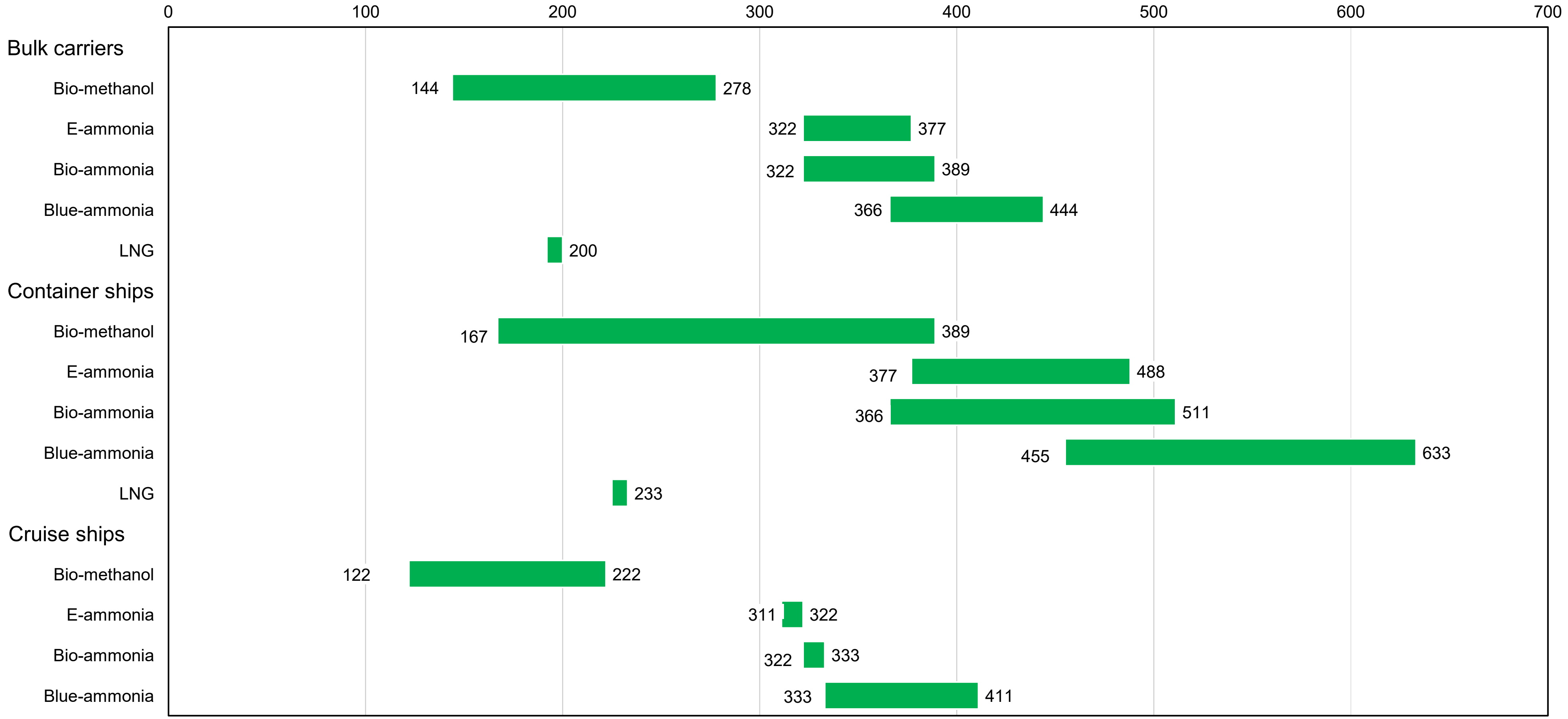
Note

- The CO_2 emissions of ammonia vary depending on how it is produced. Bio-ammonia and e-ammonia have low CO_2 emissions, while blue ammonia emits around half the CO_2 of LNG and MGO. In contrast, grey ammonia results in higher CO_2 emissions than LNG and MGO.

Source: Kanchiralla, F.M., S. Brynolf, and A. Mjelde (2024)

(5) Affordability – The abatement costs for bio-methanol and ammonia fuelled ships vary by ship type and fuel production method

Abatement cost, USD/tCO_2-eq



Source: Kanchiralla, F.M., S. Brynolf, and A. Mjelde (2024)

[Reference] Methodologies: Affordability

Methodology: Abatement cost

1. The CO_2 emissions are calculated for Well-to-Propeller. The cost includes CAPEX and OPEX and is expressed as a cost per tonne-kilometre. Abatement costs are provided for both ICEs and fuel cells. The maximum values for each fuel type assume the use of ICEs, while the minimum values are based on ships equipped with fuel cells. In most cases, the abatement cost for the fuel cell case is lower, but in the case of using bio-methanol on cruise ships, the abatement cost for the fuel cell case is higher. The values for LNG-fuelled and MGO-fuelled ships are the same as those for LNG-fuelled ships.

Methodology: Performance data used for calculation

	Bulk carriers	Container ships	Cruise ships
Capacity	65,500 DWT	6,900 TEU	4,300 passengers
Installed main engine (kW)	8,990	52,650	67,300
Design speed (knots)	14.2	24.1	21.1
Engine type	2-stroke	2-stroke	Diesel-electric, 4-stroke
Service life (years)	30	25	35
Tank capacity (TJ)	55	183	84
Distance sailed (10^6km/year)	157	272	268
Main engine fuel use (TJ/year)	159	659	1,219

1. Performance data refer to average values for evaluation.
2. DWT=Deadweight tonnage
3. TEU = Twenty-foot equivalent unit

Source: Kanchiralla, F.M., S. Brynolf, and A. Mjelde (2024)

(6) Reliability – New construction orders for methanol (can be made from biomass) ships are increasing in 2024; Ammonia fuelled ship is at the development stage

Estimated commercialisation status

- Methanol fuelled ship: TRL 8-9, In 2024 there were more than 200 vessels equipped to operate on methanol globally. (Can take bio-derived or non-bio derived methanol)
- Ammonia fuelled ship: TRL 6, In 2024, ammonia fuelled ships are being tested or operated in Japan and Singapore.

Recent project examples

	Details
Biofuel fuelled ship has been completed the net-zero voyage in 2023	• The dual-fuel vessel of Methanex and MOL completed the first-ever net-zero voyage fuelled by bio-methanol, in 2023. By blending bio-methanol with natural gas-based methanol, net-zero GHG emissions on a lifecycle basis were achieved.
Bio methanol bankering has been demonstrated	• Waterfront Shipping has conducted demonstrations of methanol fuel bunkering in the Asia-Pacific region, including South Korea, China and New Zealand.
In 2026 Ammonia-fueled medium gas carrier to be completed	• NYK, Japan Engine Corporation, IHI Power Systems, Japan Shipyards and Nippon Kaiji Kyokai sign a series of contracts for the construction of a 4,000m^3 ammonia fuelled medium gas carrier, to be completed in November 2026.
World's first use of ammonia fuelled ship in Singapore, in 2024	• Fortescue, with the support from the Maritime and Port Authority of Singapore has successfully conducted use of ammonia in combination with diesel in the combustion process in the Port of Singapore.

Source: MOL (2023), Methanol Institute (2023), IHI (2024), Maritime and Port Authority of Singapore (2024)

(7) Lock-in prevention – Biofuel fuelled ship and Ammonia fuelled ship can achieve zero emissions through three potential paths

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• There are three paths exist for biofuel fuelled and ammonia fuelled ship to be zero or near-zero emissions; – Path 1: Reduce the ratio of fossil fuels in the mix. – Path 2: Reduce N_2O emissions from ammonia combustion. – Path 3: Retrofit GHG capture technology to bio fuelled and ammonia fuelled ship.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Reduce the ratio of fossil fuels in the mix – In order to implement the advanced safety measures required as a result of the increased use of ammonia, it is necessary to develop advanced technologies for ammonia measurement, leak detection, recovery, and reuse. • Path 2: Minimise N_2O emissions from ammonia combustion and capture NO_x emissions – Current mitigation measure for N_2O is to set the combustion temperature, at which minimise N_2O production and increase NO_x production consequently, and captures NO_x with well developed NO_x filter. • Path 3: Retrofit GHG capture technology to bio fuelled and ammonia fuelled ship – GHG capture technology such as CO_2 capture on the ship remains immature, hindering immediate deployment due to technical limitations and high development costs.

Source: Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2023)

(8)(9) DNSH/social considerations – Biofuel fuelled ship and Ammonia fuelled ship need countermeasures against ammonia slip and NO_x emissions

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• Ammonia slip is highly toxic, presenting safety risks to crew, passengers, and marine life. • Incomplete ammonia combustion emits NO_x, which can lead to acid rain and harm ecosystems. • Measures must be taken to ensure that producing biomass for biofuel does not negatively affect existing ecosystems.
	Transition to circular economy	• Exhaust gas recirculation (EGR) not only reduces pollutant emissions, but also promotes fuel reuse. • There is a need to prohibit the use of hazardous substances such as asbestos and PCBs, and to establish a recycling system, as stipulated in international agreements such as the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Ammonia slip is highly toxic, presenting a safety risk for crew and passengers on board the vessel. • Proper education and training are essential for users handling new fuels like ammonia and methanol during operations and bunkering.

Source: Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2023), IMO (n.d.)

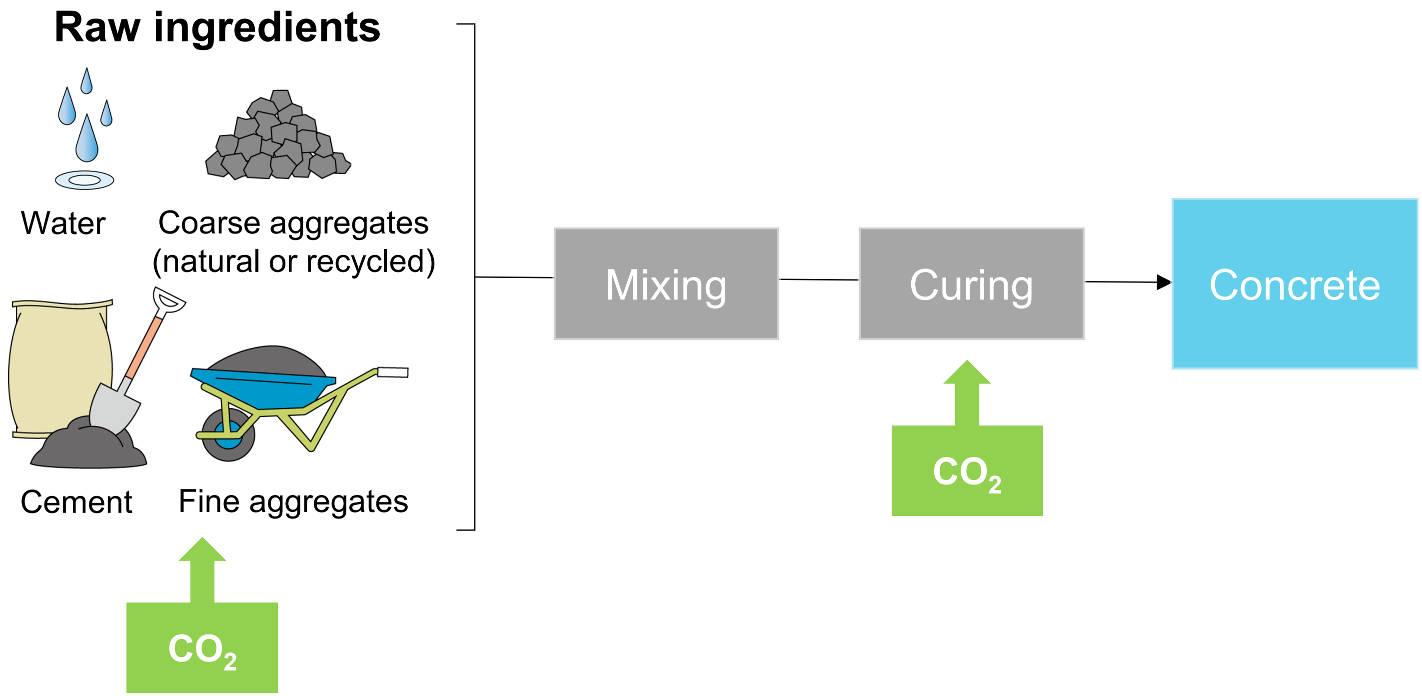
BACK TO THE LIST OF TECHNOLOGIES

Two potential transition technologies for the cement, concrete and glass sub-sector

Carbon mineralisation

NSP Kiln

(1) Carbon mineralisation – Technology schematics and overview



Source: Author created based on various literature

CO_2 can be injected into construction materials in the following stages:

(1) Raw materials: recycled concrete aggregates (RCA) or fine aggregates

(2) During the concrete formation process (concrete curing)

In this report, carbon mineralisation refers to the process of utilising CO_2 from industrial emitters as a raw material in the production of building materials.

These include:

- Carbonation of waste materials from power plants, industrial processes (e.g. iron slag, coal fly ash), or demolished buildings, which would otherwise be sent to landfill, to form construction aggregates
- Injection of CO_2 into new concrete during mixing or curing

In all of these processes, the underlying sequestration mechanism is the reaction of CO_2 with calcium oxide (CaO) in different materials to form calcium carbonate ($CaCO_3$).

Source: MRI created based on desktop research and expert interviews

(2) Carbon mineralisation – Transition suitability assessment overview

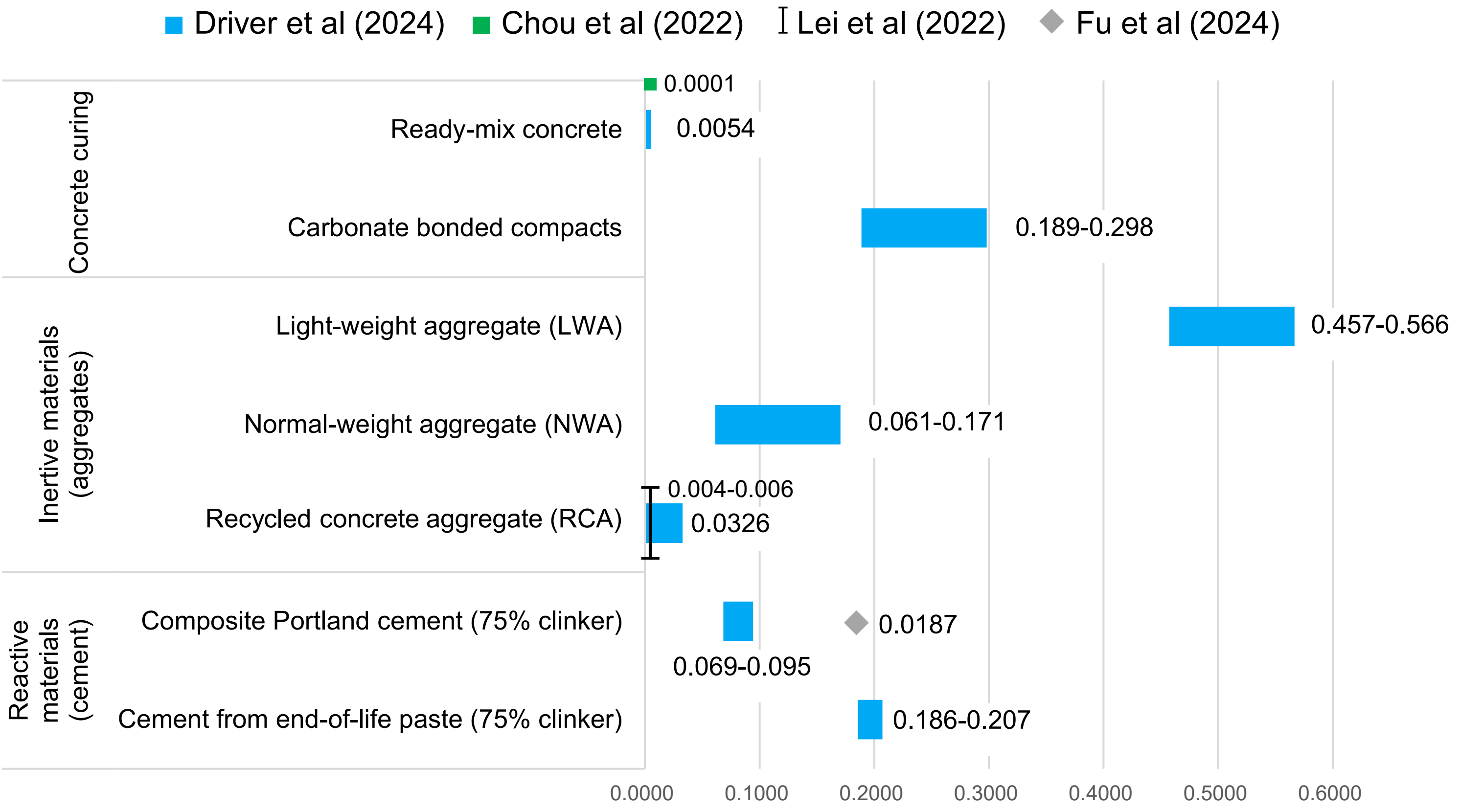
Framework dimensions	Description
Contribution to energy transition	• Mineralisation technologies may help offset 5 to 10% of emissions in the cement sector. The actual abatement potential depends on the abundance of CaO in the CO_2 -absorbing materials. Life-cycle assessment (LCA) results show that mineralisation of carbon in construction aggregates can reduce up to 60 kgCO_2 -eq per tonne, while concrete curing technologies can only reduce up to 30 kgCO_2-eq per tonne.
Affordability	• The cost of carbon mineralisation in construction aggregates would be up to six times the cost of normal aggregates. Those involving the reuse of cement paste in end-of-life mortar and concrete are more economically viable, but overall, the technology is a long way from being cost-competitive. • Policy measures such as landfill taxes, carbon credits, and regulations regarding the recycling of construction/demolition waste, etc. can potentially incentivise use of carbon mineralisation.
Reliability	• Carbon mineralisation in aggregates and concrete is a mature technology, which has been introduced into Asia (Singapore). • In addition, there are ongoing efforts to develop commercial applications to utilise CO_2 to replace clinker in cement production (TRL9).
Lock-in prevention considerations	• Path 1: Continuous R&D efforts to reduce the carbon intensity of the entire value chain, as well as to develop new materials with higher CO2 absorption potential. • Path 2: Improvement of logistics and policy frameworks for collection and recycling of construction wastes to increase abatement capacity.
DNSH considerations	• Ensure equipment is sourced from certified suppliers who measure, disclose, minimise, and potentially offset GHG emissions along the value chain. • Ensure that the raw materials are properly controlled and regulated, including that carbonation should be done in a sealed environment to avoid risks of poisoning.
Social considerations	• Positive impact on job opportunity is expected as CCUS requires additional skilled labour across its process chain in capturing & utilising CO_2.

(3) ASEAN Taxonomy – There is no relevant technical screening criteria

Eligibility	Climate Change Mitigation TSC
Includes	**Tier 1 (Green)**
	Tier 2 (Amber T2)
Excludes	**Tier 3 (Amber T3)**

(4) Contribution to Energy Transition – Carbon mineralisation of aggregates, especially light-weight aggregates, has the highest mitigation potential

Emissions reduction, $kgCO_2$ -eq per kg of product substituted



Each carbon mineralisation product's potential GHG reduction impact and abatement cost were calculated using an LCA study. Please see more details in the reference page.

Source: Driver, J.G., E. Bernard, P. Patrizio, P.S. Fennell, K. Scrivener, and R.J. Myers (2024), Chou, J., S. Moni, M. Krynock, M. Mutchek, and T.J. Skone (2022), Lei, B., L. Yu, Z. Chen, W. Yang, C. Deng, and Z. Tang (2022), Fu, X., A. Guerini, D. Zampini, and A.F. Rotta Loria (2024)

[Reference] Methodologies: Contribution to Energy Transition

Methodology: Emissions reduction

1. Each carbon mineralisation product's potential GHG reduction impact and abatement cost were calculated using an LCA study. In most applications, CO_2 is used as a substitute for some raw ingredients compared to conventional products. Thus, the LCA study uses kgCO_2-eq per kg of product substituted as the functional unit.

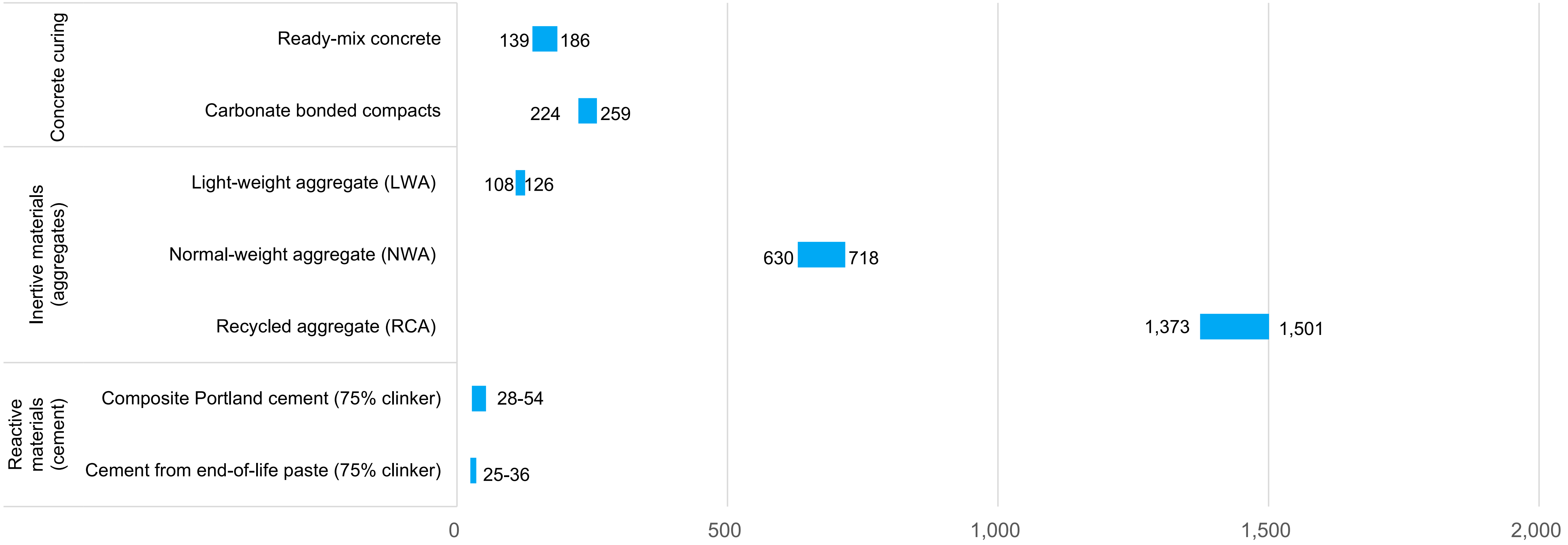
Technology	Function of CO_2	Environmental impacts captured in the LCA
Concrete curing	Concrete curing (substituting water)	• Avoided CO_2 emissions (utilising captured CO_2)
Mineralisation in inert materials (aggregates)	Aggregate substitute	• Avoided CO_2 emissions (utilising captured CO_2) • Avoided landfilling of carbonate solid materials
Mineralisation in reactive materials (cement)	Partial cement substitute	• Avoided CO_2 emissions (utilising captured CO_2) • Avoided aggregate production • Avoided landfilling of end-of-life concrete

2. In Chou et al. (2022), the emissions reduction impact of concrete curing can be measured by the difference in GWP between concrete curing technology and a comparison system that does not utilise carbon.
3. Lei et al. (2022) only discuss LCA results of recycled fine aggregate.

Source: Driver, J.G., E. Bernard, P. Patrizio, P.S. Fennell, K. Scrivener, and R.J. Myers (2024), Chou, J., S. Moni, M. Krynock, M. Mutchek, and T.J. Skone (2022), Lei, B., L. Yu, Z. Chen, W. Yang, C. Deng, and Z. Tang (2022), Fu, X., A. Guerini, D. Zampini, and A.F. Rotta Loria (2024)

(5) Affordability – Utilising CO_2 to reinforce cement, especially end-of-life cement paste, is the most cost-effective carbon mineralisation method as of now

Abatement cost, USD/tCO_2 -eq



Source: Driver, J.G., E. Bernard, P. Patrizio, P.S. Fennell, K. Scrivener, and R.J. Myers (2024)

[Reference] Methodologies: Affordability

Methodology: Abatement cost

In Driver et al (2024)'s economic analysis, the costs associated with conventional products and CO_2 mineralisation products were calculated respectively. Then, using the findings from the LCA study, the costs for avoided CO_2-equivalent emissions were assessed. Some key assumptions include:

1) There is a minimal upfront investment required for the injection of CO_2 into ready-mix concrete, based on public statements from industry vendors.
2) For cement derived from construction and demolition waste, a maximum supply radius of 50 km is assumed from the point where end-of-life concrete is generated to the cement plant.

Original estimations in EUR. The exchange rate applied is EUR 1 = USD 1.1.

Source: Driver, J.G., E. Bernard, P. Patrizio, P.S. Fennell, K. Scrivener, and R.J. Myers (2024)

(6) Reliability – Technologies are available in the Asian market, yet deployment is still relatively slow

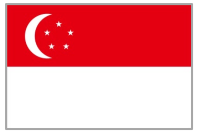
Estimated commercialisation status

- Concrete curing: TRL 9: Already commercialised & introduced to the Asian market
- Mineralisation in aggregates & cement: TRL 9: Already commercialised & further R&D efforts underway

Recent project examples

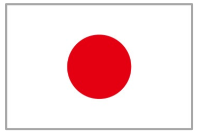
Details

CarbonCure Technologies provides carbon mineralisation solutions to the Asian market



- In 2018, CarbonCure Technologies announced that they had partnered with a Singaporean concrete innovation company, Pan-United Corporation Ltd, to bring CarbonCure's CO_2 recycling technology for concrete manufacturing to Asian markets.
- The technology has the potential to save over 4,000 tCO_2 annually at each Pan-United concrete plant.

Taiheiyo Cement is developing low-emission cement CARBOFIX®



- In 2022, Taiheiyo Cement announced the successful demonstration of a novel low-emitting cementitious material called CARBOFIX®. The production of CARBOFIX® utilises CO_2 as a hardening agent while operating at lower temperatures, effectively reducing energy-related emissions. Overall, CARBOFIX® can reduce emissions by up to 60% compared to ordinary Portland cement.
- Taiheiyo Cement is currently working towards the commercialisation of CARBOFIX®. Further emission reductions can be achieved using recycled concrete, which also contribute to a circular economy.

Source: CarbonCure (2018), Taiheiyo Cement (2022)

(7) Lock-in prevention – Cost reduction and better policy frameworks for collection and recycling of construction wastes are essential for large-scale deployment

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Two paths exist for carbon mineralisation to be zero or near-zero emissions – Path 1: Continuous R&D efforts to reduce the carbon intensity of the entire value chain, as well as to develop new materials with higher CO_2 absorption potential. – Path 2: Improvement of logistics and policy frameworks for collection and recycling of construction wastes to increase abatement capacity.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Continuous R&D efforts to reduce the carbon intensity of the entire value chain, as well as to develop new materials with higher CO_2 absorption potential. – The process of mineralising CO_2 in concrete products can be energy-intensive and carries emissions related to the transportation of CO_2 and concrete materials. Therefore, there is significant potential for improvement in decarbonising the value chain. – Developing innovative materials, such as cement and concrete with enhanced CO_2 absorption capabilities, can lead to more efficient carbon mineralisation. • Path 2: Improvement of logistics and policy frameworks for collection and recycling of construction wastes to increase abatement capacity. – In principle, the amount of CO_2 reabsorbed into concrete or aggregates can never be higher than the CO_2 emitted during production. Currently, it is estimated that cement products worldwide can reabsorb only 20% to 40% of the CO_2 emitted during their manufacturing. As a result, without effective mechanisms to collect and recycle construction waste, it will be challenging to reduce the demand for new cement production, making it difficult to achieve net-zero emissions.

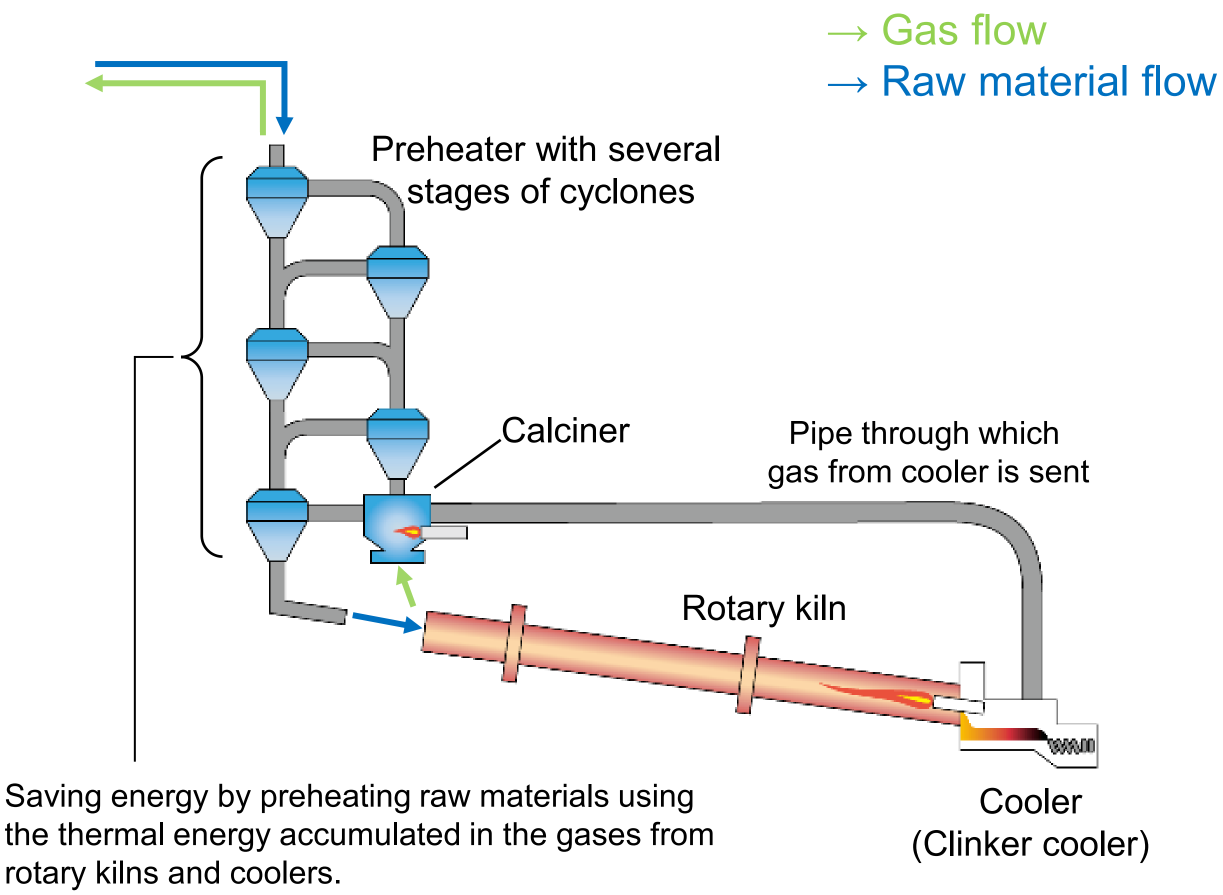
Source: Riedl, D., Z. Byrum, S. Li, H. Pilorgé, P. Psarras, and K. Lebling (2023)

(8)(9) DNSH/social considerations – Carbon mineralisation poses no significant harm to the environment or society

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• It is imperative that the raw materials are properly controlled and regulated, including that carbonation should be done in a sealed environment to avoid risks of poisoning.
	Promotion of transition to circular economy	• Carbon mineralisation involves energy use from equipment operations, as well as emissions from transporting CO_2 and concrete materials. Therefore, companies must ensure that equipment and vehicles used for material transport and processing adhere to environmental and emissions standards. Wherever possible, one should consider sourcing equipment from certified suppliers who measure, disclose, minimise, and potentially offset GHG emissions along the value chain. • Carbon mineralisation can support the transition to a circular economy by integrating construction and industrial waste into the production of cement and concrete. To achieve this, policies that incentivise recycling need to be implemented, along with strategies to optimise transportation.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Positive impact on job opportunity expected as carbon mineralisation utilising captured CO_2 would require additional skilled labour across its process chain in capturing & processing CO_2.

Source: Based on TLP version 1 (2022) and expert interviews

(1) NSP kiln – Technology schematics and overview



Source: Author created based on various literature

- New suspension preheater (NSP) kiln is a rotary kiln that creates a hard material called "clinker" from raw materials, such as limestone, sand, and clay. After the process in the NSP kiln, clinker is transformed into cement, and ground with some additives.
- NSP kiln is greatly energy-efficient compared to other types of cement kilns, including wet-process, dry-process, and SP kilns. NSP kiln basically has three to six stages of cyclones that are installed for heat recovery. Since NSP kiln has greater fuel efficiency with the preheater facilities, it tends to have higher production capacities.

Source: Gorbatenko,Y., B.A. Hedman, J.V. Shah, A. Sharabaroff (2014), JCA (n.d.)

(2) NSP kiln– Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• NSP kiln has the highest thermal energy efficiency compared to other types of cement kilns. • Therefore, NSP kiln causes least GHG emissions per tonne of clinker production.
Affordability	• When focusing on OPEX, NSP kiln can be considered as cost-competitive because of its higher energy efficiency and production capacity. • Given that a cement plant is usually a long-term business for 40-50 years, it is implied that the lifetime cost of NSP kiln could be lower than other types of cement kilns.
Reliability	• The technology is commercially available and deployed broadly across the world. (TRL 11) • NSP kiln technology represented only 35% of clinker produced by GNR[2] participants in 1990. However, it rose to 64% in 2011, becoming the most common technology to produce clinker.
Lock-in prevention considerations	• Path 1: Scaling in-plant CCUS to capture the CO_2 produced during the clinker production process. • Path 2: Electrification of kiln where the electricity is supplied by clean and renewable electricity. • Path 3: Replacement of coal and natural gas with less carbon intensive fuels, specifically, clean H_2, as fuel sources to reduce emissions associated with fuel consumption.
DNSH considerations	• There is little impact on ecosystems and biodiversity caused by the introduction of NSP kiln that has high energy efficiency. • The use of waste in the cement production can be considered as significant contribution to circular economy as the waste is effectively used with only little environmental impact.
Social considerations	• There is differing impact on the demand for skilled workers of NSP kiln, depending on the technological advancement. • General impact on the local residents and tribes, such as land right issues, needs to be considered.

Notes:
1. Low emission cement includes cement produced along with highly efficient kiln, the electrification of kiln, and the use of H_2 and CCUS.
2. GNR is the abbreviation of “Getting the Numbers Right,” which is a global database.

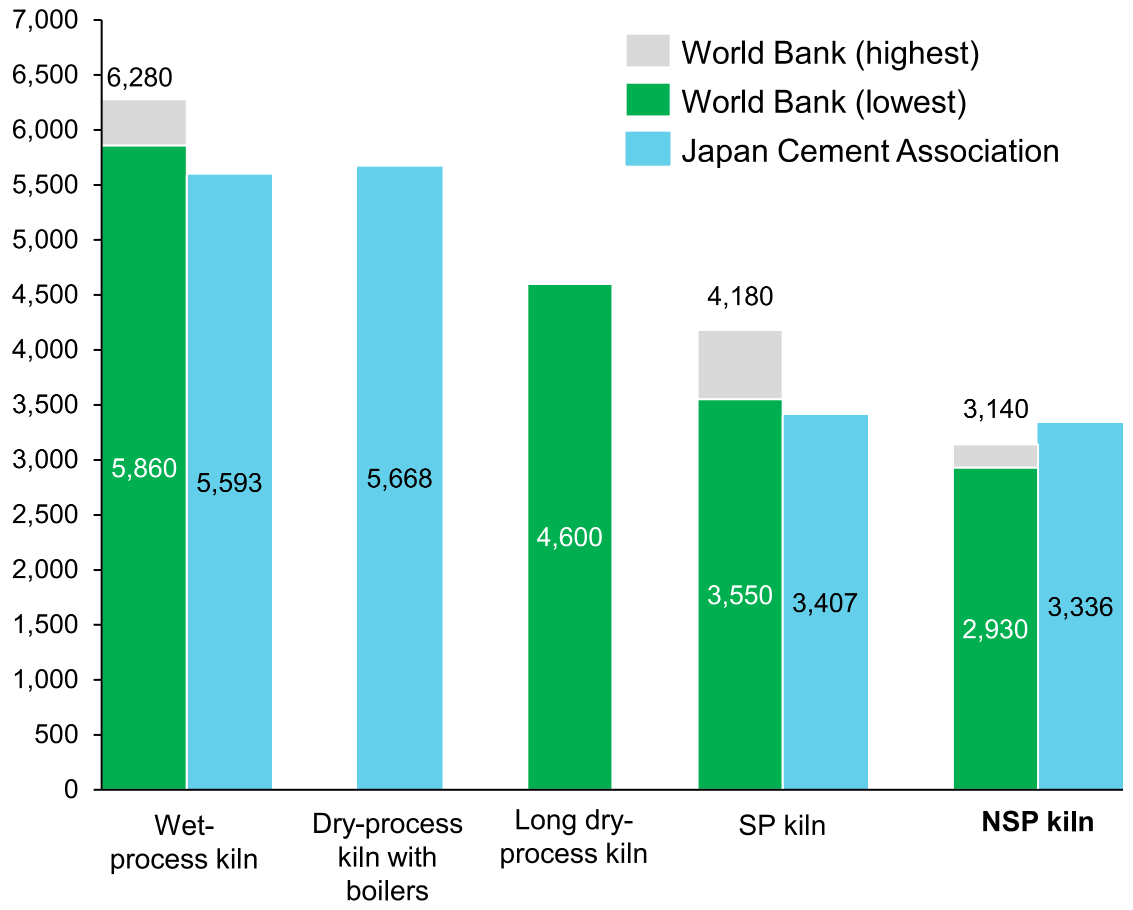
(3) ASEAN Taxonomy – There is no relevant technical screening criteria

Eligibility	Climate Change Mitigation TSC
Includes	**Tier 1 (Green)**
	Tier 2 (Amber T2)
Excludes	**Tier 3 (Amber T3)**

(4) Contribution to Energy Transition – NSP kiln has the highest thermal energy efficiency compared to other types of cement kilns

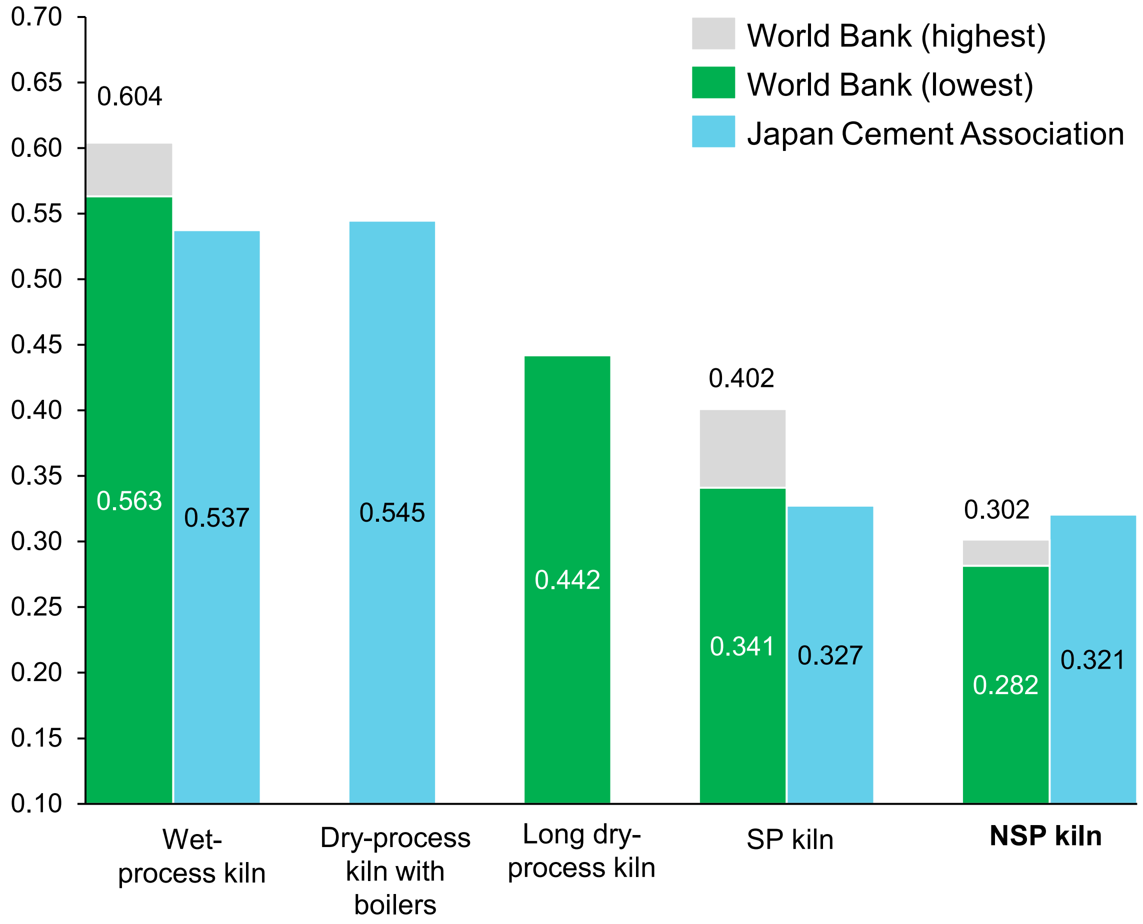
Cement kiln, MJ/t-clinker

Thermal energy efficiency by different kiln types
MJ/t-clinker



Cement kiln, tCO_2 /t-clinker

Emissions intensity by different kiln types
tCO_2/t-clinker



Source: JCA (n.d.), Gorbatenko,Y., B.A. Hedman, J.V. Shah, A. Sharabaroff (2014), IEA (2018), IPCC (2006a), JOGMEC (2022)

[Reference] Methodologies: Contribution to Energy Transition

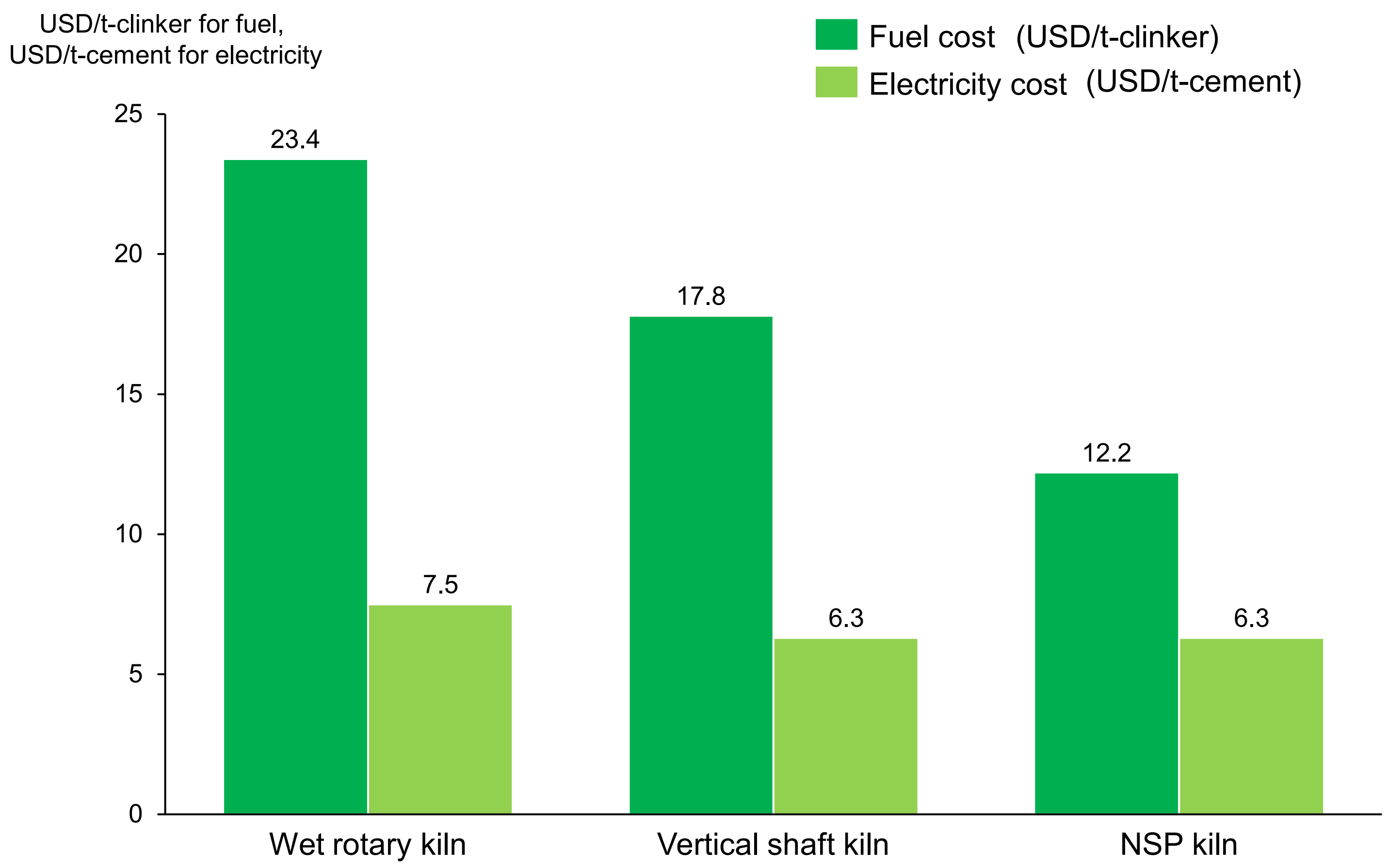
Methodology: Cement kiln

1. The emission factor of Sub-Bituminous coal in the IPCC guidelines is used here to alter the energy intensity (left-hand side graph) into emission intensity (right-hand side graph) for the following reasons.
   i. Coal is the fuel that is most widely used in cement production, representing 70% of the global cement thermal energy consumption.
   ii. Among many different types of coals, bituminous coal and sub-bituminous coal are often used for the heat generation in boilers.
   iii. In the IPCC guidelines, there are two types of categories; other bituminous coal and sub-bituminous coal. From the conservative perspective, the higher emission factor of sub-bituminous coal is used for the calculation.

Source: JCA (n.d.), Gorbatenko,Y., B.A. Hedman, J.V. Shah, A. Sharabaroff (2014), IEA (2018), IPCC (2006a), JOGMEC (2022)

(5) Affordability – When focusing on OPEX, NSP kiln can be considered as cost-competitive because of its higher energy efficiency and production capacity

OPEX(Fuel and electricity cost), USD/t-clinker, USD/t-cement



- The graph on the left shows the OPEX of cement production by different cement kilns that operated in China in 2006. As can be seen in the graph, when focusing only on OPEX of cement production, the superiority of NSP kiln stands out because of its higher energy efficiency and production capacity.
- The level of CAPEX by different cement kilns is not illustrated here. But given that a cement plant is usually a long-term business for 40-50 years, indicating the importance of OPEX rather than CAPEX, it is implied that the lifetime cost of NSP kiln could be lower than other types of cement kilns.

Source: DOE (2009), IEA (2024a), SunSirs (2024), Expert interviews

[Reference] Methodologies: Affordability

Methodology: OPEX (Fuel and electricity cost)

1. In order to calculate the cost levels of OPEX, two values are used here: The first is a price in China in 2024 of coal, which is most widely used in cement production, USD0.1/kg. The second is an industry end-user price for electricity in China in 2023, USD0.066 /kWh.

Source: DOE (2009), IEA (2024a), SunSirs (2024), Expert interviews

(6) Reliability – Commercially available with limited implementation

Estimated commercialisation status

- TRL 11: NSP kiln is commercially available and deployed broadly across the world.
- In Japan, older kiln systems, such as wet-process kiln and dry-process kiln, were replaced by SP kiln or NSP kiln. The replacement was completed by FY 1997.
- NSP kiln technology represented only 35% of clinker produced by GNR participants in 1990. However, it rose to 64% in 2011, becoming the most common technology to produce clinker.

Recent project examples

The update of the cement production facility from dry-process kiln to NSP kiln in Vietnam

Details

- The cement production factory in Da Nang city, Vietnam, was planning to update the cement kiln facility, following the government policy.
- The experts from Institute of Energy (IE) of Vietnam, Energy Conservation Center (ECC) Danang, and Japan International Cooperation Agency (JICA) were dispatched to the factory in 2008.
- The delegation assessed the efficiency of the cement kiln in the factory and proposed to replace the existing kiln with the NSP kiln.

Transition from old type of cement kiln to NSP kiln is in progress in China

- In China, transition to more productive kiln facility, which is NSP kiln, is in progress due to the national policy in the recent years.
- Thus, more investment in the cement industry is anticipated in aiming at carbon neutrality in 2050.

Source: JCA (n.d.), Gorbatenko,Y., B.A. Hedman, J.V. Shah, A. Sharabaroff (2014), JICA (2009), METI (2021a)

(7) Lock-in prevention – Three essential pathways to zero or near-zero emissions

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• The clinker production process is accounting for roughly 60% of the emissions in the cement sector. The rest of the emissions is generated through the heating energy required to heat cement kilns, mainly supplied by the combustion of fossil fuels, such as coal, oil, and gas. • There are three leading paths for the technology to be zero or near-zero emissions. – Path 1: Scaling in-plant CCUS to capture the CO_2 produced during the clinker production process. – Path 2: Electrification of kiln where the electricity is supplied by clean and renewable electricity. – Path 3: Replacement of coal and natural gas with less carbon intensive fuels, specifically, clean H_2, as fuel sources to reduce emissions associated with fuel consumption.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: High costs of carbon capture and commercial hurdles – Although it is expected that the cost of carbon capture will decrease in the future due to technical and scientific progress, high estimated costs are likely to hinder the large-scale deployment of CCUS. – Due partly to the low prices of alternative fuels and often to dependence on an abundance of renewable electricity, there are commercial hurdles to CCUS. Commerciality and scalability challenges need to be solved. – The installation of carbon capture equipment in cement plants leads to additional electricity demand and thermal energy use. • Path 2: The availability of local renewable sources and electricity prices – The availability of local renewable sources is the primary factor which influences the deployment of clean and renewable electricity at the cement kilns. Potential deployment of renewable options is highly dependent on local conditions such as electricity prices, cement plant sizes, and policy contexts. – Electricity prices may hinder the adoption of renewable-based electricity in the clinker production process. • Path 3: Less scalability and high costs of clean H_2 – Most projects are prototyped at present, and H_2 storage requirements need to be considered. In addition, clean H_2 is not cost-competitive nor widely available.

Source: WEF (2023a), IEA (2018)

(8)(9) DNSH/social considerations –Little impact caused by NSP kiln; General impact of cement production on the local communities may need to be considered

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• NSP kiln with the increased energy efficiency reduces the amount of fuel used per tonne of clinker. It then leads to less emission of exhaust gas since how much gas is produced depends on the amount of fuel used. • The clinker production process emits exhaust gas, such as CO_2 and nitrogen, and thus it is ideal to equip the NSP kiln with exhaust gas treatment facilities. However, the exhaust gas has very few toxic substances, and therefore there are few impacts on ecosystems and biodiversity.
	Promotion of transition to circular economy	• The increased use of waste, including waste plastics, waste oil, sawdust, and industrial waste, as materials for cement production is progressing. More specifically, about 400 kg of waste per tonne of cement production is utilised. The use of waste can be considered a significant contribution to a circular economy as the waste is effectively used with only little environmental impact.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• There is a potential positive impact on the demand for skilled workers for operations and maintenance of NSP kiln. However, as the automation in operating NSP kiln progresses in the future, it is possible that the employment of engineers for NSP kiln may be reduced. • Though this is not directly related to NSP kiln technology itself, developing limestone mines for the cement production could have negative impact on the local residents including land conflicts. In such cases, stakeholder consultation needs to be properly conducted before project implementation.

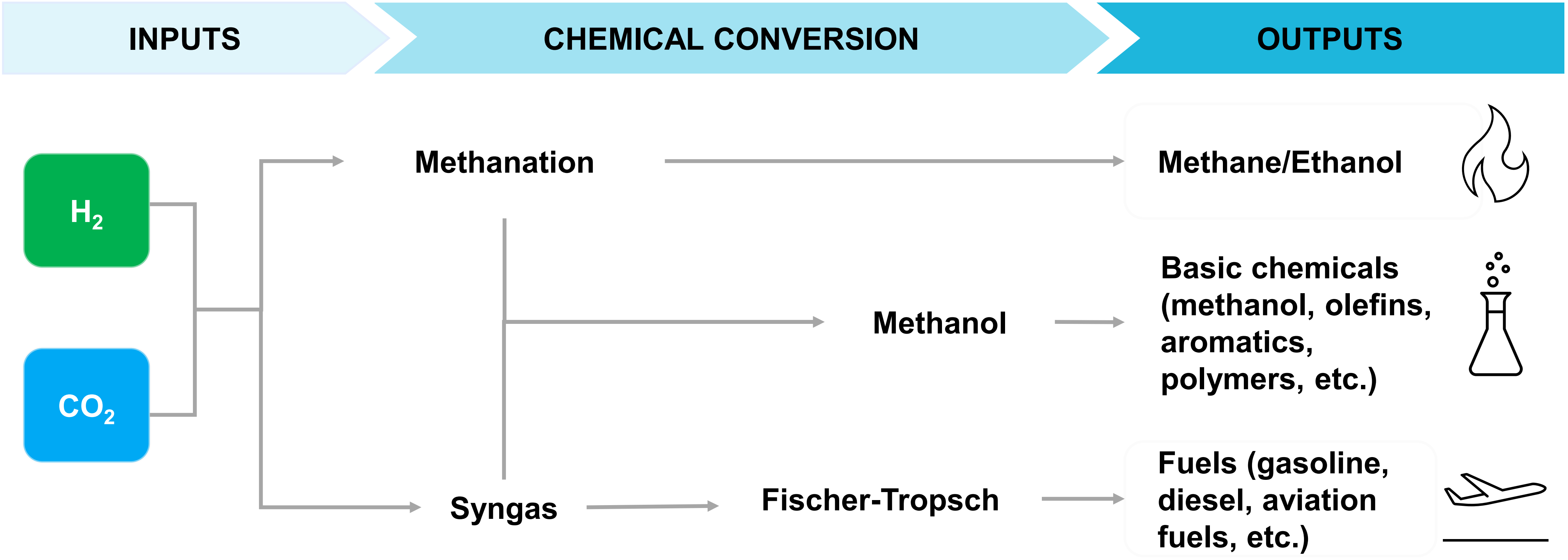
Source: Expert interview.

One potential transition technologies for the chemicals sub-sector

Production of Chemicals using Captured CO_2

[Reference] Overview of potential pathways to utilise CO_2 in chemical production

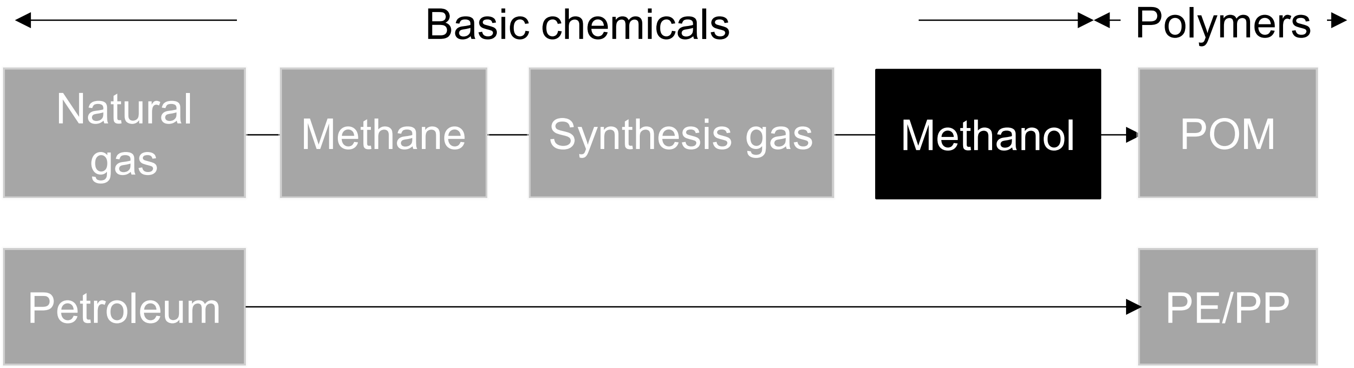
CO_2, together with H_2, can be used as feedstock to synthesise a variety of valuable petrochemicals. Methanol serves as a prime example; it is a versatile compound that can function as a fuel, an energy carrier, or an intermediate in the production of numerous chemical products.



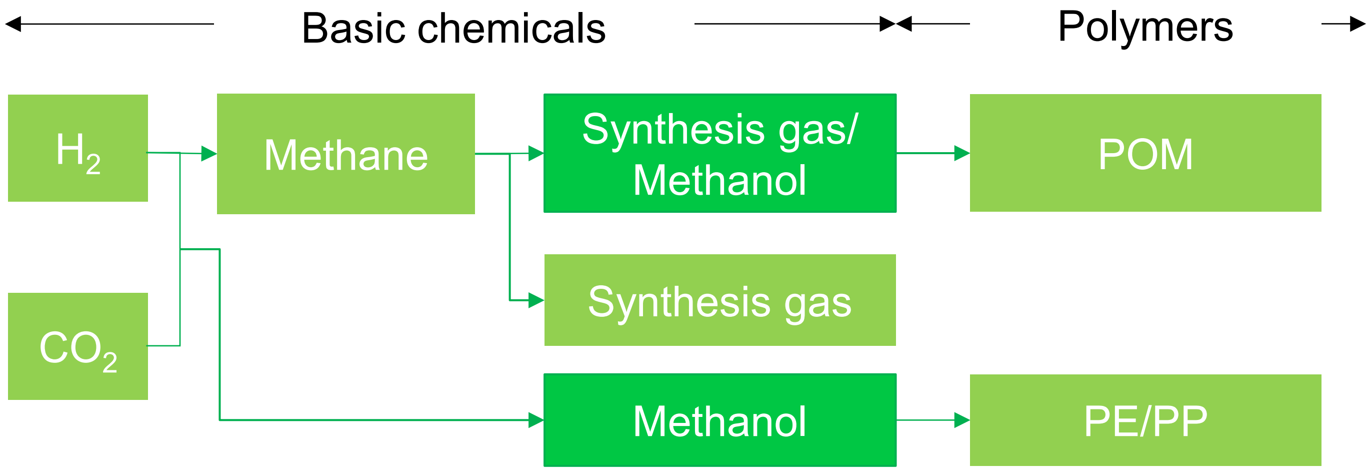
Source: MRI created based IEA (2019b) and expert interviews

[Reference] Overview of the chemical value chain and the role of methanol

Conventional petrochemical value chain



Chemical value chain with CO_2 conversion



Potential applications of methanol

- Combustion fuel:
  - Methanol can be burnt directly to produce electricity and heat in existing gas turbines and boilers.
- Transport fuel:
  - ICEVs: methanol is already used in several ICEVs, including cars, buses and taxis.
  - Maritime fuel: methanol can be used as a marine fuel, or blended with other biofuels to replace diesel
  - Methanol fuel cell: methanol can also act as a fuel in fuel cell systems for FCEVs.
- Energy carrier:
  - H_2 is difficult to handle, so converting it to methanol makes it easier to transport and store. Methanol can then be reformed into H_2, serving as a transportation medium.
- Intermediate chemical product:
  - Methanol is also an intermediate chemical product in the production process of important polymers such as polyoxymethylene (POM), polyethylene (PE), polypropene (PP).

Source: EC (2019) and expert interviews

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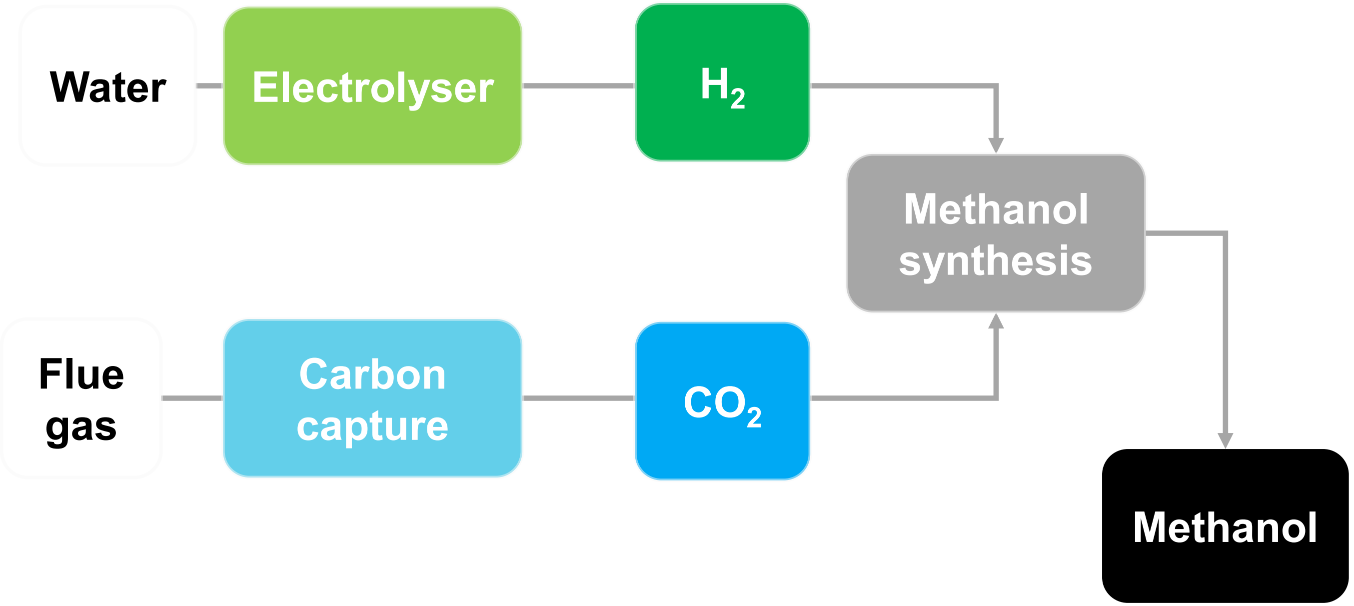
(1) Production of chemicals using captured CO_2 – Technology schematics and overview



Methanol has been selected as an example to showcase how chemicals can be produced from captured CO_2.

There are several ways to produce synthetic methanol (e-methanol) from CO_2 via electrochemical processes:

- The most mature method is to make H_2 through the electrolysis of water using renewable electricity, followed by a synthesis process with captured CO_2 to form methanol (described in the chart to the right).
- Another approach is to produce both components of syngas, CO and H_2, through electrolysis. While this route has the potential to achieve a higher conversion efficiency, it is less mature than water electrolysis.
- Direct electrochemical conversion of CO_2 and water to methanol is also being studied, but so far only limited efficiency and yield have been achieved at a laboratory scale.

Source: MRI created based on I IRENA and MI (2021) and expert interviews

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(2) Production of chemicals using captured CO_2 – Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• It is estimated that producing 1 tonne of methanol utilises 1.4 tCO_2. In addition, about 10-11 MWh of electricity is required, most of it for the electrolysis of water (assuming CO_2 is provided from another source).
Affordability	• The estimated capital investment for a methanol synthesis unit utilising CO_2 and H_2 is comparable to that of a conventional methanol plant, especially concerning methanol synthesis equipment. Most of the production costs will be to produce H_2 from renewable sources and to source CO_2 from carbon capture facilities. • Currently, this method is significantly more expensive than other methanol production pathways. Although policy incentives may assist in bringing these products to market, consumer interest will be a key factor in driving demand over the long term.
Reliability	• The first project to produce liquid methanol from CO_2 at industrial scale has been in operation since 2012. Furthermore, some efforts are underway to create a cross-border e-methanol supply chain, which involves transporting captured CO_2 to the methanol production site. Electrolysis of water to H_2, followed by catalytic methanol synthesis: TRL 9, Electrolysis of water and carbon dioxide, followed by catalytic methanol synthesis: TRL 5, Direct electrocatalytic of ethanol : TRL<4
Lock-in prevention considerations	• Path 1: H_2 is sourced from 100% renewable sources (green H_2). • Path 2: CO_2 is made from biogenic CO_2 sources or CO_2 from the air through direct air capture (DAC). • Path 3: Electricity of the whole process must come from renewables.
DNSH considerations	• Environmental viability assessment measures should be implemented to monitor and minimise risks to the ecosystem. • Converting CO_2 to valuable chemicals can facilitate transition to a circular economy by closing the carbon cycle and reduce reliance on fossil fuels for carbon-based products.
Social considerations	• Positive impact on job opportunities expected as CCUS requires additional skilled labour across its process chain in capturing & utilising CO_2.

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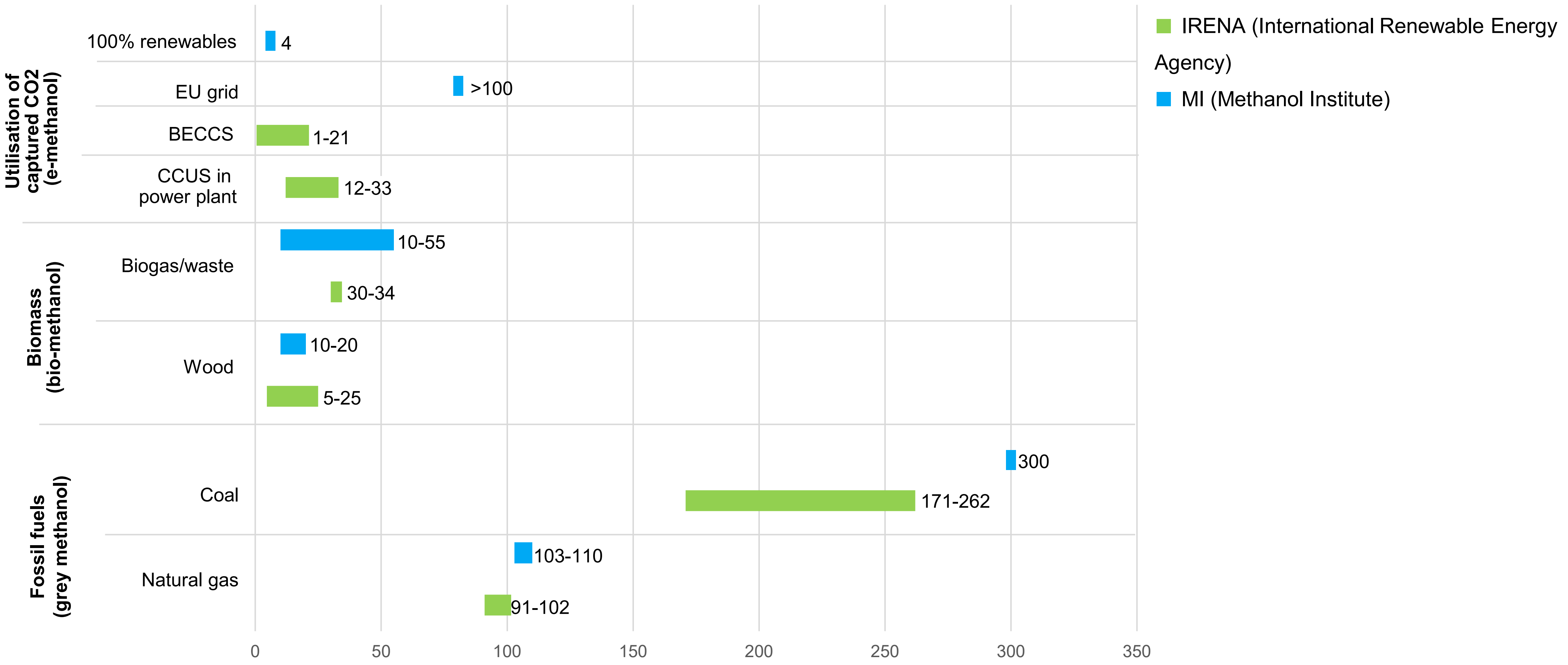
(3) ASEAN Taxonomy – There is no relevant technical screening criteria

Eligibility	Climate Change Mitigation TSC
Includes	**Tier 1 (Green)**
	Tier 2 (Amber T2)
Excludes	**Tier 3 (Amber T3)**

(4) Contribution to Energy Transition – Production of methanol from CO_2 can reduce a considerable amount of emissions compared to conventional production route

GHG emissions of methanol from various sources, gCO_2-eq/MJ



GHG emissions of different methanol production rotes were calculated based on LCA. Please see more details in the reference page.

Source: IRENA and MI (2021), MI (2022)

[Reference] Methodologies: Contribution to Energy Transition

Methodology: LCA

To estimate the GHG emissions of different methanol production routes, one can perform an LCA analysis, where all the steps of methanol production, from raw materials extraction, production to distribution and end-use have to be considered, addressing the environmental impacts of each of these steps, including GHG emissions, other pollutant emissions (NO_x, CO, particulates, SO_x, etc.) and water usage.

On the right is the LCA results of 3 main production routes (e-methanol, bio-methanol, and conventional fossil fuels), gathered from existing studies.

Source: IRENA and MI (2021), MI (2022)

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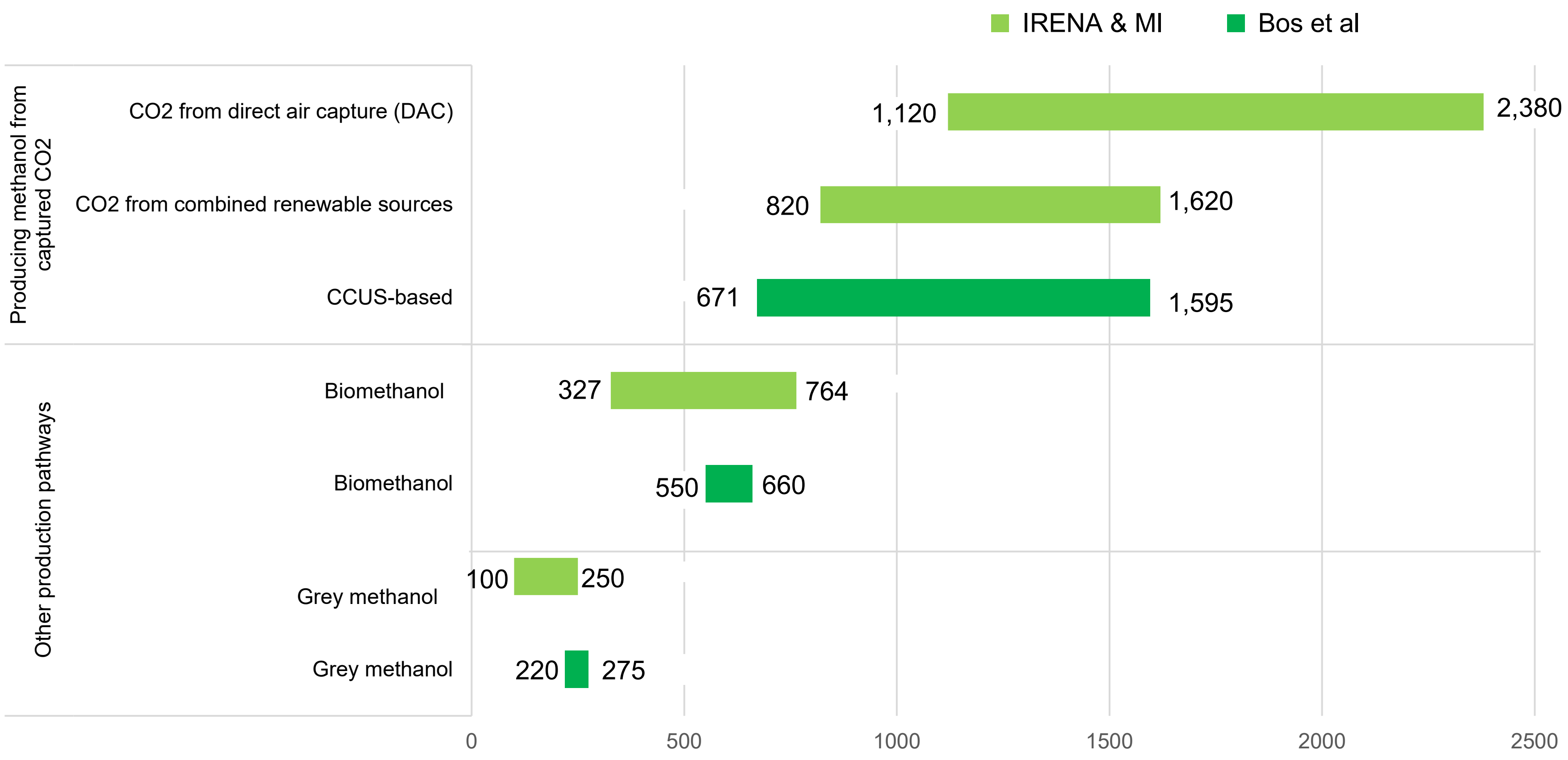
(5) Affordability – Production of e-methanol is costly due to the high cost of green H_2 and carbon capture

Cost of producing methanol from CO_2 and other production pathways, USD/t methanol



Source: IRENA and MI (2021), Bos, M.J., S.R.A. Kersten, and D.W.F. Brilman (2020)

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[Reference] Methodologies: Affordability

Methodology: Cost of producing methanol from CO_2 and other production pathways

Item	Amount required to produce 1 tonne of methanol	Price (market price as of 2020)
H_2	0.19 t	• USD4,000-8,000 /tH_2
CO_2	1.4 t	• CO_2 from combined sources: USD10-50 /tCO_2 DAC: USD300-600 /tCO_2
Synthesis process	-	USD50/t methanol

1. The prices of main cost items are based on IRENA & MI (2021).
2. CO_2 from combined renewable sources (IRENA & MI, 2021) include DAC and CO_2 from bio-based sources such as BECCS/BECCU[1], biogas, biomass-to-ethanol plants, biomass gasification and biomethane reforming. CO_2 captured from fossil fuel-based processes, including those at industrial plants, is excluded.
3. CCUS-based production costs (Bos et al, 2020) provide cost estimates for producing methanol from captured CO_2 at CCUS facilities, including both DAC and post-combustion capture.
4. Bio-methanol production costs (IRENA & MI, 2021) in this graph assume low feedstock costs of less than USD 6/GJ.
5. Cost estimations from Bos et al (2020) are provided in EUR. The exchange rate applied is EUR 1 = USD 1.1.

Notes:
1. BECCU = Bioenergy with carbon capture and utilisation

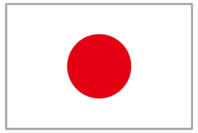
Source: IRENA and MI (2021), Bos, M.J., S.R.A. Kersten, and D.W.F. Brilman (2020)

(6) Reliability – Facilities to produce methanol from CO_2 at scale already exists, and companies are working to develop a full supply chain

Estimated commercialisation status

Technology	TRL
Electrolysis of water to H_2, followed by catalytic methanol synthesis	TRL 9
Electrolysis of water and carbon dioxide, followed by catalytic methanol synthesis	TRL 5
Direct electrocatalytic of ethanol	TRL<4

Recent project examples / Details

Recent project examples	Details
George Olah Renewable Methanol plant in Svartsengi, Iceland 	• The first production site to produce liquid methanol at industrial scale. • In operation since 2012, as of now, the production capacity has reached 1,300 - 4,000 tonnes per year, which enables the recycling of 5,500 tCO_2 emissions. The plant has the capacity to achieve an 80-90% reduction in CO_2 emissions compared to the use of a similar quantity of fossil fuels. • The production process creates no toxic by-products.
Development of synthetic fuel/ methanol supply chain 	• In March 2024, a shipping company MOL, oil & gas company Idemitsu Kosan, and e-fuel company HIF announced that they are working together to develop a synthetic fuel/methanol supply chain, including marine transport of CO_2. • The feasibility of the following items will be studied: – CO_2 marine transport from Japan to HIF's production site overseas – A supply chain to transport synthetic fuels/methanol produced by HIF at overseas production plants to Japan – Efficient and cost-competitive marine transportation of CO_2 and synthetic methanol

Source: Carbon Recycling International (n.d.), HIF Global, Idemitsu Kosan, and MOL (2024)

(7) Lock-in prevention – Sourcing of sustainable H_2, CO_2 and renewables is key to achieving net-zero

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Three paths exist for chemical production using captured CO_2 to be zero or near-zero emissions. – Path 1: H_2 is sourced from 100% renewable sources (green H_2). – Path 2: CO_2 is made from biogenic CO_2 sources or CO_2 from the air through DAC. – Path 3: Electricity of the whole process must come from renewables.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: H_2 is sourced from 100% renewable sources (green H_2) – Production of green H_2 is currently expensive due to the high costs of renewable energy sources, and also technically challenging due to the limited capacity of electrolysers and energy losses during the conversion process. – To accelerate green H_2 production, in addition to addressing the abovementioned technical challenges, there need to be additional investments into H_2 storage and transport infrastructure. • Path 2: CO_2 is made from biogenic CO_2 sources or CO_2 from the air through DAC – The process of capturing CO_2 from biogenic sources or DAC can be very costly due to the installation of specialised equipment. – Moreover, both processes are currently less efficient and less scalable than carbon capture of fossil fuel sources. There needs to be significant technological breakthroughs for these processes to be viable. • Path 3: Electricity of the whole process must come from renewables – Besides electrolysis, electricity is also needed for other stages in the production process, such as compression of H_2 and CO_2, and running the methanol reactor. When renewables become more widespread thanks to falling costs and better grid stability, it is possible to power the entire process with green electricity.

Source: Based on IRENA and MI (2021)

(8)(9) DNSH/social considerations – With sufficient risk management measures, converting CO_2 into chemicals can help shift towards a circular economy

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• Exposure to methanol can have adverse effects on specific species. In the event of methanol being extensively utilised as an alternative fuel, it is important to implement environmental assessment measures and standards to effectively monitor and minimise potential risks to the surrounding ecosystem.
	Promotion of transition to a circular economy	• The conversion of CO_2 into useful chemicals or fuels has the potential to facilitate the transition to a circular economy by effectively closing the carbon cycle and reducing resource consumption. Given the extensive use of carbon-based materials across various industries, the efficient recycling of CO_2 can contribute to the development of sustainable products and diminish the dependency on fossil fuels.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• If byproducts are effectively utilised, positive impact on job opportunities can be expected as carbon recycling technology requires additional skilled labour across its process chain in capturing & utilising CO_2.

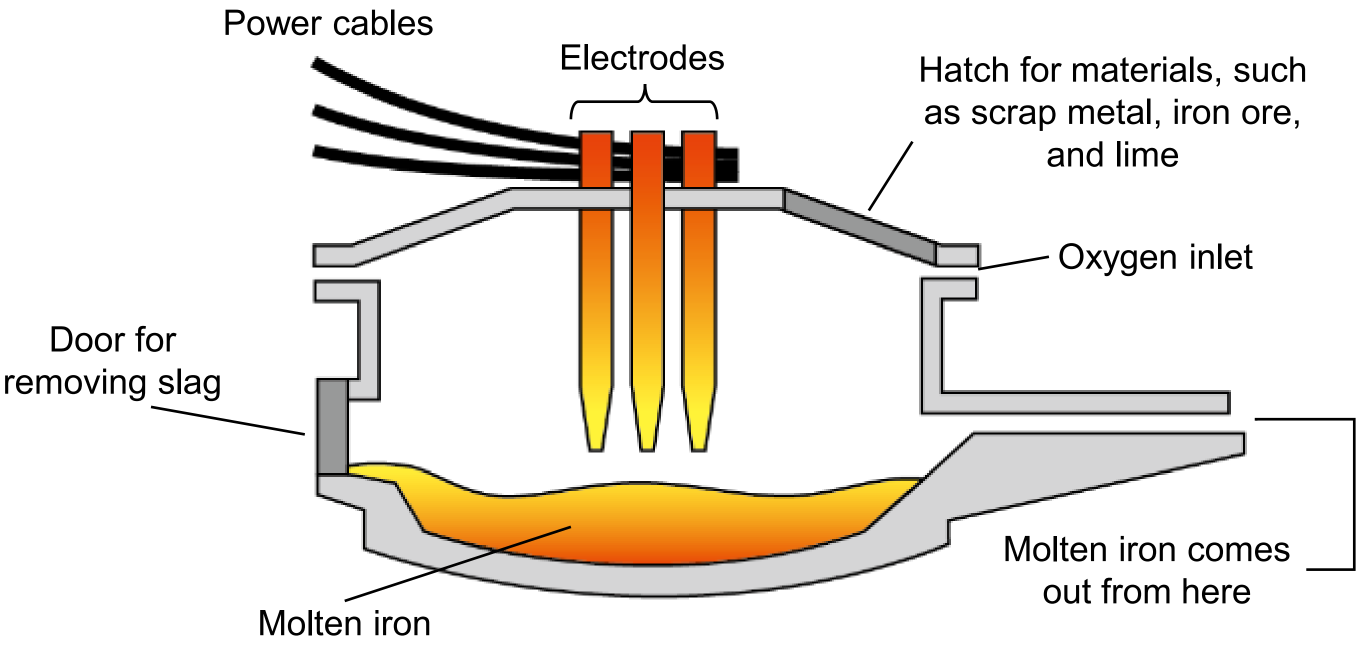
Source: TLP version 1 (2022); Expert interviews; IRENA and MI (2021); DCCEEW (2022)

Two potential transition technologies for the iron & steel sub-sector

Electric Arc Furnace (EAF)

Direct Reduced Iron (DRI)

(1) Electric Arc Furnace – Technology schematics and overview



Source: Author created based on various literature

- Electric Arc Furnace (EAF) utilises electricity to generate a high-intensity electric arc for the purpose of melting and refining metals. High-intensity electric arc creates the intense heat energy through which EAF transforms scrap metals into molten steel.
- EAF, often called the secondary steel method, reduces energy intensity to 40% of that of traditional steel production methods, such as blast furnace-basic oxygen furnace (BF-BOF). This is because melting scrap metals through EAF requires much less energy than traditional steelmaking.

Source: SMA (n.d. b), WEF (2023b)

(2) Electric Arc Furnace – Transition suitability assessment overview

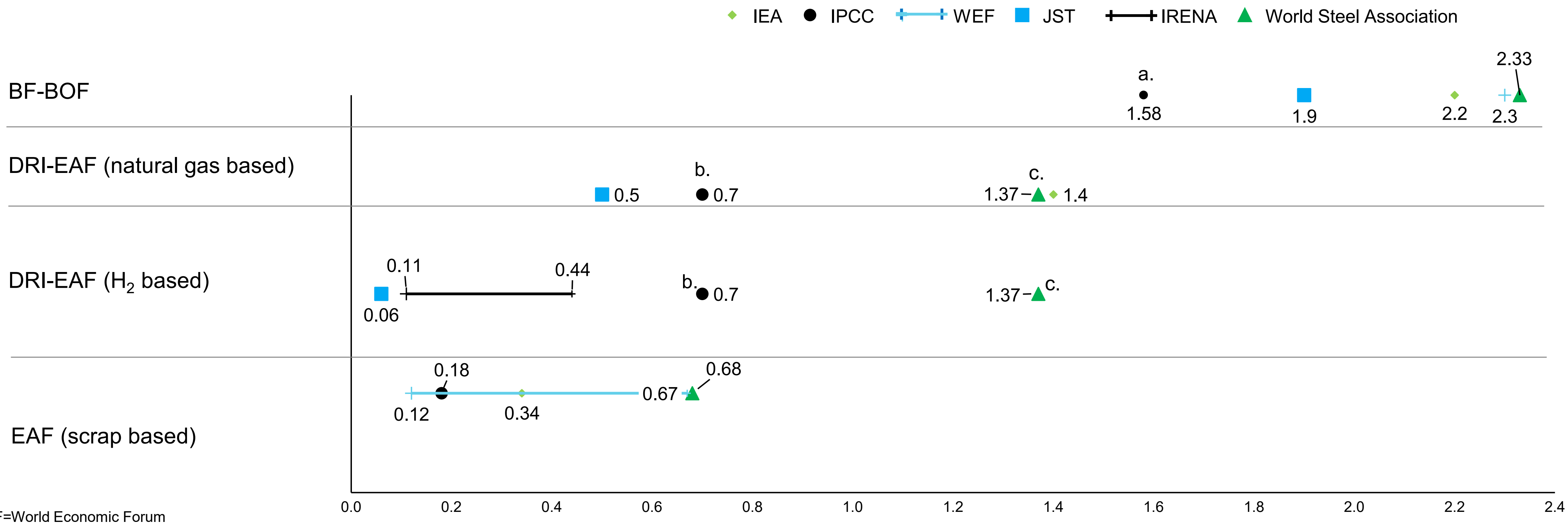
Framework dimensions	Description
Contribution to energy transition	• Emission intensity of EAF (scrap-based) is much lower than traditional steel making process, i.e. BF-BOF. • But the estimate of emission intensity differs depending on studies.
Affordability	• EAF (scrap-based) generally has a bit higher cost estimates than traditional steel making, BF-BOF. • In the total cost which includes raw materials, fuel, fixed OPEX, and CAPEX, raw materials account for the majority. This implies that the cost variation of EAF depends on the avaialbility of low-price scrap metals.
Reliability	• EAF-based production that uses 100% renewable electricity is a mature and available technology. (TRL11) • More than 70% of steel made in the U.S. is produced using EAF. • Regional limitations of scrap availability at a competitive cost, as well as differences in the quality of raw materials and energy prices, are the main factors affecting the routes of steel production.
Lock-in prevention considerations	• Path 1: Use of 100% renewable electricity • Path 2: Maximum use of low-quality scrap
DNSH considerations	• EAF emits pollutants such as dust and NO_x, particularly when low-quality scrap metals are used for steel production. Environmental regulations and effective use of exhaust gas could be enforced to prevent the air pollution. • Recycling steel in the form of scrap can improve circularity by allowing steel sourced from end-of-life products to be reused for other applications.
Social considerations	• Limited access to high quality scrap metals could be an issue in emerging and developing countries. • EAF requires large-scale electricity power. Hence, introduction of EAF may cause the shortage of electricity supply. • Introduction of EAF could lead to high demand for workers collecting scrap, raising an employment rate.

(3) ASEAN Taxonomy – There is no relevant technical screening criteria

Eligibility	Climate Change Mitigation TSC
Includes	**Tier 1 (Green)**
	Tier 2 (Amber T2)
Excludes	**Tier 3 (Amber T3)**

(4) Contribution to Energy Transition ー Direct Reduced Iron (DRI) and EAF technologies' emission intensities are generally below traditional steel making

Emissions intensity by different steel-making, tCO_2/t-steel



WEF=World Economic Forum

JST=Japan Science and Technology Agency

Source: IEA (2020c), IPCC (2019), WEF (2023b), JST (2022a), IRENA (2023), World Steel Association (2024)

[Reference] Methodologies: Contribution to Energy Transition

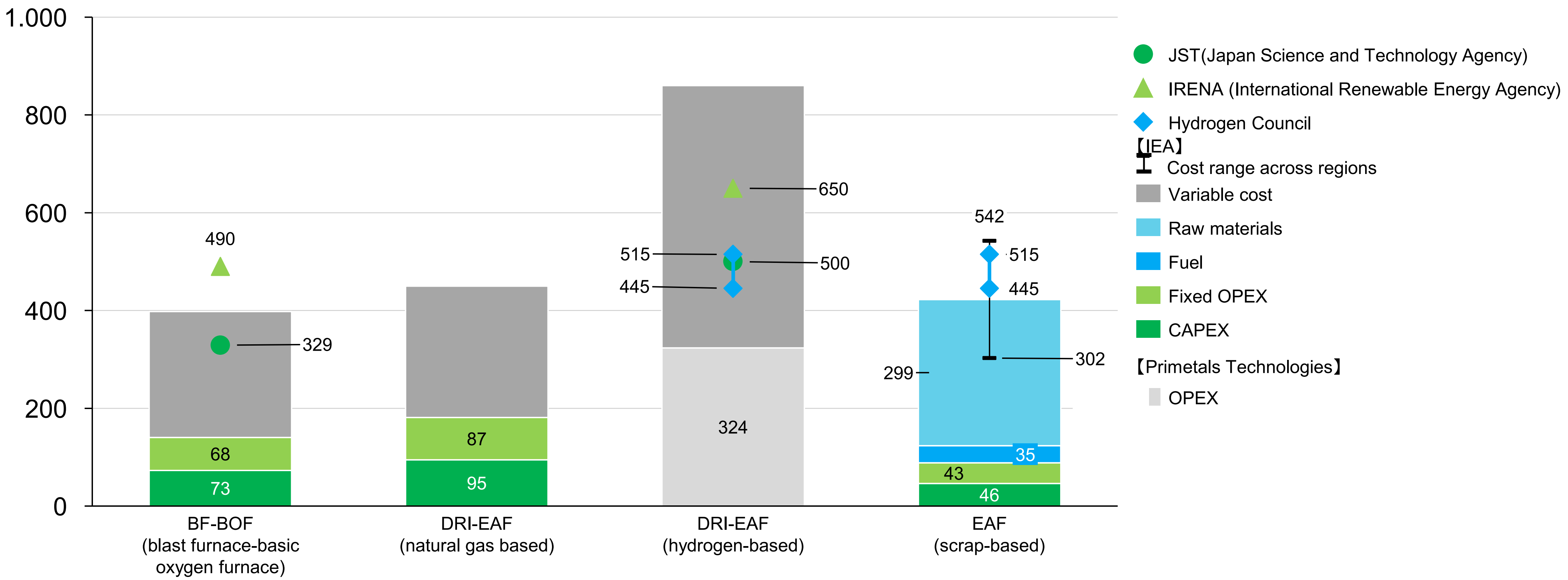
Methodology: Emissions intensity by different steel -making

a. Emission from BF is only included (that is why the emission value is relatively low).
b. This is the average emission value of DRI-EAF, but only includes emission from DRI (that is why the emission value is relatively low).
c. This is the average emission value of DRI-EAF (including natural gas based and H_2 based DRI-EAF)

Source: IEA (2020c), IPCC (2019), WEF (2023b), JST (2022a), IRENA (2023), World Steel Association (2024)

(5) Affordability – The lower emission technologies, including DRI-EAF and scrap-based EAF, tend to have higher cost estimates than traditional steel making

Simplified levelised cost of steel production by different technologies, USD/t-steel



Source: IEA (2020c), Hydrogen Council (2021), JST (2022a), IEA, IRENA, and UN Climate Change High-Level Champions (2023), Millner, R., J. Rothberger, B. Rammer, C. Boehm, W. Sterrer, H. Ofner, and V. Chevrier (2021)

[Reference] Methodologies: Affordability

Methodology: Simplified levelised cost of steel production by different technologies

1. The prices of energy and raw materials, such as coal, natural gas, iron ore and scrap metals, have strong influence on the final production cost of crude steel.
2. The value of Hydrogen Council is the estimated cost for an optimised setup with 40% scrap-based EAF and 60% H_2 -based DRI.
3. Cost range across regions indicates the maximum and minimum costs of 'EAF (scrap-based)', whereas the bar graph shows the average.
4. Variable costs include prices of fuel, such as coal and natural gas, and raw materials, such as iron ore. Since they are subject to regionall and periodic variances, definite values are not presented here. For the purpose of illustrating the cost levels, the rough estimates are used referring to several studies.
5. OPEX includes prices of H_2, natural gas, lime, electricity and other materials. The figure (USD 324) is the average of the minimum and maximum assumed energy prices.

Source: IEA (2020c), Hydrogen Council (2021), JST (2022a), IEA, IRENA, and UN Climate Change High -Level Champions (2023), Millner, R., J. Rothberger, B. Rammer, C. Boehm, W. Sterrer, H. Ofner, and V. Chevrier (2021)

(6) Reliability – Technology is mature, but there exists the regional variability in the adoption of EAF due to the limitations of scrap availability

Estimated commercialisation status

- TRL 11: EAF-based production that uses 100% renewable electricity is a mature and available technology.
- More than 70% of steel made in the U.S. is produced using EAF.
- Regional limitations of scrap availability at a competitive cost, as well as differences in the quality of raw materials and energy prices, are the main factors affecting the routes of steel production.

Recent project examples

Details

New EAF at Gwangyang Works to be built by POSCO.

- POSCO, which is the South Korean steelmaker, is to build a new EAF at its Gwangyang Works. The construction was started in January 2024 and was scheduled to be full operated by 2026.
- The new EAF will have an annual production capacity of 2.5 million tons.

SteelAsia announced a plan to build an EAF at Batangas, Philippines.

- On March 13, 2018, SteelAsia announced its plan to build a steel plant equipped primarily with EAF at Batangas, Philippines.
- Although it is unclear how much production capacity the plant will reach, it was expected to start commercial operation in July 2024.

Approval given to New Zealand Steel to build and start to operate EAF in 2026.

- New Zealand Steel, the country's leading steelmaker, received approval from the government to build and start the operation of EAF in 2026. The EAF will enable New Zealand Steel to reduce its emissions, using renewable energy and recycling scrap steel.
- The new EAF will replace the current oxygen furnace and two coal-fueled kilns, achieving a considerable reduction in coal use and CO_2 emissions.

Source: WEF (2023b), SMA (n.d. a), SEAISI (2023), Global Energy Monitor Wiki (2024), Pacific Steel (n.d.)

(7) Lock-in prevention – Two potential pathways to decarbonisation of EAF exist including use of clean power sources and the maximum use of low-quality scrap

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• There are two major paths for EAF to be net-zero or near-zero emissions; – Path 1: Use of 100% renewable electricity – Path 2: Maximum use of low-quality scrap
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Use of 100% renewable electricity – EAF-based steel production that uses 100% renewable electricity is a mature and available technology. Moreover, EAF technology can reduce emissions considerably compared to BF-BOF, with a marginal cost premium of 8-13%. – However, the fact that EAF consumes a significant amount of electricity may result in higher operating costs especially where electricity prices are high. Clean power generation should be prioritised in regions where EAF production is expected to increase. • Path 2: Maximum use of low-quality scrap – There are limitations regarding the applications for EAF owing to the variances in the quality and composition of available scrap, which may affect the quality and consistency of the steel produced. – Even if all scrap metal is recycled, it is not enough to meet the annual demand for crude steel production. It should also be noted that scrap availability varies considerably between developed and developing countries, with the latter more dependent on primary production methods to meet steel demand.

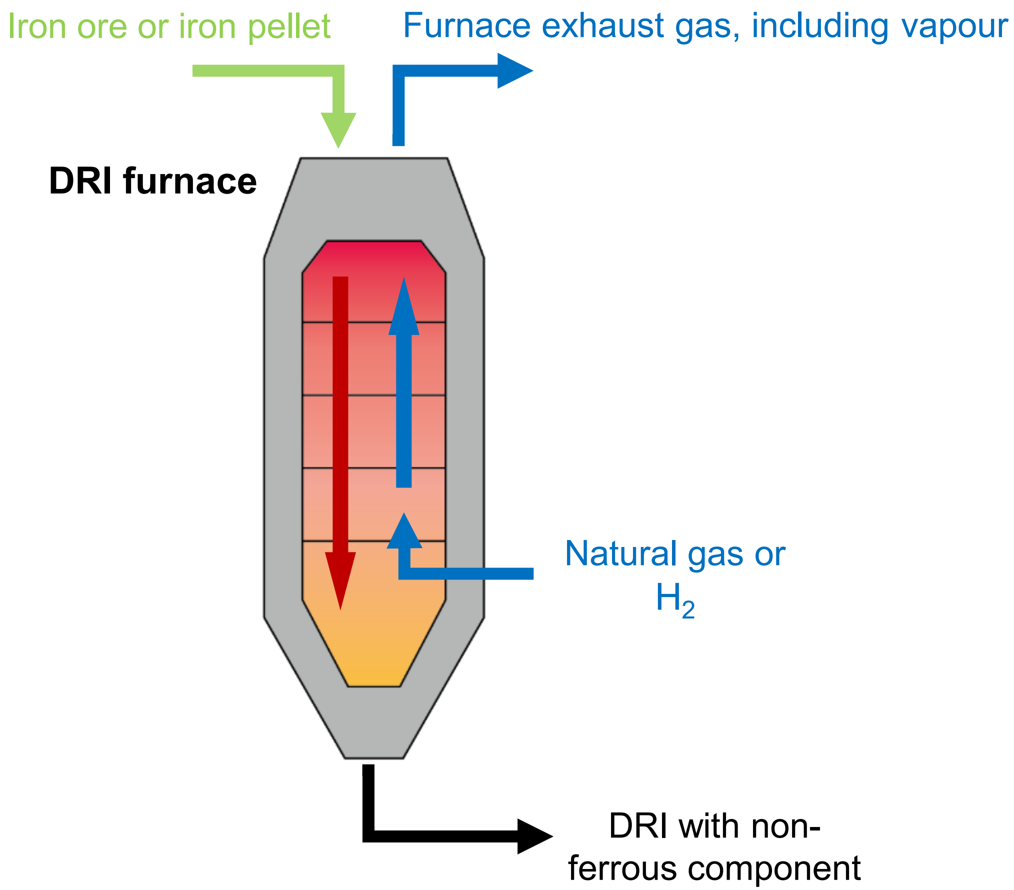
Source: METI (2021d), IRENA (2023), WEF (2023b), Testbook Edu Solutions (2023), Nippon Steel (2021)

(8)(9) DNSH/social considerations – EAF could have a few environmental impacts, including exhaust gas emission, and social impacts on scrap and power supply

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• While EAF produces fewer GHG emissions compared to conventional steel-making, it can still emit pollutants such as dust, particulate matter, and NO_x, particularly when there are some low-quality scrap metals that contain polyvinyl chloride. There are two potential countermeasures against them: environmental regulations and measures in place for maintaining air quality and installing dust collection system along with an effective use of exhaust gas as heat supply sources.
	Promotion of transition to circular economy	• Recycling steel in the form of scrap can improve circularity by allowing steel sourced from end-of-life products to be reused for other applications. Recycling steel reduces the need for primary steel production.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Access to high quality scrap metals could be limited in emerging and developing countries, as more and more EAF is introduced across the world. Policy interventions and public commitment might be needed in order to prevent the unbalance of scrap availability between countries. • EAF requires large-scale electricity power. Hence, the introduction of EAF may cause a shortage of electricity supply in near-site communities. Securing a stable power supply needs to be well considered. In addition, with conventional types, EAF may affect the grid side through a phenomenon called flicker. To prevent this, EAF should be equipped with anti-flicker facilities. • Since EAF needs scrap metals as raw materials, the introduction of EAF could lead to a high demand for workers collecting scrap metals. According to the IEA, establishing recycling industries in the steel sector creates around 17 jobs per million USD of investment.

Source: IRENA (2023), WEF (2023b), Testbook Edu Solutions (2023), IEA (2020a), Expert interviews

(1) Direct Reduced Iron – Technology schematics and overview



Source: Author created based on various literature

- Direct Reduced Iron (DRI) is the product of the direct reduction of iron ore in a solid state in the DRI furnace without melting iron ore. This process is different to the liquid phase in the BF, which is the conventional steel-making process where iron ore is melted.

- After the direct reduction in the DRI furnace, DRI is melted in the EAF, BF, or BOF, and frequently mixed with some scraps. DRI is produced in the DRI furnace based mainly on natural gas, but increasingly on H_2 in the recent years.

Source: Nippon Steel (2021), JST (2022a), IEA (2020c)

(2) Direct Reduced Iron – Transition suitability assessment overview

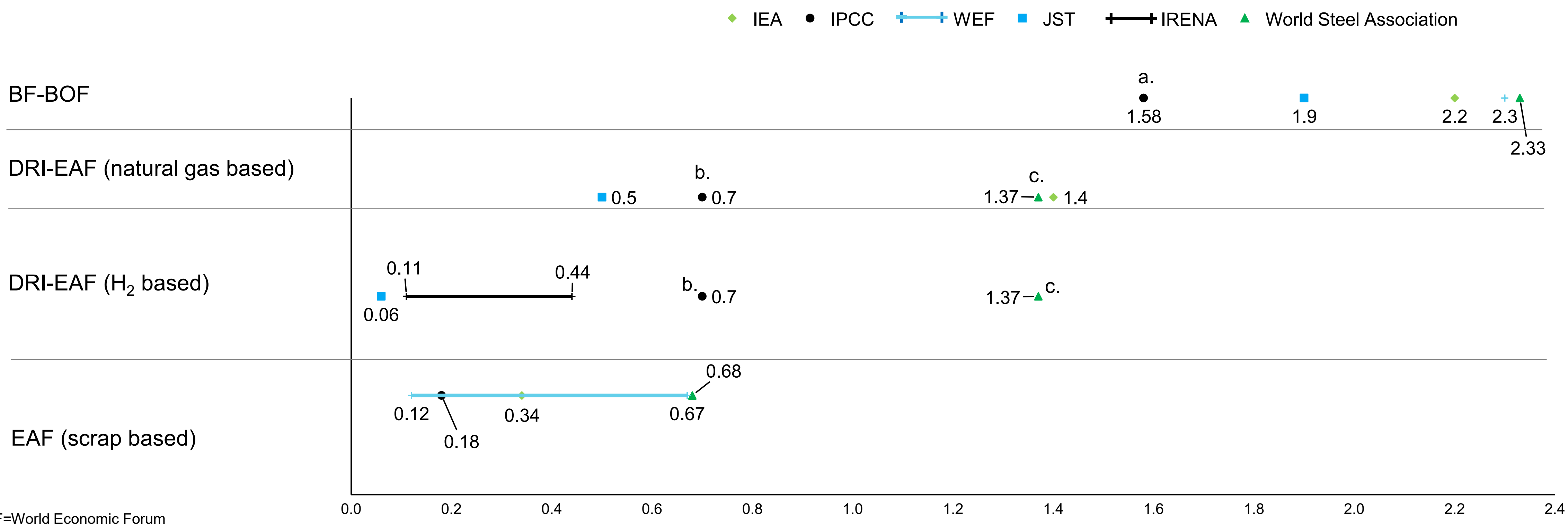
Framework dimensions	Description
Contribution to energy transition	• Emission intensity of DRI-EAF (both natural gas based and H_2 based) is much lower than traditional steel making process, BF-BOF. • However, the estimate of emission intensity differs considerably according to each study due to variance in calculation process.
Affordability	• DRI-EAF (both natural gas based and H_2 based) generally has higher cost estimates than traditional steel making, which is BF-BOF. Particularly, H_2 based DRI-EAF potentially costs significantly compared to BF-BOF. • Cost ranges of two ways of DRI-EAF could be broader than other technologies due to regional variances
Reliability	• TRL of DRI based on 100% electrolytic H_2 is 6-8, partially commercialised, but mostly at prototype stage. • TRL of DRI based on natural gas with high levels of electrolytic H_2 blending is 9. The current commercial technology is already fit for up to 30% natural gas displacement by H_2, without considerable changes. • TRL of DRI based on 100% natural gas is 10, already commercialised.
Lock-in prevention considerations	• Path 1: Replacing all the reducing gas with H_2 • Path 2: DRI based partially on natural gas along with CCUS technology
DNSH considerations	• DRI has little impacts on ecosystems and biodiversity. Additionally, improving energy efficiency, through the effective use of waste heat, can enhance circularity as it minimises the demand for resources in steel production.
Social considerations	• Cost consideration needs to be given along with policy interventions like carbon pricing, subsidies, and incentives for technology development and dissemination. • H_2 can ignite easily and requires high pressure and low temperature conditions. Thus, adequate ventilation, leak detection, ideally retrofitting infrastructure, such as pipelines, are needed for the safety. • There is a potential positive employment impact for DRI technologies across the construction, operation and procurement.

(3) ASEAN Taxonomy – There is no relevant technical screening criteria

Eligibility	Climate Change Mitigation TSC
Includes	**Tier 1 (Green)**
	Tier 2 (Amber T2)
Excludes	**Tier 3 (Amber T3)**

(4) Contribution to Energy Transition ー DRI and EAF technologies' emission intensities are generally below traditional steel making

Emissions intensity by different steel-making, tCO_2/t-steel



WEF=World Economic Forum

JST=Japan Science and Technology Agency

Source: IEA (2020c), IPCC (2019), WEF (2023b), JST (2022a), IRENA (2023), World Steel Association (2024)

[Reference] Methodologies: Contribution to Energy Transition

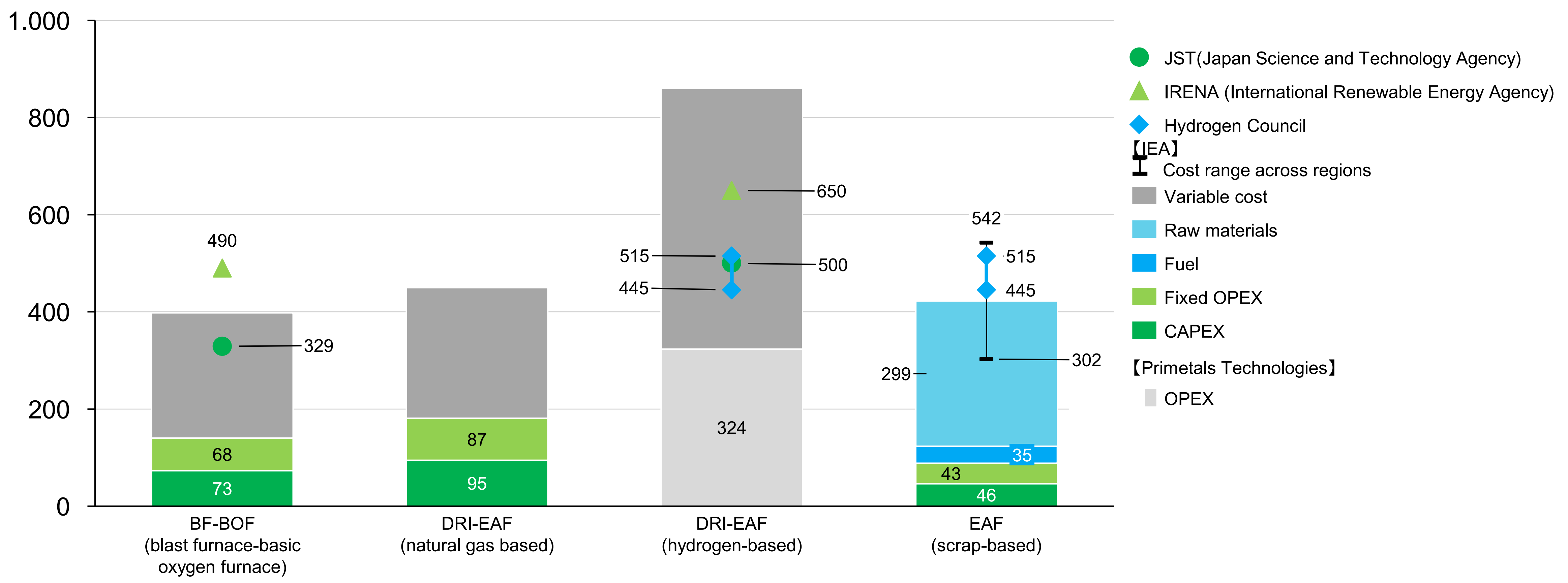
Methodology: Emissions intensity by different steel -making

1. Emission from BF is only included (that is why the emission value is relatively low).
2. This is the average emission value of DRI-EAF, but only includes emission from DRI (that is why the emission value is relatively low).
3. This is the average emission value of DRI-EAF (including natural gas based and H_2 based DRI-EAF)

Source: IEA (2020c), IPCC (2019), WEF (2023b), JST (2022a), IRENA (2023), World Steel Association (2024)

(5) Affordability – The lower emission technologies, including DRI-EAF and scrap-based EAF, tend to have higher cost estimates than traditional steel making

Simplified levelised cost of steel production by different technologies, USD/t-steel



Source: IEA (2020c), Hydrogen Council (2021), JST (2022a), IEA, IRENA, and UN Climate Change High-Level Champions (2023), Millner, R., J. Rothberger, B. Rammer, C. Boehm, W. Sterrer, H. Ofner, and V. Chevrier (2021)

[Reference] Methodologies: Affordability

Methodology: Simplified levelised cost of steel production by different technologies

1. The prices of energy and raw materials, such as coal, natural gas, iron ore and scrap metals, have strong influence on the final production cost of crude steel.
2. The value of Hydrogen Council is the estimated cost for an optimised setup with 40% scrap-based EAF and 60% H_2 -based DRI.
3. Cost range across regions indicates the maximum and minimum costs of 'EAF (scrap-based)', whereas the bar graph shows the average.
4. Variable costs include prices of fuel, such as coal and natural gas, and raw materials, such as iron ore. Since they are subject to regionall and periodic variances, definite values are not presented here. For the purpose of illustrating the cost levels, the rough estimates are used referring to several studies.
5. OPEX includes prices of H_2, natural gas, lime, electricity and other materials. The figure (USD 324) is the average of the minimum and maximum assumed energy prices.

Source: IEA (2020c), Hydrogen Council (2021), JST (2022a), IEA, IRENA, and UN Climate Change High -Level Champions (2023), Millner, R., J. Rothberger, B. Rammer, C. Boehm, W. Sterrer, H. Ofner, and V. Chevrier (2021)

(6) Reliability – DRI based on natural gas and hydrogen is reaching commercial maturity

Estimated commercialisation status

- DRI based on 100% electrolytic hydrogen
  - **TRL 6-8**
  - 100% hydrogen-based DRI is partially commercialised, but mostly at prototype stage.
- DRI based on natural gas with electrolytic hydrogen blending
  - **TRL 9**
  - The current commercial technology is already fit for up to 30% natural gas displacement by hydrogen, without great changes.
- DRI based on 100% natural gas is commercialised.
  - **TRL 10**

Recent project examples

	Details
Demonstration test of hydrogen-based DRI done by Baosteel 	• In July 2020, Baoshan Iron & Steel Co., Ltd. (hereinafter referred to as Baosteel), a Chinese leading steel company, announced the commencement of a demonstration test of DRI ironmaking based on hydrogen in a small-scale BF. • This achieved a CO_2 reduction rate of more than 21%. Baosteel would begin applying this technology to an existing BF with a capacity of 2,500 m³, which is about six times larger than the test one.
Hydrogen blowing test on an actual BF conducted by Tata Steel 	• Tata Steel, a leading global steel company headquartered in Mumbai, announced that it conducted a hydrogen blowing test on an actual BF in April 2023.The test was expected to reduce CO_2 emissions by approximately 7-10% per ton of crude steel produced.
Demonstration project of hydrogen-based DRI by Japanese corporations 	• Demonstration project that tries to directly reduce low-grade iron ore with hydrogen in a medium-scale direct reduction furnace is in progress by Japanese steel companies. Additionally, one DRI furnace based on 100% hydrogen has been commercially introduced in Europe. • This is expected to reduce CO_2 emissions by 50% or more compared to the current BF method.

Source: IEA (2021), IEA (2020c), METI (2023a), Expert interviews

(7) Lock-in prevention – Two possible decarbonisation pathways with DRI technology

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• There are two possible paths for DRI technology to be zero or near-zero emissions. – Path 1: Replacing all the reducing gas with H_2 – Path 2: DRI based partially on natural gas along with CCUS technology
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Replacing all the reducing gas with H_2 – Financial viability is the major factor preventing the dissemination of the DRI technology. In Japan, DRI based on 100% natural gas has not been implemented domestically due to cost, production scale, and quality. ○ DRI based solely on H_2 is thought to come with an expected green premium of 35-70% when compared to conventional BF-BOF processes. ○ There exist constraints around the capacity of EAF in comparison to larger BFs ○ In the DRI-EAF process, energy efficiency is low since two separate furnaces are required for reduction and melting. Additionally, it is difficult to remove the impurities in the EAF method. Impurity removal technology in EAF process needs to be established. • Path 2: DRI based partially on natural gas along with CCUS technology – DRI plants could be equipped with chemical or physical absorption-based CO_2 capture. The details are discussed in 'Carbon capture' section.

Source: METI (2021d), IEA (2021)

(8)(9) DNSH/social considerations – Little impacts on ecosystems and biodiversity; On the other hand, could have several social impacts

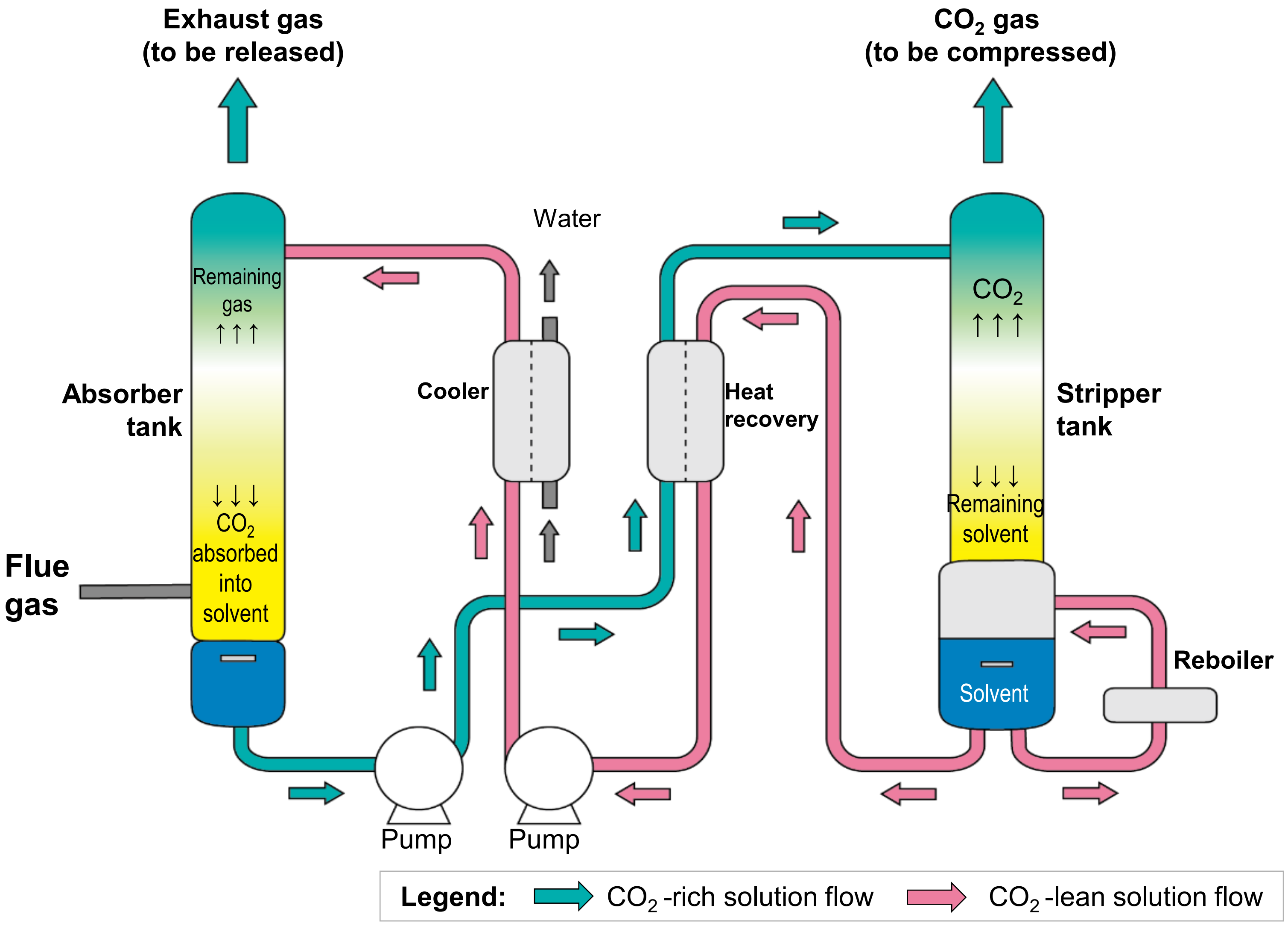
Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• There is no definite negative impact on the ecosystems and biodiversity by introducing DRI technology. Rather, DRI can reduce environmental impact with much less CO_2 emission.
	Promotion of transition to circular economy	• Improving energy efficiency, through the effective use of waste heat for example, can enhance circularity as it minimises the demand for heat sources in steel production. Similarly, keeping the temperature of produced DRI by introducing hot transport conveyors after the DRI furnace could contribute to the resource circularity as it promotes effective use of heat energy. • In order to produce high quality steel, DRI is often utilised in EAF with scrap metals. Thus, the use of DRI can promote more use of scrap metals, which can contribute to the resource recycling.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• The customers' capability to accept a green premium of 40-70% per tonne of steel has not yet been tested beyond prototype projects since low-emission steel accounts for less than 1% of global supply. Thus, cost consideration needs to be given along with policy interventions like carbon pricing, subsidies, and incentives for technology development. • H_2 can ignite more easily, compared to gasoline or natural gas, as it has lower ignition temperature. Additionally, H_2 requires high-pressure and low-temperature conditions. Thus, adequate ventilation, leak detection, and retrofitting of infrastructure, such as pipelines, are needed for safety. • There is a positive employment impact across the construction, operation and procurement phases (engineering of existing plants, procurement of H_2, plant operation, and its maintenance).

Source: METI (2021b), IRENA (2023), WEF (2023b), Expert interviews

Six potential transition technologies for the industries cross-cutting sub-sector

- Carbon Capture
- Lower Emission Fuel Fuelled Equipment
- Large-scale Industrial Heat Pump
- Waste Heat Recovery
- Electric Heating
- Small-scale Once Through Boiler

(1) Carbon capture– Technology schematics and overview



Source: Author created based on various literature

A typical post-combustion chemical absorption carbon capture process consists of the following stages:

- **Absorption**: The cooled flue gas is passed through an absorber column where it comes into contact with a solvent). The CO_2 in the flue gas reacts with the solvent to form a compound, effectively removing CO_2 from the gas stream.
- **Solvent Regeneration**: The CO_2-rich solvent is then pumped to a regeneration unit, typically a stripper column. Here, the solvent is heated, causing the CO_2 to be released from the solvent. The regenerated solvent is then recycled back to the absorber column for reuse.

[Reference] CCUS Technical Considerations

CO_2 capture efficiency depends on source concentration

CO_2 conc.	Example situations	CO_2 capture efficiency
High	H_2, bioethanol, ethylene oxide production	High
Low	Cement, Iron and steel	Low

3 major CO_2 capture technologies

Technology	Maturation/usage
Chemical absorption	Most widely used. Post-combustion capture with amine-based solvents is the state-of-the-art technology. (TRL 9-11)
Physical absorption	Used only in selected cases such as natural gas processing, etc. (TRL 7-9). Common solvents include Selexol™ and Rectisol™. Limited applications in the industry sector.
Membrane separation	Under development. Used in cement kilns. (TRL 4)

Source: Based on TLP version 1 (2022), IEA (2020d), IEA (2023b)

(2) Carbon capture – Transition suitability assessment overview

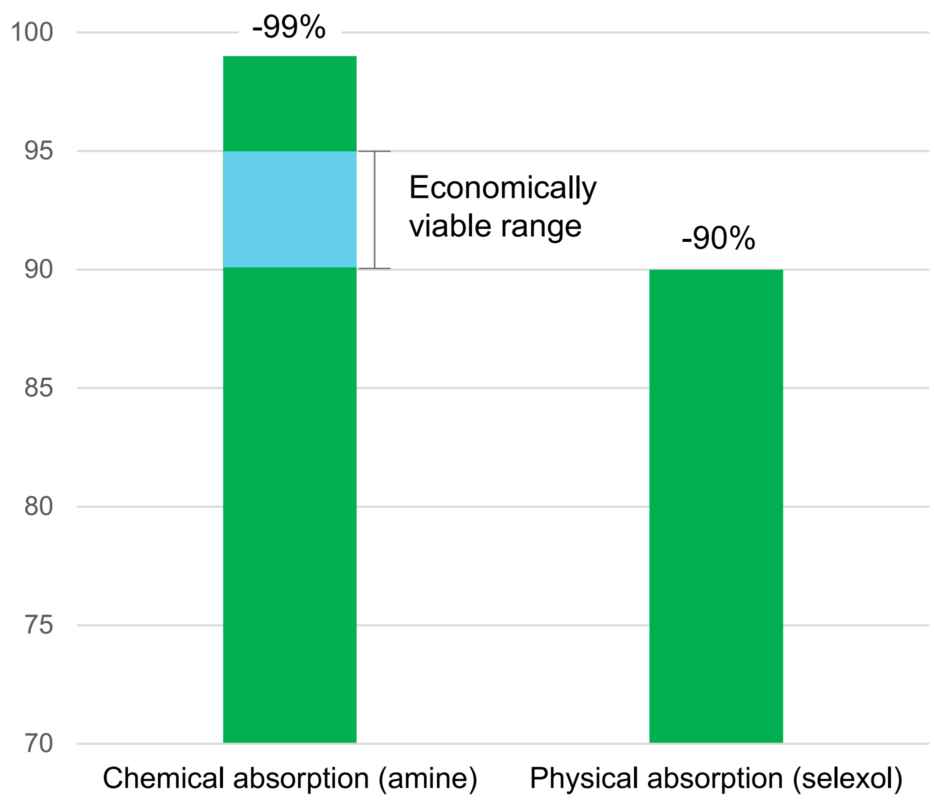
Framework dimensions	Description
Contribution to energy transition	• State-of-the-art carbon capture technologies can generally achieve capture rate of >90%. Emissions impact largely depends on the emissions level at the facility at which the carbon capture unit is installed.
Affordability	• The cost of carbon capture varies significantly by sector and region and is influenced by factors such as scale of operations and characteristics of flue gas. For a large-scale plant emitting around 5,000tCO_2 a year, the cost of capturing 1 tCO_2 typically ranges from USD 60 to 70. • Asia may benefit from lower labour costs for the construction and maintenance of carbon capture facilities, as well as the availability storage sites; however, the lack of infrastructure for CO_2 processing and transport might impact the economic viability of CCUS implementation.
Reliability	• Chemical absorption technology based on amine solvents is a relatively mature technology. Opportunities to develop new solvents with better properties exist but can be limited. Chemical absorption: TRL 9-10, Physical absorption: TRL 7-9, Membrane separation: TRL 4
Lock-in prevention considerations	• Path 1: Increase CO_2 recovery rate from current 90% to near 100% • Path 2: Develop infrastructure for transportation, utilisation and storage
DNSH considerations	• Environmental viability assessment should be conducted for major new infrastructure installations associated with carbon capture implementation. Ensure equipment is sourced from certified suppliers who measure, disclose, minimise, and potentially offset GHG emissions along the value chain. • Waste management should be evaluated according to local regulations to ensure safe disposal especially solvent waste.
Social considerations	• Positive impact on job opportunities expected as CCUS requires additional skilled labour across its process chain in capturing & utilising CO_2. • Health, safety, and environment (HSE) risks with Carbon Capture and Utilisation (CCU) implementation especially with regards to chemicals used in CO_2 separation need to be assessed with prevention and mitigation measures implemented based on local regulations and industry standards.

(3) ASEAN Taxonomy – There is no relevant technical screening criteria

Eligibility	Climate Change Mitigation TSC
Includes	**Tier 1 (Green)**
	Tier 2 (Amber T2)
Excludes	**Tier 3 (Amber T3)**

(4) Contribution to Energy Transition – State-of-the-art technology can achieve a capture rate of higher than 90%, yet the current process is energy-intensive

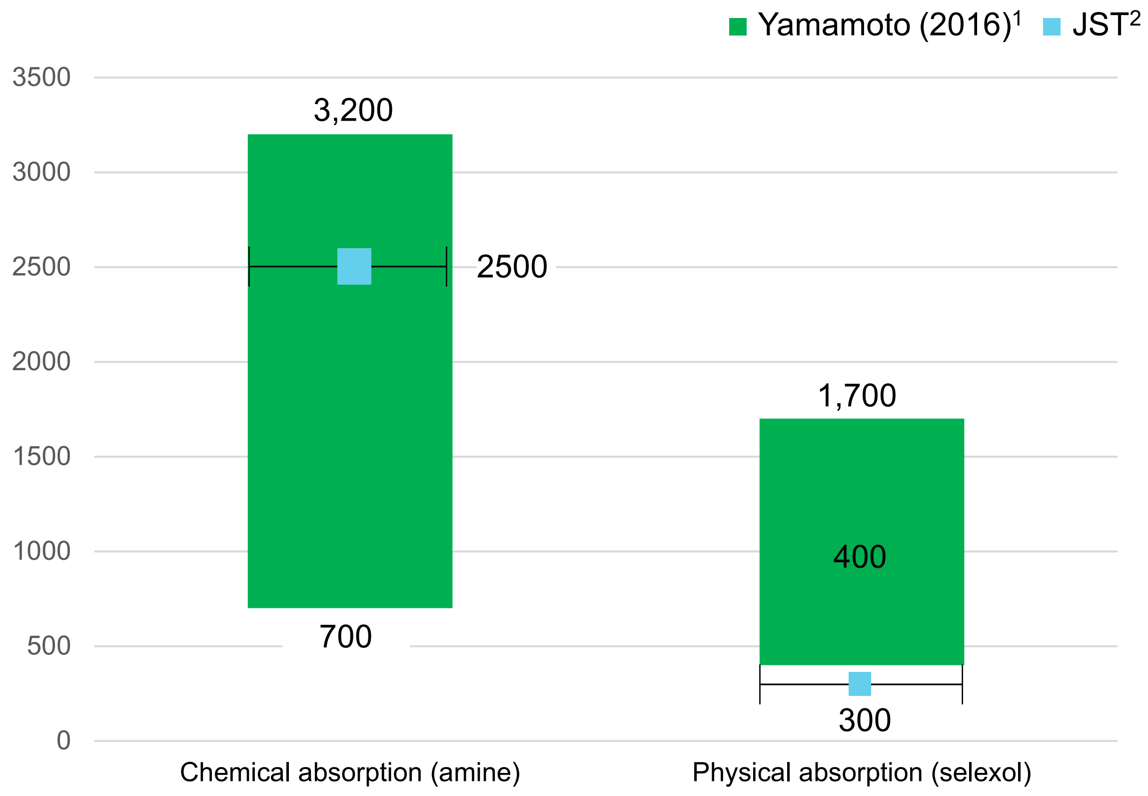
CO2 capture rate, %



Source: MRI created based on desktop research and expert interviews

State-of-the-art chemical absorption technology can typically reach a capture rate of 90%-95%. Very high (>95%) capture rate can be achieved in theory, but it requires much larger investments as well as high energy consumption, which weakens the economic case.

Energy required for CO_2 capture, MJ/tCO_2



JST=Japan Science and Technology Agency

Source: Yamamoto, S. (2016), JST (2022b))

[Reference] Methodologies: Contribution to Energy Transition

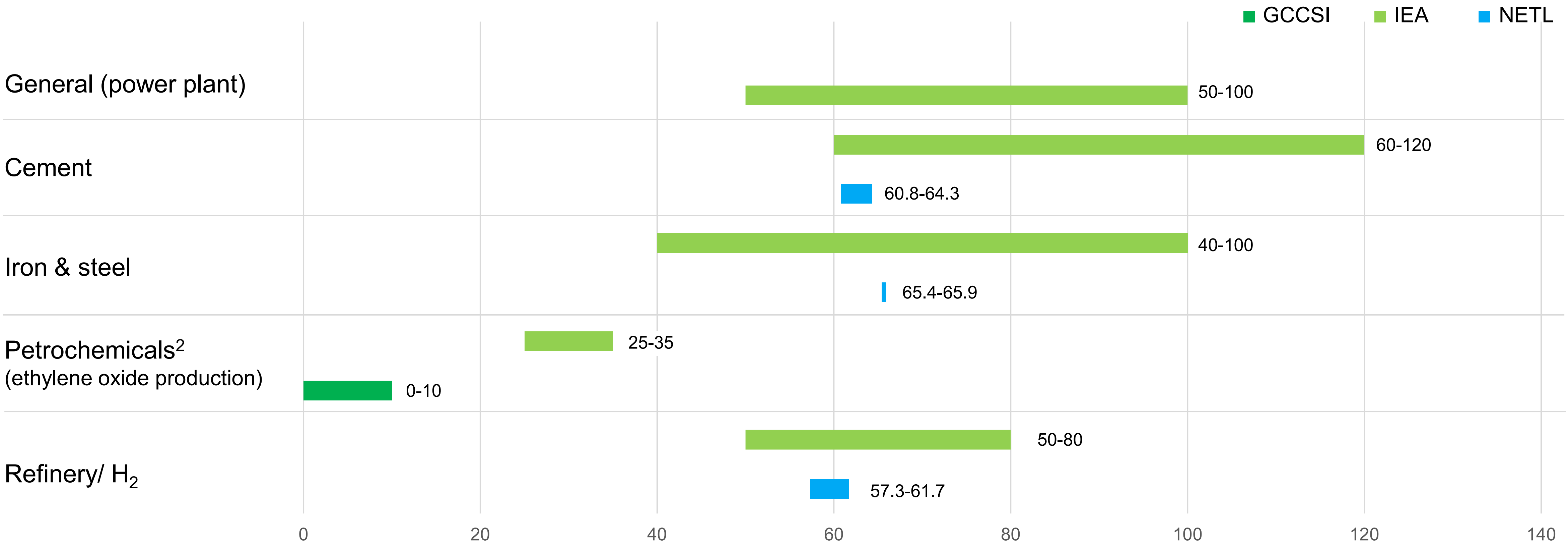
Methodology: Energy required for CO_2 capture

1. Yamamoto (2016): Energy use differs on a case-by-case basis. Factors such as properties of exhaust gas, types of solvents, equipment design etc. can influence the energy efficiency of the capture process.
2. JST: Energy required for CO_2 compression process is excluded.

Source: Yamamoto, S. (2016), JST (2022b))

(5) Affordability – Cost of capturing CO_2 varies significantly across projects due to economy-of-scale and other factors

Cost of capturing 1 tCO_2 by industry, USD/tCO_2 -eq



Source: GCCSI (2021), IEA (2020d), Hughes, S., and A. Zoelle (2022), desktop research and expert interviews

[Reference] Methodologies: Affordability

Methodology: Cost of capturing 1 tCO_2 by industry

1. Cost of capturing 1 tCO_2 by industry: Assuming the conventional amine-based chemical absorption process is applied. Average cost may vary across projects and regions, as larger emitters may benefit from economy-of-scale. Inflation and other variations in labour costs, material costs, etc. also significantly impact the financials of carbon capture projects.

2. Petrochemicals: In GCCSI (2021), for industrial processes with high concentration CO_2 or inherent CO_2 capture processes, such as ethylene oxidation production, a cost range of USD0-10 per tCO_2 captured is assumed for CO_2 conditioning.

Source: GCCSI (2021), IEA (2020d), Hughes, S., and A. Zoelle (2022), desktop research and expert interviews

(6) Reliability – Carbon capture is a mature technology, and there are recent movements to develop carbon capture projects for ASEAN industry sector

Estimated commercialisation status

	Maturity level
Chemical absorption	• **TRL 9-10** • Most widely used
Physical absorption	• **TRL 7-9** • Used in selected cases
Membrane separation	• **TRL 4**[1] • Under development

Note:
1. TRL assessment for membrane separation technology in cement kiln applications

Recent project examples

	Details
Carbon capture pilot project at Arcelor Mittal factory, Belgium 	• In May 2024, Arcelor Mittal, Mitsubishi Heavy Industries (MHI), BHP Group Ltd., along with Mitsubishi Development, announced the start of a pilot carbon capture unit on the BF off-gas at an ArcelorMittal production site in Gent, Belgium. • Starting with testing the feasibility of carbon capture from BF off-gases and off-gases from the hot strip mill reheating furnace, the pilot project may also cover the prospects of carbon capture from other important steelmaking gases such as reformer flue gas from a DRI plant.
CCU project at Thailand cement factory 	• In January 2023, Thai Siam Cement Group (SCG) signed a Memorandum of Understanding with Nippon Steel Engineering (NSE) to jointly study the feasibility of implementing ESCAP™, an in-house developed chemical absorbent CO_2 capture system, to capture CO_2 from exhaust gases emitted from SCG's cement plants in Saraburi Province. • SCG and NSE will further develop projects and business models for utilising CO_2, such as converting it into methane, with the oxygen produced during process being recycled in cement plants. In addition, a portion of the heat generated in this process will be recycled in the ESCAP™ system for maximum energy efficiency.

Source: IEA (2023b), MHI (2024), NSE (2023)

(7) Lock-in prevention – Efforts are needed to efficiently increase CO_2 recovery rate, as well as developing infrastructure for transportation, utilisation and storage

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Two paths exist for zero or near-zero emissions: – Path 1: Increase CO_2 recovery rate from current 90% to near 100% – Path 2: Develop infrastructure for transportation, utilisation and storage
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Increase CO_2 recovery rate – Although current technology can potentially achieve a capture rate close to 100%, it is not economically viable to do so. Therefore, more efforts are needed to bring down installation and operation costs, for example, by developing less energy-intensive capture methods. • Path 2: Develop infrastructure for transportation, utilisation and storage – Lack of availability of CCUS infrastructure for transportation and storage is expected to be the bottle neck, and thus a company needs to develop partnership to build a CCUS value chain. – Policy incentives to support the development of CCUS infrastructure, including carbon pricing policies, can also help strengthen the incentives for CCUS investment.

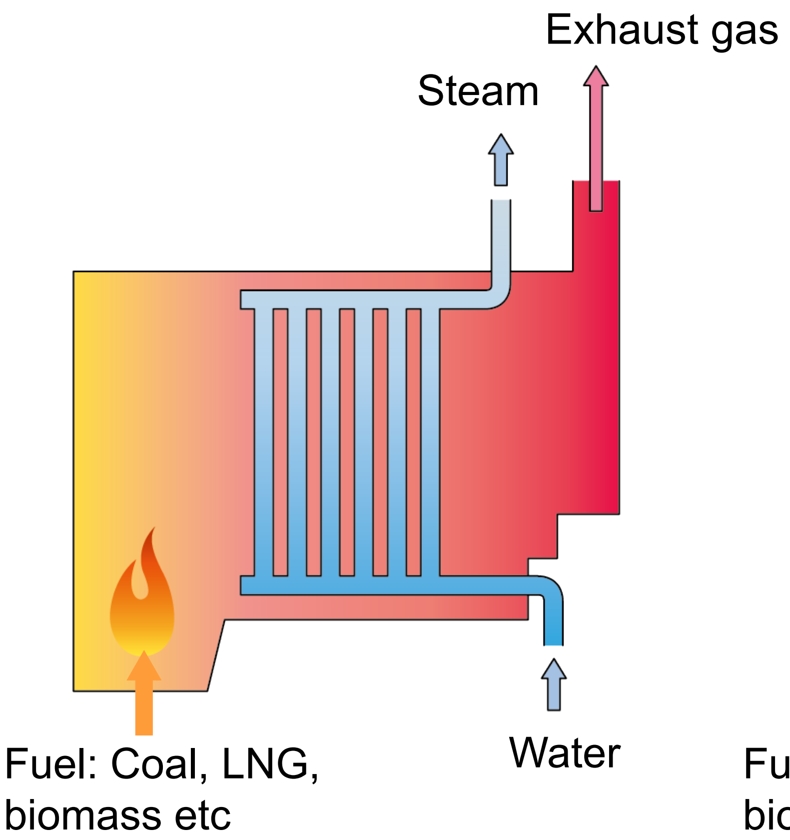
Source: Based on TLP version 1 (2022)

(8)(9) DNSH/social consideration – Appropriate measures to contain the risks from hazardous chemicals need to be in place

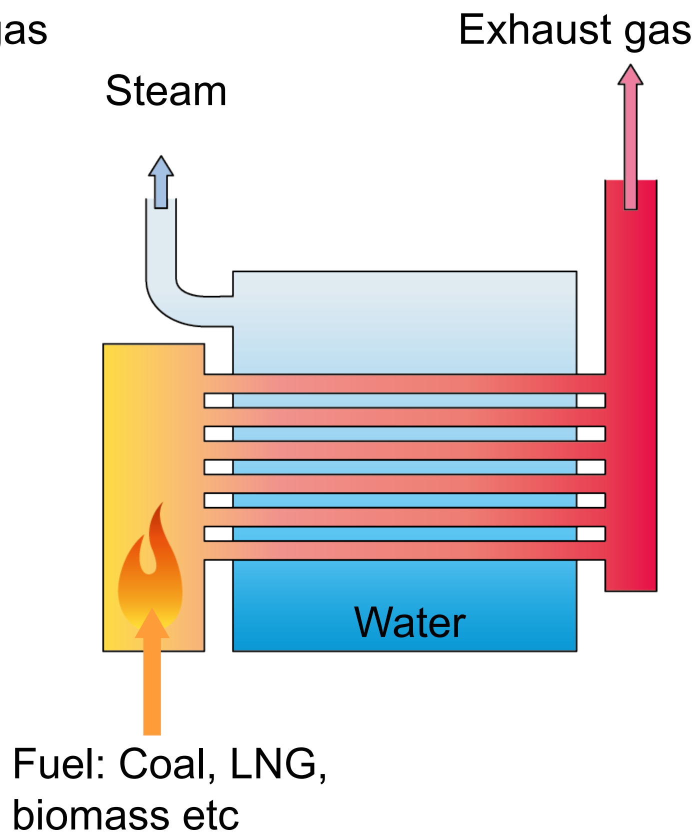
Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystem and diversity**	• The infrastructure required for carbon capture can disrupt surrounding environment due to land use changes, energy use and water use. Therefore, environmental viability assessment (or equivalents) should be conducted for major new infrastructure associated with CCUS implementation. • Solvent waste must be treated and disposed of properly according to local regulations to ensure no negative environmental impact.
	Promotion of transition to circular economy	• Since the carbon capture process can be resource intensive, it is important to ensure equipment is sourced from certified suppliers who measure, disclose, minimise, and potentially offset GHG emissions along the value chain. • Resource circularity can be achieved with the potential utilisation of captured CO_2 as construction materials (e.g. CO_2 -cured cement and construction aggregates), fuel supplements (e.g. synfuel), plastic and chemical raw materials (e.g. polycarbonate and carbon fiber) and fertiliser (e.g. biochar and greenhouse fertilisation).
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Positive impact on job opportunities is expected. CCUS requires additional skilled labour across its process chain in capturing, transporting, and gas injection. • The use of chemicals as CO_2 -capturing solvents, such as amine-based chemicals, may result in leaks. Thus, HSE risks with CCUS implementation must be assessed and prevention and mitigation measures must be implemented based on local regulations and industry standards.

Source: Based on TLP version 1 (2022) and expert interviews

(1) Lower emission fuel fuelled equipment – Technology schematics and overview



Water tube boiler



Fire tube boiler

Source: Author created based on various literature

- Boilers require heat and water to produce steam. There are two types of boilers; fire tube boilers and water tube boilers.
- In a fire tube boiler, combustion gases pass through a tube, which is surrounded by water contained in a shell. On the other hand, in a water tube boiler, water is in a tube surrounded by hot gasses.
- Lower emission fuels such as biomass, LNG, electricity, and H_2 can be used for those types of boilers. Also, they can be used either as 100% fuel, or in combination with other fossil fuels or gas.

Source: ChemTreat (n.d.)

(2) Lower emission fuel fuelled equipment– Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• Biomass, LNG and H_2 boilers have lower GHG emissions than the coal and oil equivalents. • The emission impacts depend on a boiler efficiency and heat generation capacity.
Affordability	• The lifecycle costs of heat from biomass and natural gas are cheaper than heat from oil and coal. • The major contributor to the total lifetime costs is fuel, which makes up more than 70% of the total, and the second greatest contributor is capital investment.
Reliability	• Biomass and LNG equipment (boilers and furnaces) are already available. • H_2 -fuelled equipment is not yet widely available. • Biomass boilers: TRL 10-11, Natural gas boilers: TRL 11, H_2 boilers and burners: TRL 9
Lock-in prevention considerations	• Path 1: Improve the co-firing ratio of lower emission fuels • Path 2: Improve the energy efficiency
DNSH considerations	• Solid biomass combustion can emit various air pollutants that negatively affect human health. Therefore, properly designed gas cleaning systems should be installed.
Social considerations	• Unsustainable biofuel production may pose negative effects on society such as competition for land use, impacts on food prices, impacts on biodiversity and net increases in emissions.

(3) ASEAN Taxonomy – Relevant technical screening criteria

Production of heating/cooling from renewable non-fossil gaseous and liquid fuels (1/2)

Eligibility

Includes

- Heating/cooling resulting from non-biological renewable non-fossil gaseous and liquid fuels only.
- Heating/cooling resulting from a blend of non-biological renewable non-fossil gaseous and liquid fuels and biofuels.

Excludes

- Heating/cooling as part of co-generation
- Heating/cooling resulting from bioenergy only.

Climate Change Mitigation TSC Details

Tier 1 (Green)	• Lifecycle GHG emissions < 28 gCO_2 -eq/MJ per unit of heating and/or cooling produced
Tier 2 (Amber T2)	• Lifecycle GHG emissions < 65 gCO_2 -eq/MJ per unit of heating and/or cooling produced
Tier 3 (Amber T3)	• No TSC available.
TSC applicable to all Tiers	1. Anaerobic digestion of organic biowaste or sewage which is conducted at the site of fuel combustion must comply with the following: a. Implement monitoring and contingency plan to minimise methane leakage; b. Biogas produced onsite at a facility for the conduct of this Activity must be used only for this Activity or other Activities defined by the ASEAN Taxonomy, etc.; AND c. Any bio-waste that is used for anaerobic digestion is source segregated and collected separately. 2. For facilities that are equipped with CCUS, CO_2 from energy provision that is captured for underground storage, must be transported and stored in accordance with the TSC for Activities 000[010] and 000[020]

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Production of heating/cooling from renewable non-fossil gaseous and liquid fuels (2/2)

Eligibility	Climate Change Mitigation TSC	Details
Includes • Heating/cooling resulting from non-biological renewable non-fossil gaseous and liquid fuels only. • Heating/cooling resulting from a blend of non-biological renewable non-fossil gaseous and liquid fuels and biofuels. **Excludes** • Heating/cooling as part of co-generation • Heating/cooling resulting from bioenergy only.	**Tier 1 (Green)**	• Lifecycle GHG emissions < 28 gCO_2 -eq/MJ per unit of heating and/or cooling produced
	Tier 2 (Amber T2)	• Lifecycle GHG emissions < 65 gCO_2 -eq/MJ per unit of heating and/or cooling produced
	Tier 3 (Amber T3)	• No TSC available.
	TSC applicable to all Tiers	3. The Activity meets either of the following criteria: a. at construction, measurement equipment for monitoring of physical emissions, such as methane leakage, is installed, or a leak detection and repair programme is introduced; b. at operation, physical measurement of methane emissions is reported, and leak is eliminate

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

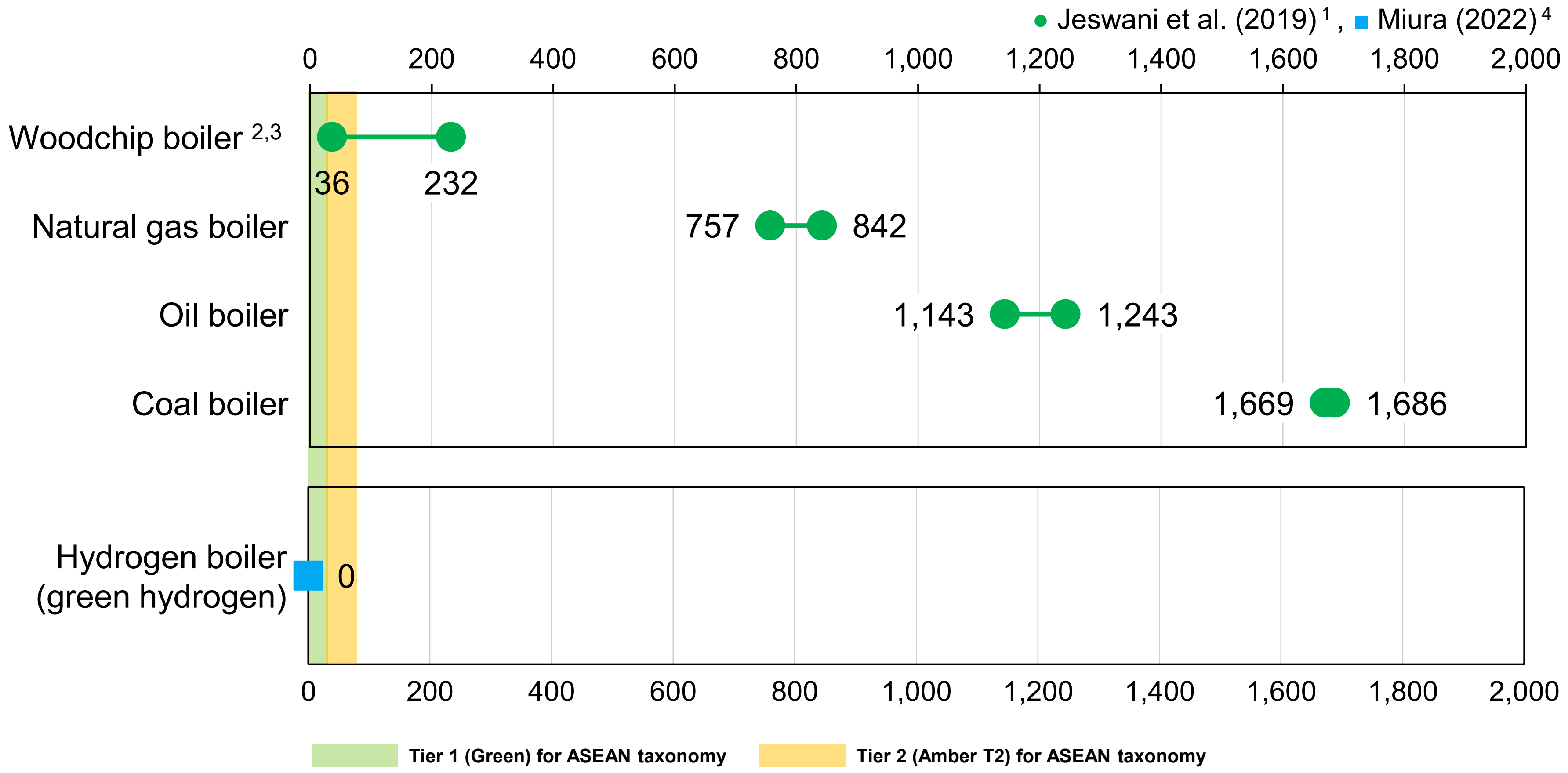
Production of heating/cooling from fossil gas

Eligibility	Climate Change Mitigation TSC	Details
Includes	**Tier 1 (Green)**	• Lifecycle GHG emissions < 28 gCO_2-eq/MJ per unit of heating and/or cooling produced
	Tier 2 (Amber T2)	• Lifecycle GHG emissions < 65 gCO_2-eq/MJ per unit of heating and/or cooling produced
	Tier 3 (Amber T3)	• No TSC available.
Excludes • Fossil heating/cooling as part of co-generation	**TSC applicable to all Tiers**	1. For facilities that are equipped with CCUS, CO_2 from energy provision that is captured for underground storage, must be transported and stored in accordance with the TSC for Activities 000[010] and 000[020]. 2. The Activity meets either of the following criteria: a. at construction, measurement equipment for monitoring of physical emissions, such as methane leakage is installed, or a leak detection and repair programme is introduced; OR b. at operation, physical measurement of methane emissions is reported, and leak is eliminated. 3. This Activity permits the storage of fossil gas, as long as it meets the thresholds shown, which are aligned with principles explained above in the bases for TSC setting. This inclusion is subject to review and may be revised at the end of the first TSC Period.

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition – Biomass and H_2 boilers have lower emissions than the coal or oil equivalents

CO_2 emissions for heat generation, gCO_2 /MJ



Tier1 and Tier2 refers to Climate Change Mitigation TSC for Production of heating/cooling from fossil gas. Since ASEAN TSC is based on lifecycle GHG emissions, while this graph represents operational emissions only, a direct comparison is not available. The Tier1 and Tier2 ranges are provided for reference only. (1MWh=3,600MJ)

Comparison with ASEAN Taxonomy

There are two TSCs which are potentially applicable to lower emission fuel fuelled equipment. Those TSCs set threshold on lifecycle GHG emissions per heat generated.

Lifecycle GHG emissions would vary depending on many factors, e.g. distance and means of fuel transport, lifetime of a boiler, the end-of life processes etc. Therefore, eligibility towards the ASEAN Taxonomy labelling should be assessed on a project-to-project basis.

The left graph uses the TSC for "producing heating/cooling from fossil gas". Since the TSC is based on lifecycle GHG emissions, while this graph represents operational emissions only, a direct comparison is not available. The ASEAN Taxonomy's Tier1 and Tier2 ranges are provided for a reference purpose only.

Source: Jeswani, H. K., A. Whiting, and A. Azapagic (2019), Takemoto, M. (2022)

[Reference] Methodologies: Contribution to Energy Transition

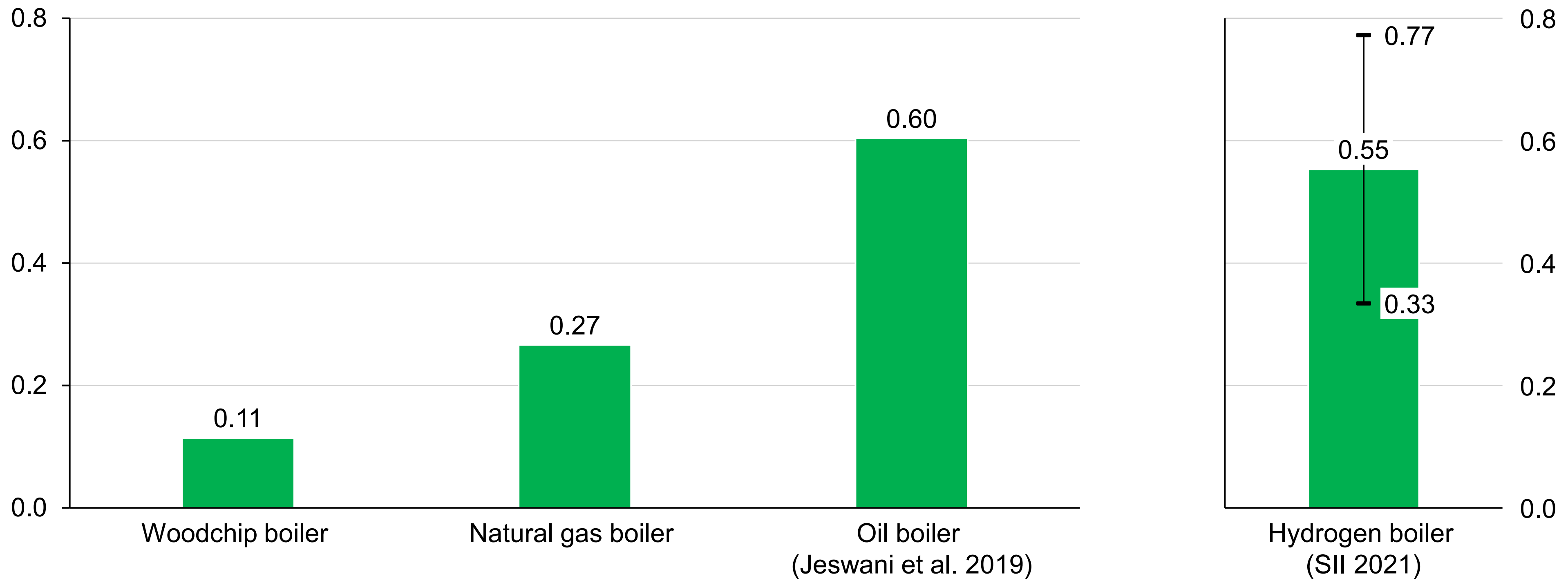
Methodology: CO_2 emissions for heat generation

1. Jeswani et al. (2019): Boiler capacity: 470kW, lifetimes: 20 years, thermal efficiency: 76%
2. Woodchip boiler: Including the provision of biomass feedstock, boiler construction, operation, decommissioning, and ash disposal.
3. Woodchip boiler: Emissions vary based on the type of biomass fuel used, ranging from 10 to 64 $kgCO_2$/MWh according to existing LCA research. Emissions vary depending on the transportation distances, the amount of electricity needed for palletisation, and the ways of ash disposal.
4. Miura (2022) calculated the amount of CO_2 emissions when producing one ton of steam (steam pressure 0.7 MPa). Based on this data, emissions for different fuel types of boiler were calculated assuming the specific enthalpy of saturated steam (dry saturated steam) at a pressure of 0.7 MPa to be 2,755 kJ/kg.
5. In the calculation above, hydrogen was assumed to be produced from renewable sources. However in the transition period, CO_2 emissions for H_2 boilers depend on the method of H_2 production.

Source: Jeswani, H. K., A. Whiting, and A. Azapagic (2019), Takemoto, M. (2022)

(5) Affordability – H_2 boiler has the highest installation cost and abatement cost when replacing coal boiler; Would decrease with H_2 supply chain establishement

Abatement cost, USD/kgCO_2



Source: MOE (2024b), Jeswani, H. K., A. Whiting, and A. Azapagic (2019), SII (2021), IEA (2024e)

[Reference] Methodologies: Affordability

Methodology: Abatement cost

1. Abatement costs were calculated by dividing the total cost of each boiler by the expected reductions that would result from replacing the coal boiler.
2. For the fuel costs of woodchip, natural gas, and oil, the estimated unit costs in the Asian region were referenced from literature published in 2013. Specifically, the unit cost of fuel in the Asian region as of 2024 was adjusted using the average inflation rate in the ASEAN region to derive the unit cost of fuel as of 2012.
3. Hydrogen fuel costs refer to the IEA's 'Global average levelised cost of hydrogen production by energy source and technology, 2019 and 2050'.

Source: MOE (2024b), Jeswani, H. K., A. Whiting, and A. Azapagic (2019), SII (2021), IEA (2024e)

(6) Reliability – Biomass boilers, LNG boilers, and electric boilers are already available while H_2 boilers are not yet widely available

Estimated commercialisation status

- Biomass boilers: TRL 10-11
  Biomass based boilers providing steam and low-temperature heat to industrial processes are already available and cost-effective, especially for processes with capacities above 1 MW.
- Natural gas boilers: TRL 11
  Natural gas based boilers are commercialised and widely available.
- H_2 boilers and burners: TRL 9
  H_2 boilers and burners have been commercialised but not widely deployed yet.

Recent project examples

Biomass-based steam generation in a food factory

Details

- In June 2020, DANONE Group for its Indonesian entity PT Sarihusada Generasi Mahardhika implemented a biomass-based steam generation project.
- By replacing the fossil-fired thermal system with the 100% biomass boiler, CO_2 emissions reduce by 5,800 tCO_2 /year.

Installation of LNG boilers in a plastic plant

- In 2018, Polyplastics' Fuji Plant changed the fuel from C fuel oil to LNG for its boilers.
- As a result, SO_x emissions reduced by 99%, NO_x emissions reduced by 30%, and CO_2 emissions reduced by 20%.

Source: BECIS (n.d.), Polyplastics (2018)

(7) Lock-in prevention – Net zero will be achieved by improving the co-firing ratio, improving the energy efficiency, or lowering fuels' carbon intensity

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Two paths exist for lower emission fuel fuelled equipment to be zero or near-zero emissions: – Path 1: Improve the co-firing ratio of lower emission fuels – Path 2: Improve the energy efficiency
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path1: Improve the co-firing ratio of lower emission fuels – Switching to lower emission fuel will reduce CO_2 emissions from fuel combustion equipment. – The local availability of lower emission fuels such as H_2 or biomass should be improved by reducing the cost of collection, handling, preparation, storage and transportation. However, the lack of investment in the necessary infrastructure is one of the largest hindered to the widespread use of lower emission fuels for heat generation systems. – Switching from heavy oil or coal to natural gas will reduce CO_2 emissions; however, since emissions cannot be completely eliminated, it will be necessary to transition to H_2 or carbon-free gas. – Impacts on product quality when using biomass, waste and H_2 in the heating process need to be properly assessed. • Path2: Improve the energy efficiency – Further R&D is essential to improve energy efficiency.

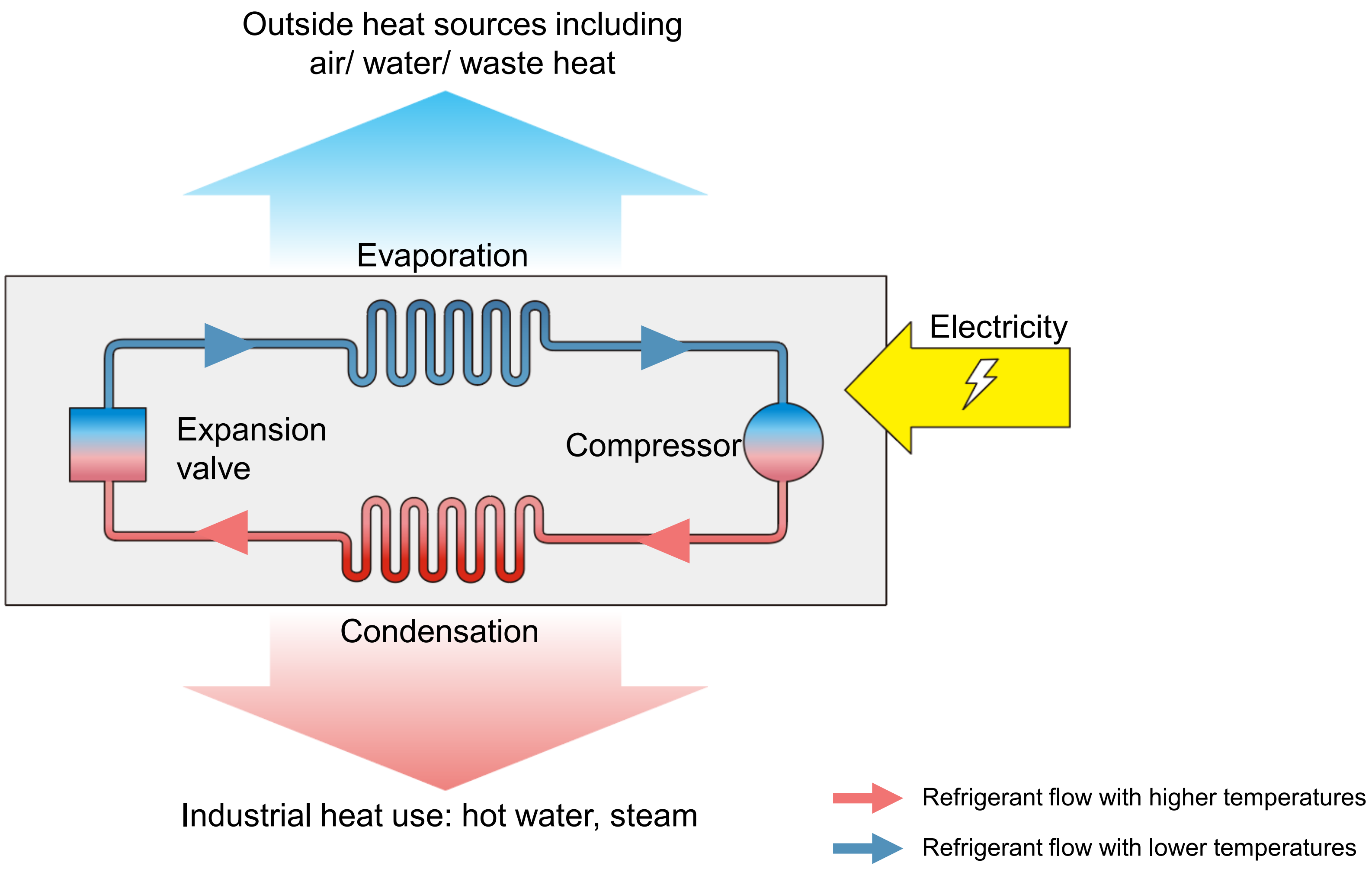
Source: IRENA and IEA-ESTAP (2013a)

(8)(9) DNSH/social consideration – When using biomass or H_2 fuels, it is essential to consider safety management and competition with existing usage of feedstocks

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• Biomass, such as waste wood contaminated with heavy metals and organochlorine compounds may emit additional gaseous pollutants such as NO_x and SO_x. • Unsustainable biofuel production may pose negative effects on society such as competition for land use, impacts on food prices, impacts on biodiversity and net increases in emissions. • There is a possibility of damage to the surrounding environment due to H_2 leaks or fires, so safety management measures are required.
	Transition to circular economy	• When biomass is burned, ash accumulates as waste in the boiler and filter, which needs to be properly disposed of or recycled.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Solid biomass combustion can emit various air pollutants that negatively affect human health. Emissions levels vary significantly according to a type of heating system, how the system is operated, and the characteristics of the fuel used. • Air pollutants can cause a negative impact to human health but can be reduced by installing appropriately designed flue gas cleaning systems.

Source: IEA (2019a), IEA (2023a)

(1) Large-scale industrial heat pump– Technology schematics and overview



Source: Author created based on various literature

In contrast to their use in the building sector, heat pumps in the industrial sector are generally larger in scale and require higher operating temperatures.

Large-scale industrial heat pumps (IHP) can transfer thermal energy from a lower-temperature source such as air, or water. IHPs can provide hot water, hot air or steam to industrial processes.

Nowadays, IHP with output temperature below 100 °C are well-commercialised for industrial use. High-temperature IHP are mainly concentrated in temperature range from 100 °C to 160 °C. Systems capable of reaching higher temperatures (>200°C) are still under development and have limited applications in the current market.

Source: IEA (2022b)

(2) Large-scale industrial heat pump– Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• As a green alternative to conventional gas boilers, IHP could achieve lower emissions by electrification. • Emission reductions effects vary from country to country due to the difference in their grid emission factors. Efficiencies of IHP can vary significantly depending on various conditions.
Affordability	• Investment cost for IHP under 100°C are relatively lower than those above 100°C owing to their higher level of commercialisation. • The cost depends strongly on the size and application of the heat pump for the given technology.
Reliability	• IHP for low-temperature processes are highly commercialised while high-temperature applications are still under development. • Temperature < 100 °C: TRL 10-11, Temperature > 100 °C: TRL 6-8.
Lock-in prevention considerations	• Path 1: Improve energy efficiency to reduce electricity consumption • Path 2: Cut F-gas emissions by preventing leaks of the refrigerants and using natural refrigerants • Path 3: Develop clean energy to achieve lower carbon intensity of local electricity
DNSH considerations	• F-gas emissions occur during the refrigeration cycle when using and decommissioning of heat pumps. • IHPs may require more materials for piping, compressors, etc. compared to gas boilers. These parts and materials as well as refrigerants need to be properly collected and recycled.
Social considerations	• Safety measures based on flammability or toxicity levels is needed to ensure the safety of O&M workers and installers. • Large industrial equipment can affect nearby communities in terms of noise.

(3) ASEAN Taxonomy – Relevant technical screening criteria

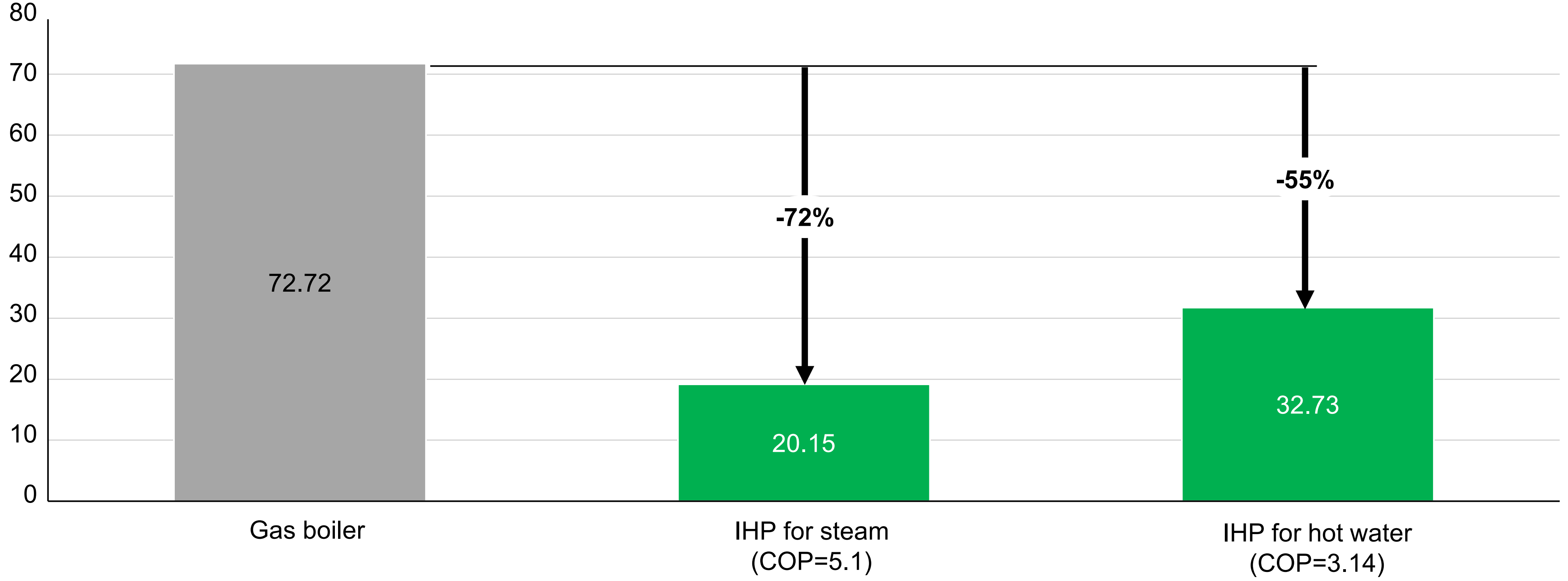
Production of heating/cooling using electric heat pump

Eligibility	Climate Change Mitigation TSC	Details
Includes -	**Tier 1 (Green)**	• Activity is operation of electric heat pumps complying with both of the following criteria: i. Refrigerant threshold: Global Warming Potential does not exceed 675; ii. Demonstrate a high standard of energy efficiency according to an internationally recognised certifications scheme.
	Tier 2 (Amber T2)	• No TSC available.
Excludes -	**Tier 3 (Amber T3)**	• No TSC available.

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition – Efficiencies of IHP can vary significantly depending on various conditions such as supply temperature

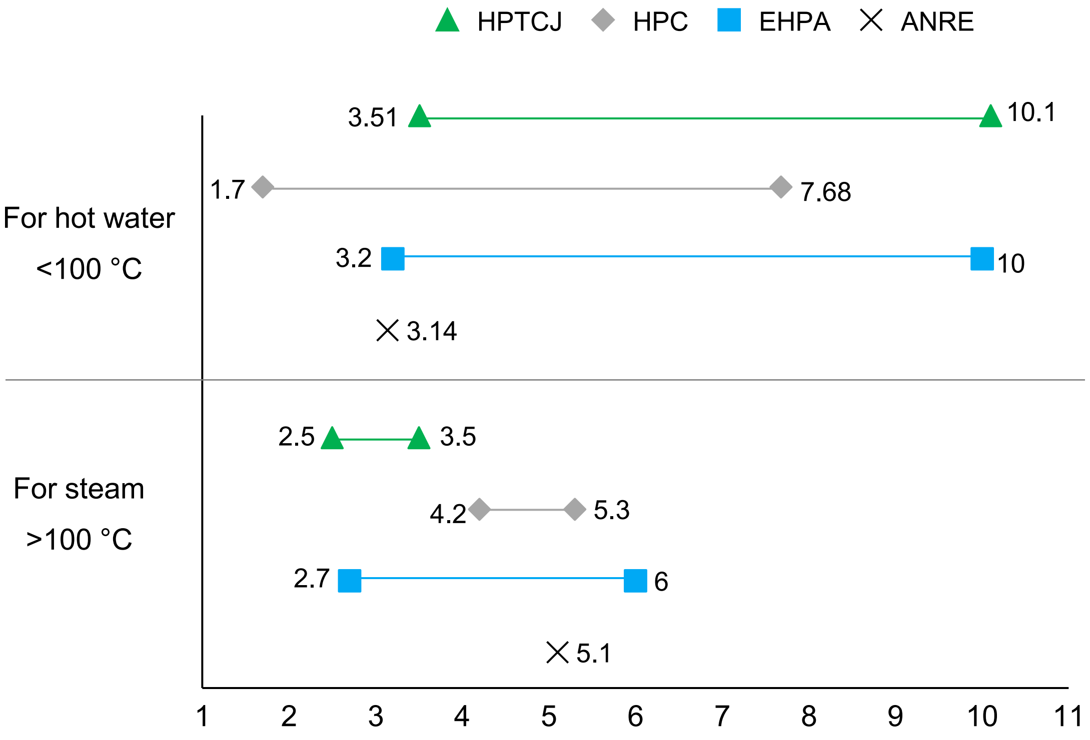
CO2 emission for heat production [3], $kgCO_2$ /GJ



Source: HPC (2023), EHPA (2022a), HPTCJ (2023), MRI (2017)

[Reference] Methodologies: Contribution to Energy Transition

Methodology: Energy efficiency of IHP by supply temperature



1. W/W represents the ratio of the energy output (heat or cooling energy) to the energy input (electrical energy). This unit expresses COP, which measures the heat pump's efficiency.
2. The data was collected from catalogue information provided by representative manufacturers at each source. According to HPTCJ, IHP data is typically categorized by supply temperature: under 100°C mainly for hot water, and over 100°C mainly for steam.

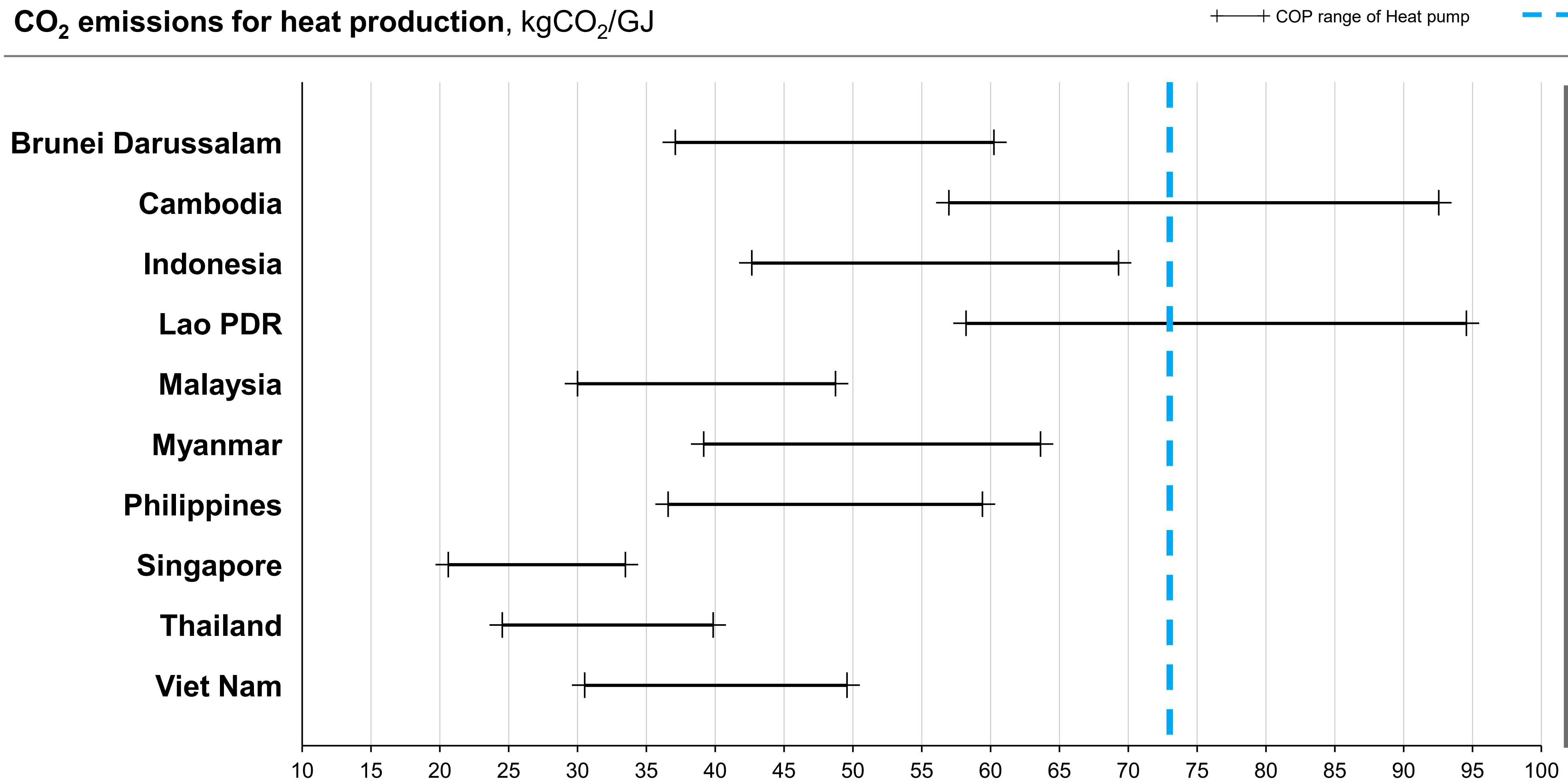
Methodology: CO2 emission for heat production

1. Emission impact for heat pumps were calculated by {the energy input (kWh) * emission factor of the energy(tCO_2 -eq/ kWh)} /{heat produced (MJ or GJ)* the energy conversion coefficient)}. As an example, COP of 5.1 was assumed for IHPs operating above 100 °C, and 3.14 for those below 100 °C, emission factor of electricity at 370gCO_2-eq/kWh based on data from Japan's IHP subsidy project by ANRE (2018). To compare the CO_2 savings, the baseline refers to a conventional gas boiler with efficiency at 90%.

Source: HPC (2023), EHPA (2022a), HPTCJ (2023), MRI (2017)

(4) Contribution to Energy Transition – IHP achieves lower emissions compared to natural gas boilers; Emission effects differ among ASEAN due to varying grid mix

CO_2 emissions for heat production, $kgCO_2/GJ$



Comparison with ASEAN Taxonomy

There is one TSC potentially applicable to heat pumps for the industrial use.

TSC for heating/cooling using electric heat pump sets a threshold on GWP of refrigerant used in a heat pump, which should be assessed on a product by product basis and therefore a direct comparison is not available.

IHPs typically use HFCs[1], HFOs[2] or natural refrigerants such as CO_2 and ammonia. The representative GWP of these refrigerants is as follows: HFCs (R134a): 1430, HFOs(R1234zd):1, CO_2(R744):1, ammonia (R717)<1. Under the ASEAN Taxonomy, refrigerants with a GWP of 675 or lower are classified as "Tier 1 (Green)."

Notes:
1. HFC = Hydrofluorocarbons
2. HFO = Hydrofluoroolefin

[Reference] Methodologies: Contribution to Energy Transition

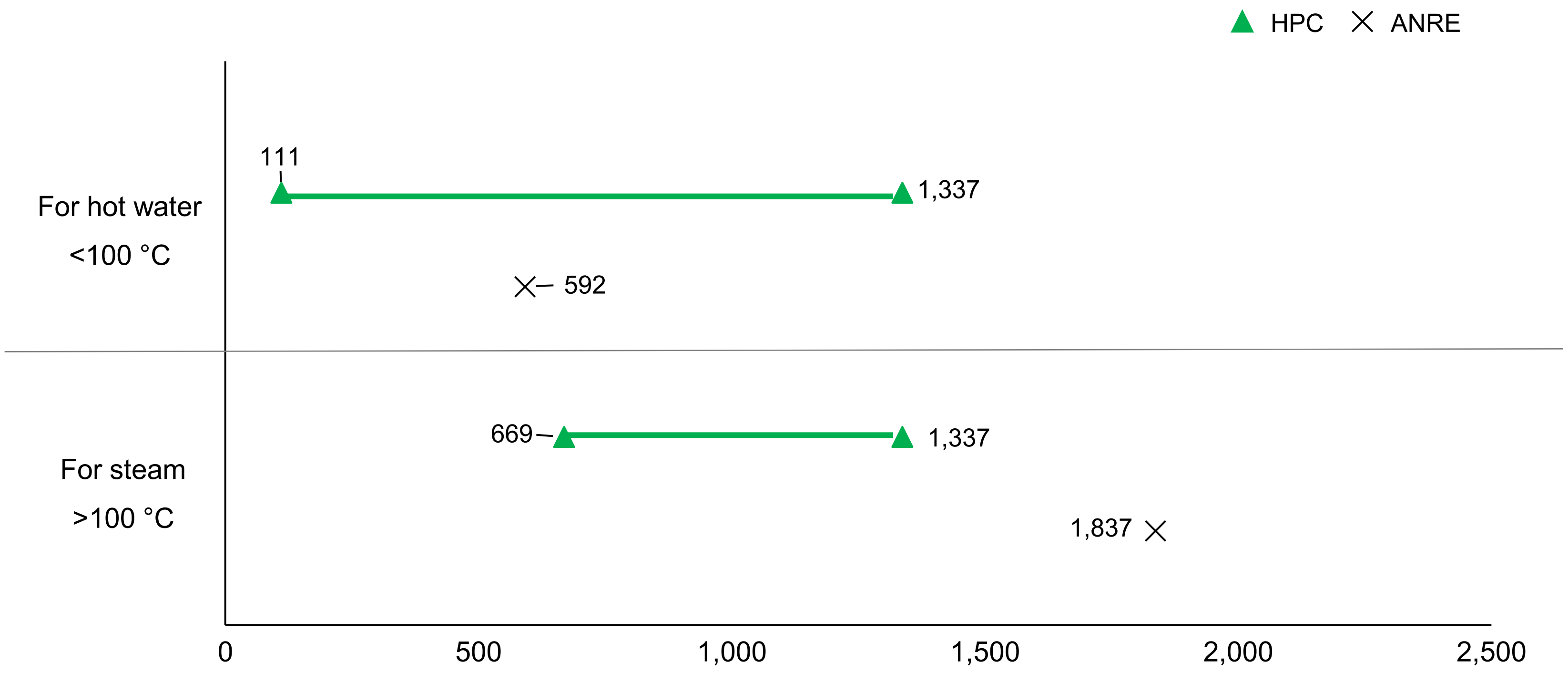
Methodology: CO_2 emissions for heat production

1. The ranges of CO_2 emissions for heat production reflect variations in the efficiency of heat pump installations, with assumed COP from 3.1 to 5.1.
2. Emission impact for heat pumps were calculated by {the energy input (kWh) * emission factor of the energy(tCO_2 -eq/ kWh)} /{heat produced (MJ or GJ)* the energy conversion coefficient)}. As an example, COP of 5.1 was assumed for IHPs operating above 100 °C, and 3.14 for those below 100 °C, emission factor of electricity at 370gCO_2-eq/kWh based on data from Japan's IHP subsidy project by ANRE (2018). To compare the CO_2 savings, the baseline refers to a conventional gas boiler with efficiency at 90%.
3. The maximum emission for each range assume COP at 3.1, while the minimum emission assume COP at 5.1.
4. The higher COP indicates greater energy efficiency which result in lower emission when producing the same amount of heat. Grid emission factors refer to the database from UNFCCC (2021), Harmonized Grid Emission Factor data.

Source: HPC (2023), EHPA (2022a), HPTCJ (2023), MRI (2017)

(5) Affordability – Investment cost for IHP under 100°C are relatively lower than those above 100°C owing to their higher level of commercialisation

Investment cost[1], USD/kW



- For temperatures under 100°C, there are relatively more manufacturers and a wider range of IHPs available on the market, typically resulting in lower costs compared to those above 100°C.
- In addition to the investment cost shown in the left graph, integration cost and O&M cost also need to be considered when implementing IHP technologies. These additional costs can differ significantly depending on various factors such as the design of the industrial process and electricity prices in each region.

Source: HPC (2023), MRI (2017), Zuberi, M.J.S., A. Hasanbeigi, and W. R. Morrow (2022)

[Reference] Methodologies: Affordability

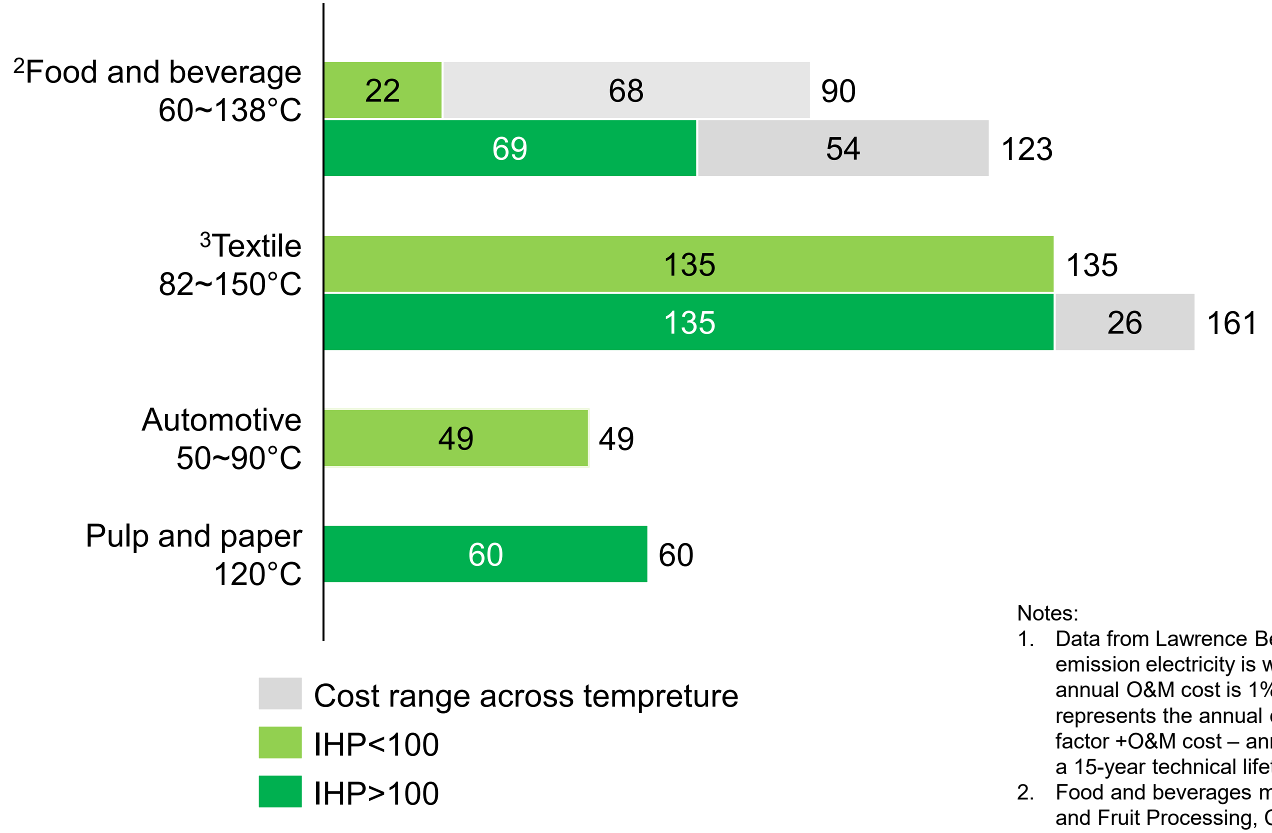
Methodology: Investment cost

1. Same as COP, the cost data were categorised by supply temperature: under 100°C mainly for hot water, and over 100°C mainly for steam. Investment costs refer to CAPEX only.

Source: HPC (2023), MRI (2017), Zuberi, M.J.S., A. Hasanbeigi, and W. R. Morrow (2022)

[Reference]The abatement cost of IHP varies significantly over industrial process, temperature, and electricity prices, needing case-specific assessment

Abatement costs 2050[1], USD/tCO_2



- The abatement cost of IHP is substantially influenced by variables including applied industrial processes, temperature, and electricity prices. Therefore, the abatement cost needs to be evaluated on a case-by-case basis across varying national and industrial contexts, as there is currently no one-size-fits-all solution.
- As a reference, a recent study based on U.S. conditions shows that the CO_2 abatement costs of IHP in different industries across various temperature applications could range from USD 22 to 135 and USD 60 to 161 tCO_2 for IHP application under 100 °C and above 100 °C, respectively.

Notes:
1. Data from Lawrence Berkeley National Laboratory(2022). predicted the abatement cost that can be achieved by IHP in 2050 where net zero emission electricity is widely available. The figures were calculated based on the hypothesis that the grid emission factor is zero and the annual O&M cost is 1% of the capital costs. The difference between natural gas and electricity costs for the same amount of heat generation represents the annual cost benefits. The used formula can be described as: Abatement cost =(Capital investment cost*Capital recovery factor +O&M cost – annual cost benefits)/potential CO_2 abatement. The recovery factor is calculated based on a 10% real discount rate and a 15-year technical lifetime for the IHP.
2. Food and beverages merge the range of its subcategories including Beet Sugar, Cane Sugar Refining, Meat Processing, Canned Vegetable and Fruit Processing, Canned Fruits, Corn Wet-milling, Soybean Oil, Beer, and Dairy.
3. Textile merges the range of Textile and Textile Wet-Processing.

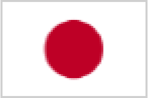
Source: Zuberi, M.J.S., A. Hasanbeigi, and W. R. Morrow (2022)

(6) Reliability – IHP for low-temperature processes are highly commercialised while high-temperature applications are still under development

Estimated commercialisation status

- **Temperature < 100 °C: TRL 10-11.** Well-commercialised for low-temperature processes in the paper, food and chemicals industries.
- **Temperature > 100 °C : TRL 6-8.** There are already some products in the 100 °C to 160°C temperature range, but higher temperature heat pumps are still under development. The higher the temperature, the lower the TRL.

Recent project examples

	Details
20% energy saving and 40% CO_2 emission reduction by replacing conventional boilers with IHP 	• Mitsubishi Heavy Industries Thermal Systems, Ltd., a Japanese machinery company, received the Energy Conservation Center, Japan Chairman's Award in 2023 for its efforts to implement IHP. • By replacing conventional boilers with IHP for hot water (60~75°C) needed processes like parts cleaning and surface treatment, this initiative achieved a 20% reduction in crude oil equivalent consumption and a 40% decrease in CO_2 emissions.
R&D and demonstration of high-temperature heat pumps using natural refrigerants	• The Sustainable process heating with high-temperature heat pumps using natural refrigerants (SuPrHeat) project is a research, development and demonstration project with 16 partners from Denmark, Germany, UK and Sweden to facilitate the uptake of high-temperature heat pumps(up to 200 °C) in industry process and heat supply.

Source: SuPrHeat (n.d.), Daily Industrial News (Nikkan Kogyo Shimbun) (2024), MHI (2023b)

(7) Lock-in prevention – Process optimisation and sustainable power would be the key to achieve net zero

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Two paths exist for IHP to be zero or near-zero emissions – Path 1: Improve energy efficiency to reduce electricity consumption – Path 2: Cut F-gas emissions by preventing leaks of the refrigerants and using natural refrigerants – Path 3: Develop clean energy to achieve lower carbon intensity of local electricity
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Energy efficiency – High cost for high-efficiency equipment. • Path 2: F-gas emissions – Although there are already many products using natural refrigerants, many products use F-gas as refrigerants. • Path 3: Clean energy – Using IHP in regions where electricity is not yet green may not be the most sustainable choice until the grid becomes greener over time. – Nearly 76.7% of the electricity in ASEAN still generated from fossil fuel power plants. Shift from fossil fuel to clean energy is required for indirect emission reduction of heat pumps.

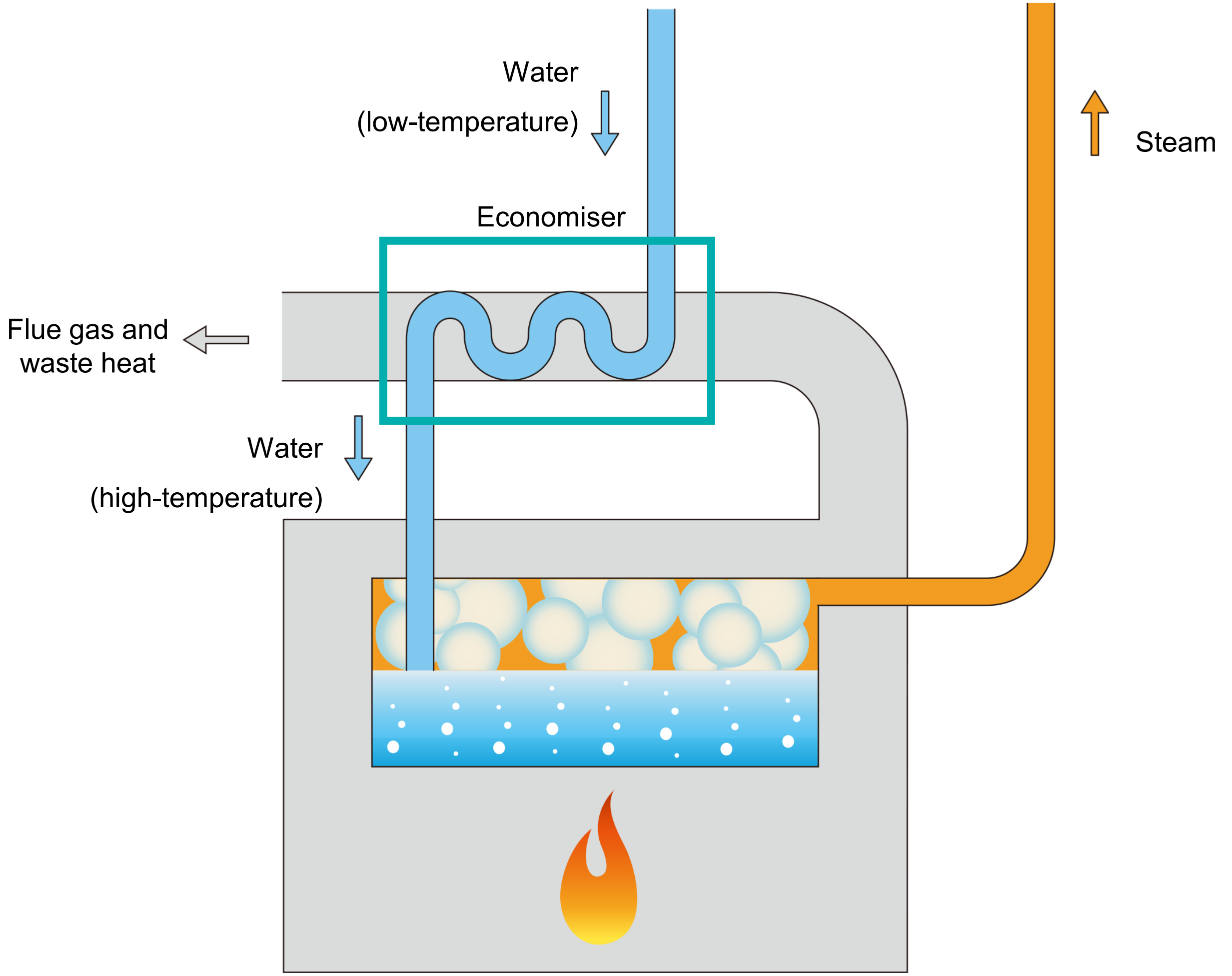
Source: HPC (2024c), HPC (2024a), ACE (2023)

(8)(9) DNSH/social considerations – high temperature with high pressure, and noise pollution could lead to negative impact

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• F-gas emissions occur during the refrigeration cycle when using and decommissioning of heat pumps. • IHPs are increasingly utilizing natural refrigerants, such as water, CO2 and ammonia. These options have minimal environmental impact compared to conventional HFCs, though hydrocarbons pose flammability risks.
	Transition to circular economy	• IHPs may require more materials for piping, compressors, etc. compared to gas boilers. These parts and materials as well as refrigerants need to be properly collected and recycled.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Safety measures based on flammability or toxicity levels is needed to ensure the safety of O&M workers and installers. • Large industrial equipment can affect nearby communities in terms of noise. Communication with local communities and environmental compliance are necessary to minimise community impact.

Source: HPC (2024b), and expert interview.

(1) Waste Heat Recovery– Technology schematics and overview



Schematics of WHR using economiser as an example

Source: Author created based on various literature

- Waste heat recovery (WHR) technology involves recovering and transferring waste heat from processes that use gases or liquids and returning it to the system as an extra energy source. As a result, it can reduce fuel consumption and emissions.
- According to McKinsey & Company (2023), the global recoverable waste heat potential is at least 3,100 TWh per year, compared to the current global final energy consumption of 116,000 TWh.
- Since there are various types of WHR equipment, it is important to select a type based on the temperature of the waste heat and combination with existing facilities;
  - Economiser
  - WHR boiler
  - Heat recovery steam generator
  - Absorption chiller
  - Steam thermocompression
  - Heat pump

Source: McKinsey & Company (2023)

(2) Waste Heat Recovery– Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• WHR can reduce energy consumption, resulting in CO_2 emissions reduction. • The global recoverable waste heat potential is at least 3,100 TWh per year, compared to the current global final energy consumption of 116,000 TWh per year [1]. • A WHR boiler potentially can reduce CO_2 emissions by more than 1,000t annually.
Affordability	• The overall cost of steam generated from waste gas source ranges from USD1.2-4.5/t steam, and the abatement cost ranges from USD 8-30 /tCO_2.
Reliability	• TRL 10-11,WHR is well-commercialised globally. The use of WHR may be limited in ASEAN but is expected to grow as the awareness for energy efficiency and climate change mitigation grows.
Lock-in prevention considerations	• Path1: Improve WHR ratio at low-temperature • Path2: Replace coal and natural gas with less carbon-intensive fuels, such as biomass and H_2. • Path3: Plan a layout of the manufacturing plant taking WHR equipment and heat sharing into consideration from the initial stage.
DNSH considerations	• WHR technologies potentially mitigate the heat island effect. • WHR replaces some of the need for additional boilers thus contributes to the transition to circular economy.
Social considerations	• Many thermoelectric conversion materials utilise cadmium, tellurium, and mercury, which require attention to their effects on human health.

Source: McKinsey & Company (2023), Based on the data from MOE (n.d.)

(3) ASEAN Taxonomy – Relevant technical screening criteria

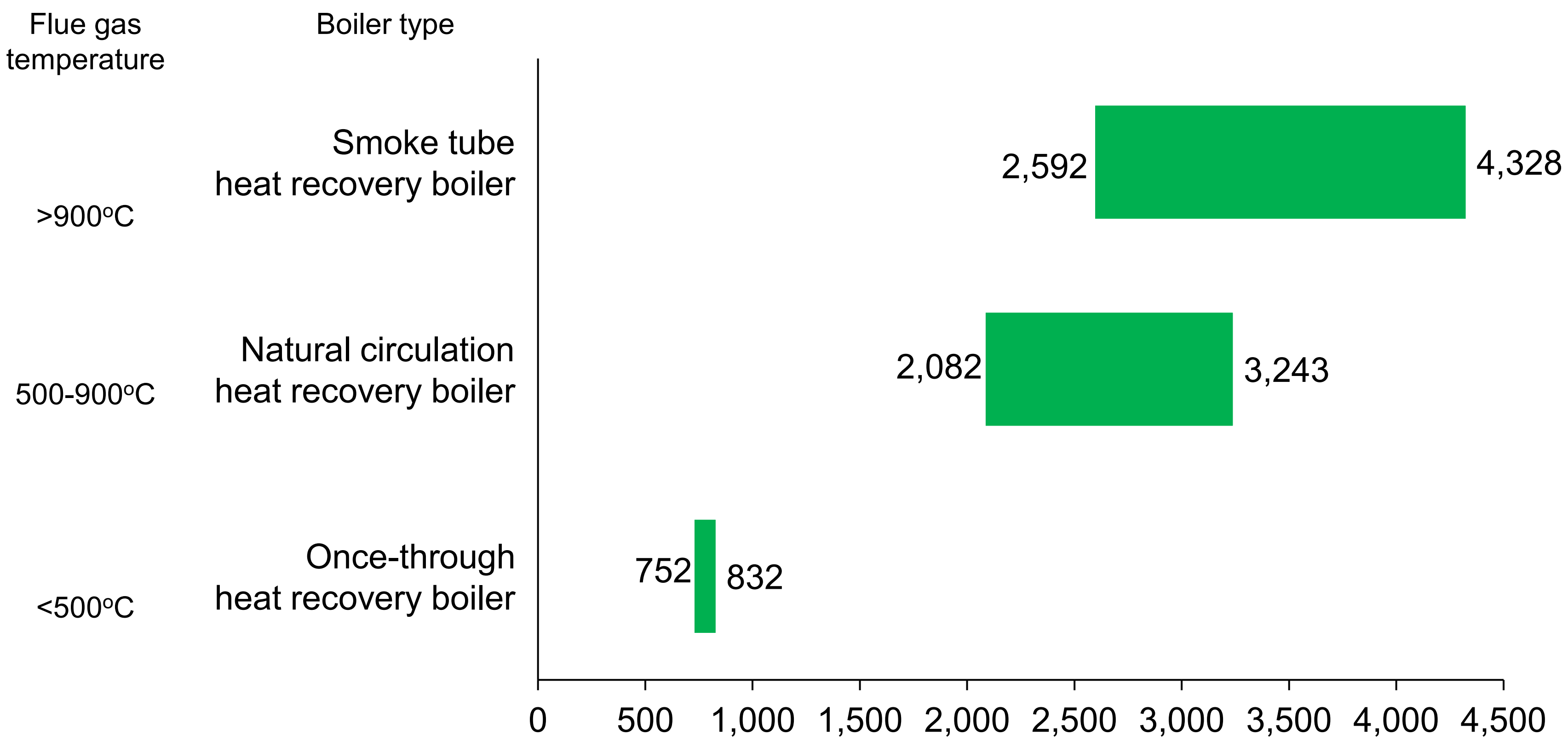
Production of heating/cooling using waste heat

Eligibility	Climate Change Mitigation TSC	Details
Includes	**Tier 1 (Green)**	1. Heating/cooling from waste heat resulting from another process; AND 2. It must be shown that such waste heat would otherwise be lost and would result in no utility
	Tier 2 (Amber T2)	• No TSC available.
	Tier 3 (Amber T3)	• No TSC available.
Excludes • Any heating/cooling conducted by a co-generation (CHP) plant		

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition –WHR boilers potentially reduce CO_2 emissions by more than 1,000t annually

Annual emission reduction of WHR boilers, tCO_2/year



- There are mainly three types of WHR boilers, and it is recommended to choose an appropriate WHR boiler based on the flue gas temperature.
  - For temperatures below 500°C, a once-through WHR boiler is suitable.
  - For temperatures between 500-900°C, a natural circulation heat recovery boiler is suitable.
  - For temperatures between 900-1,450°C, a smoke tube heat recovery boiler is suitable.

Comparison with ASEAN Taxonomy

All the WHR boilers can be labelled as "Green" as heating/cooling from waste heat resulting from another processes is the criterion for the green label under the TSC for "production of heating/cooling using waste heat".

Source: Based on Miura (2024), Kawasaki Thermal Engineering (2024), IPCC (2006a)

[Reference] Methodologies: Contribution to Energy Transition

Annual emission reduction of WHR boilers

1. Assuming the CO_2 emissions from the WHR boiler are zero, the difference in emissions compared to a natural gas boiler producing the same amount of heat is considered the "annual emission savings".
2. Natural gas boiler's efficiency is assumed to be 85%. The emission factor is 1.885 kg/m^3 (IPCC 2023).
3. The operating time of boilers is assumed to be 6,000 hours per year.
4. The flue gas volume, inlet temperature, steam pressure, and steam quantity were set based on the boiler manufacturer's catalogue. The outlet temperature was assumed to be 150°C and the feedwater temperature was assumed to be 60°C.

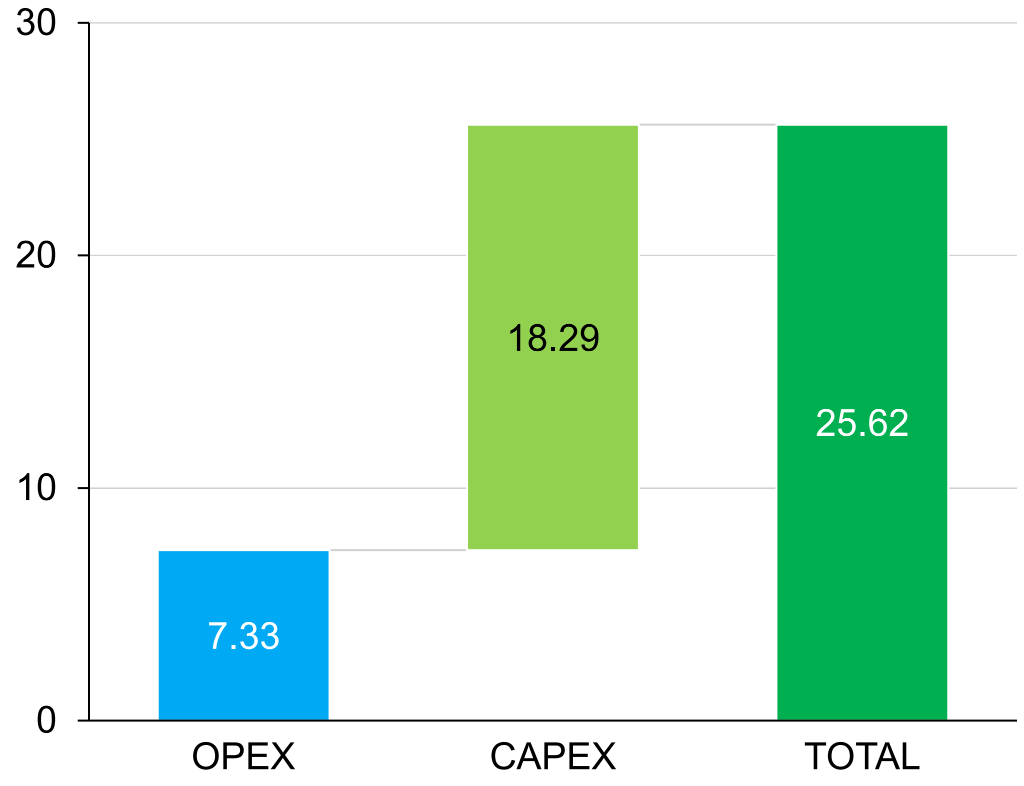
Note

1. The amount of CO_2 reduction varies significantly over conditions under which a WHR boiler is deployed, and is influenced by the temperature and volume of the flue gas. The higher the temperature of the flue gas, the greater the reduction in CO_2 emissions.

Source: Based on Miura (2024), Kawasaki Thermal Engineering (2024), IPCC (2006a)

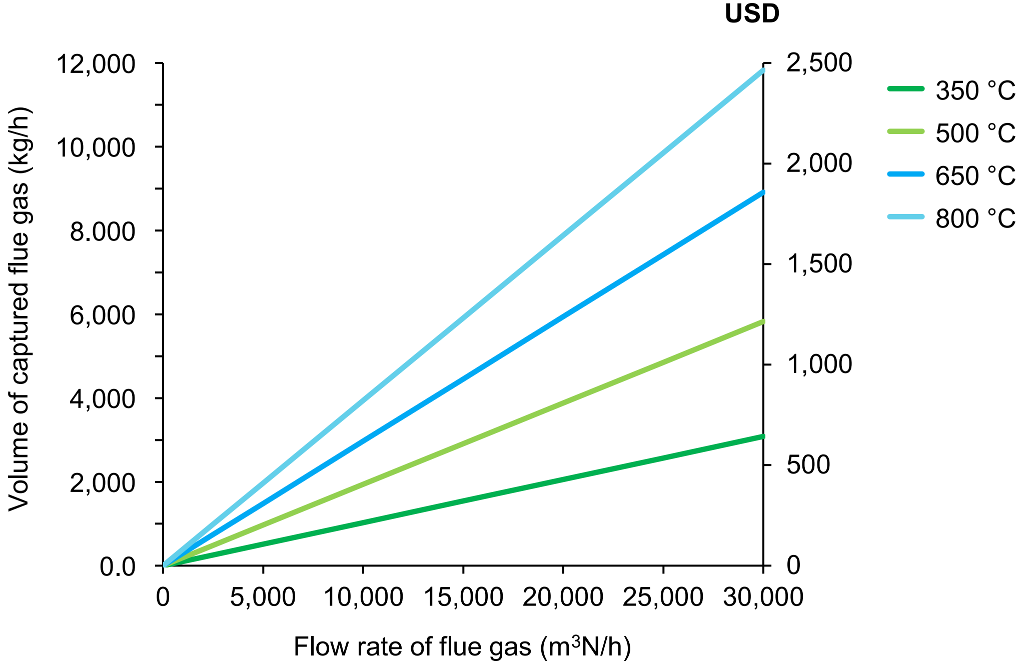
(5) Affordability – The overall cost of steam generated from waste gas source ranges from USD1.2-4.5/t steam, and the abatement cost ranges from 8-30 USD/tCO$_2$

Abatement cost, USD/tCO$_2$



Case of WHR boiler installation in a cement plant

Installation cost of WHR boiler and CO_2 reduction rate vary significantly depending on the amount , temperature and flow rate e of available flue gas, operating hours a year, etc. Abatement cost therefore needs be calculated on a case-by-case basis. The graph below provides a general relationship between the amount and flow rate of flue gas and the cost reduction that can be achieved in a year (USD).



Source: KHI (2022), SII (2023), Miura (2024)

[Reference] Methodologies: Affordability

Methodology: Abatement cost

1. The figures were calculated based on the assumption that WHR boiler is attached to a natural gas boiler.
2. Natural gas boiler's efficiency is assumed to be 85%. The emission factor is 1.885 kg/m^3 (IPCC 2023). The operating time of boilers is assumed to be 6,000 hours per year.
3. The abatement cost: It is assumed that installation cost was USD8,400,000/unit and O&M cost was USD170,000/ year. The cost and CO_2 emission reduction are the values for the entire system, including the WHR boiler, steam turbine, and generator. USD1= JPY140, EUR1= USD1.114, as of 13/09/2024.
4. General relationship between the amount and flow rate of flue gas and the cost reduction that can be achieved in a year (USD) was calculated based on the condition where the pressure of flue-gas is 0.8 Mpa and output water temperature is 60 °C. The cost reduction was calculated assuming that a WHR boiler operates 6,000 hours a year using city gas (13A).

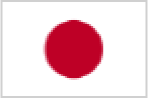
Source: KHI (2022), SII (2023), Miura (2024)

(6) Reliability – WHR is commercially available globally; Use of WHR in ASEAN may be limited but expected to grow as the awareness for energy efficiency grows

Estimated commercialisation status

- TRL 10-11, WHR is well-commercialised globally. The use of WHR may be limited in ASEAN but is expected to grow as the awareness for energy efficiency and climate change mitigation grows.

Recent project examples

	Details
Installation of WHR boiler in a steel manufacturing factory 	• Nippon Steel Nisshin Co., Ltd installed a WHR boiler in the annealing facility of a hot dip galvanizing line. The waste heat from combustion exhaust gas, which had previously been dissipated into the atmosphere is recovered as steam. • The thermal efficiency was improved from 58.4% to 82.8%, reducing the fuel cost of the liquefied petroleum gas (LPG) gas-fired boiler that had been in operation until then by 45.2% and reducing 4,500 tCO_2 per year.
Power generation by WHR in the cement plant 	• PT Semen Indonesia (Persero) Tbk has installed a WHR boiler steam turbine generator system at a cement production plant. • WHR boilers generate steam using the waste heat exhausted from the plant, and the steam is fed to the steam turbine generator to generate 28MW of electricity. • Emission reduction is 149,063 tCO_2 per year.

Source: Miura (2024), Numata, M. (2011), GEC (n.d. b)

(7) Lock-in prevention – Zero emissions will be achieved by improving the WHR ratio and decarbonising the energy source

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	Three paths exist for WHR to be zero or near-zero emissions • Path1: Improve WHR ratio at low-temperature • Path2: Replace coal and natural gas with less carbon-intensive fuels, such as biomass and H_2 • Path3: Plan a layout of the manufacturing plant taking WHR equipment and heat sharing into consideration from the initial stage
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path1: Improve WHR ratio at low-temperature – Most of the waste heat is at low temperatures, less than 200°C while currently available WHR boilers can be used for temperatures above 500 °C or above. Therefore, further R&D is needed to develop low-temperature heat recovery technologies, including electricity generation and heat pumps. • Path2: Replace coal and natural gas with less carbon-intensive fuels – Need to ensure the sustainable supply of H_2 and biomass fuels. – Need to cut costs and increase the supply of green H_2. • Path3: Plan a layout of a manufacturing plant taking WHR equipment into consideration from the initial stage – Demand and supply of heat do not necessarily match. Even within the same manufacturing plant, the locations of heat generation and consumption do not necessarily match. Thus during the initial planning of plant layout, WHR equipment should be considered. – Additionally, the development of local, regional, and national forums for matchmaking that facilitate contact and interaction between waste heat owners and district heating operators could help promote waste heat utilisation.

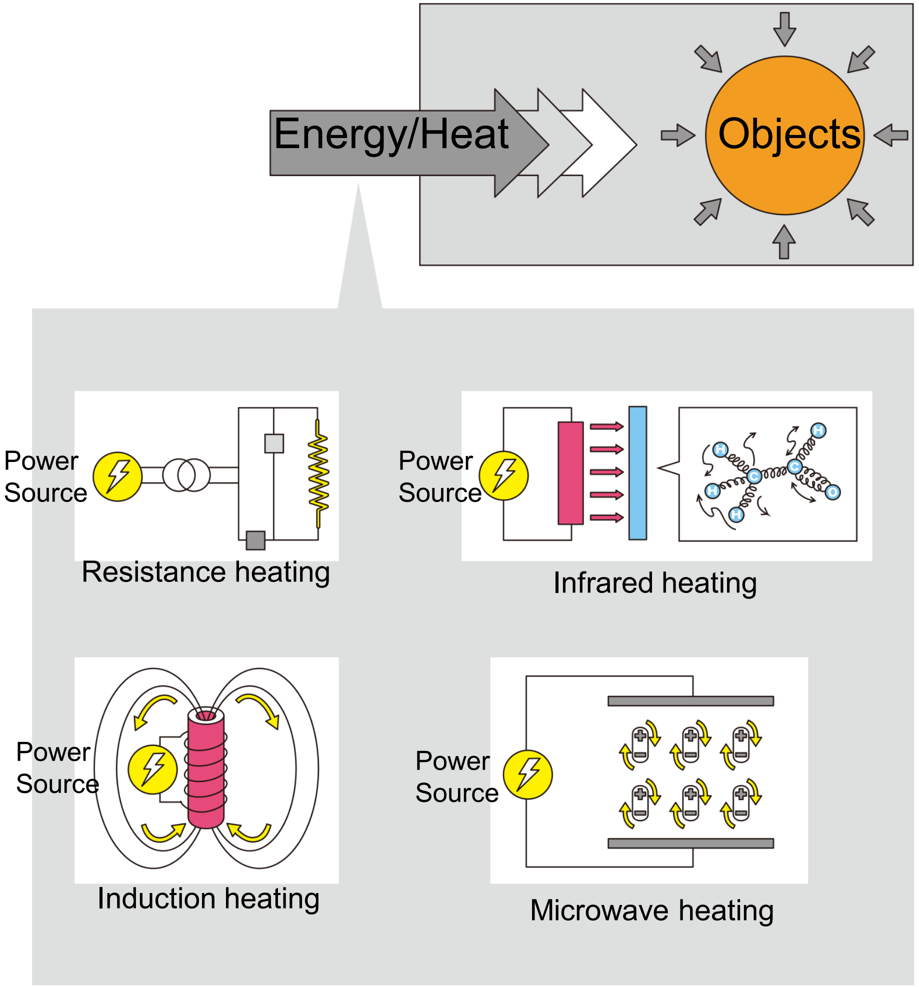
Source: Johnson, Ilona, Choate, William T., & Davidson, Amber (2018), WEF (2023a), Kobayashi, M. (2022)

(8)(9) DNSH/social considerations – Desirable to develop thermoelectric conversion materials that do not use toxic substances

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• WHR technologies potentially mitigate the heat island effect. • Even if WHR equipment is installed on boilers, NO_x will still be produced in the combustion processes. Further R&D efforts would be required to reduce NO_x emissions from the boilers for WHR to be equipped with. Additionally, a regulation to limit the NO_x emissions should be introduced.
	Transition to circular economy	• WHR systems capture and reuse the heat that would otherwise be wasted in industrial processes, reducing the need for additional boilers to produce steam or heat, as the recovered heat can fulfill some or all of those needs, contributing to the transition to circular economy.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Many thermoelectric conversion materials utilise cadmium, tellurium, and mercury, which require attention to their effects on human health.

Source: Kobayashi, M. (2022)

(1) Electric heating– Technology schematics and overview



Source: Author created based on various literature

- Electric heating uses electrical energy to heat objects, with several technologies available, each operating through different mechanisms and temperature ranges:
  - Resistance heating: Generate heat by passing an electric current through a conductive material (400 to 3,000°C).
  - Induction heating: Generate heat by passing alternating magnetic fields through conductive materials (50 to 3,000°C).
  - Infrared heating: Generate heat by passing current through a solid resistor, emitting infrared radiation (40 to 900°C).
  - Microwave heating: Generate heat by friction of molecules irradiated with microwaves (50 to 1,000°C).
- Various forms of heating and melting systems have been introduced in a wide range of industrial fields, including material production, machining, food processing, and waste disposal.

Source: DOE (2015)

(2) Electric heating– Transition suitability assessment overview

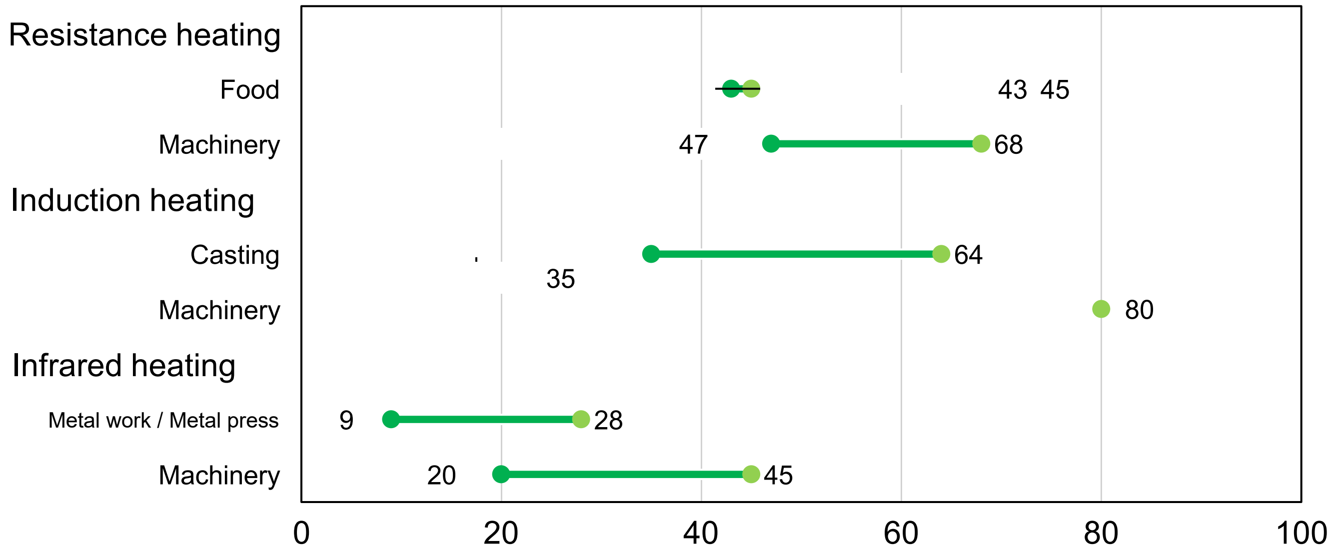
Framework dimensions	Description
Contribution to energy transition	• Electric heating allows for efficient energy conversion. Compared to combustion, there is less heat loss, making it possible to save energy. • The introduction of electric heating can reduce CO_2 emissions in manufacturing by up to 70-80%.
Affordability	• Installation cost and abatement cost are high for industries which require high temperatures. • Case studies show that the abatement costs range from USD-73 to 78/tCO_2.
Reliability	• Resistance heating, induction heating, infrared heating, and microwave heating : TRL 10-11. • Electric heating equipment is also being commercialised in the ASEAN region, with manufacturers of induction furnaces present in Vietnam.
Lock-in prevention considerations	• Path 1: Improving energy efficiency, through optimised operation control and effective use of waste heat. • Path 2: Shift to electricity generated from 100% renewable sources.
DNSH considerations	• Switching to electric heating lowers fuel use but increases electricity demand. If the electricity comes from fossil fuels, it can increase local pollution, such as NO_x.
Social considerations	• Some electric heating systems produce electric waves (e.g. high frequency induction furnaces), requiring careful use. Companies must set guidelines and train operators to handle the electric heating system appropriately and HSE risks must be properly addressed.

(3) ASEAN Taxonomy – There is no relevant technical screening criteria

Eligibility	Climate Change Mitigation TSC
Includes	**Tier 1 (Green)**
	Tier 2 (Amber T2)
Excludes	**Tier 3 (Amber T3)**

(4) Contribution to Energy Transition– The introduction of electric heating can reduce CO_2 emissions in manufacturing by up to 70-80%

Ratio of CO_2 reduction per product unit, %



Resistance heating			Induction heating			Infrared heating		
Sector	Previous energy	CO_2 reduction rate	Sector	Previous energy	CO_2 reduction rate	Sector	Previous energy	CO_2 reduction rate
Food [1]	Gas	43%	Casting [3]	Electricity + coke	35%	Metal work [1]	Gas	9%
Food [1]	Gas	45%	Casting [4]	Coke	43%	Machinery [1]	Gas	20%
Machinery [1]	Gas	47%	Casting [5]	Coke	64%	Metal press [1]	Gas	28%
Machinery [2]	Gas	50%	Machinery [1]	Heavy oil	80%	Machinery [1]	Gas	45%
Machinery [1]	Fuel oil	68%						

Source: JEHC (n.d.), Tanaka, T.(2013), J -Credit Scheme (n.d. b), MOE (2022c), Oda, H., K. Okajima, and Y. Uchiyama (2008)

[Reference] Methodologies: Contribution to Energy Transition

Methodology: Ratio of CO_2 reduction per product unit

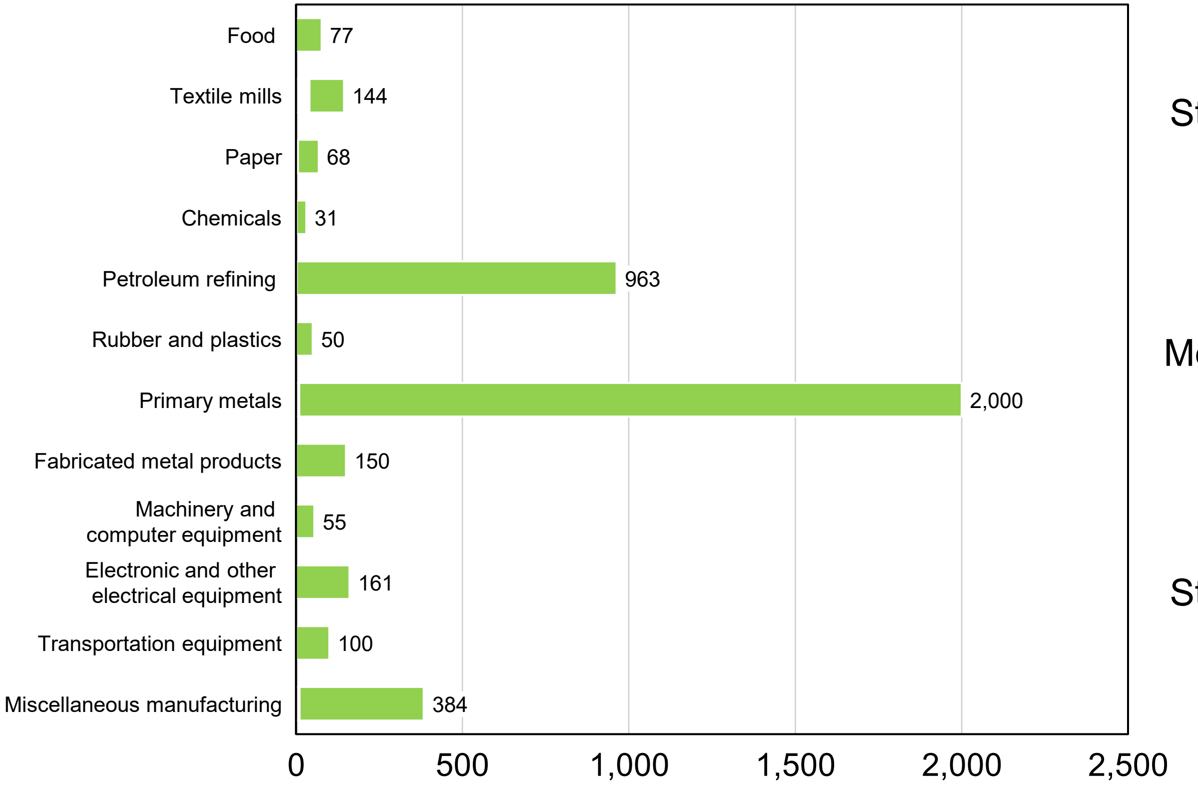
- The left figure shows the range of CO_2 reduction rates for different electric heating methods. And below table provides supporting data for the left figure, including examples from industries like machinery, food, metal, and casting.
- The CO_2 reduction rate varies by heating method and application, with reductions ranging from 9% to 80%.

1. The Japan Electro-Heat Center's "Case Study Search" provides many examples of electric heating systems introduced across various sectors, along with data on CO_2 reduction rates. The CO_2 reduction rates in the table were sourced as follows: For the first source, the rates were obtained directly from the Japan Electro-Heat Center's database. For the other sources, the rates were calculated based on CO_2 emissions before and after the introduction of the system.

Source: JEHC (n.d.), Tanaka, T.(2013), J -Credit Scheme (n.d. b), MOE (2022c), Oda, H., K. Okajima, and Y. Uchiyama (2008)

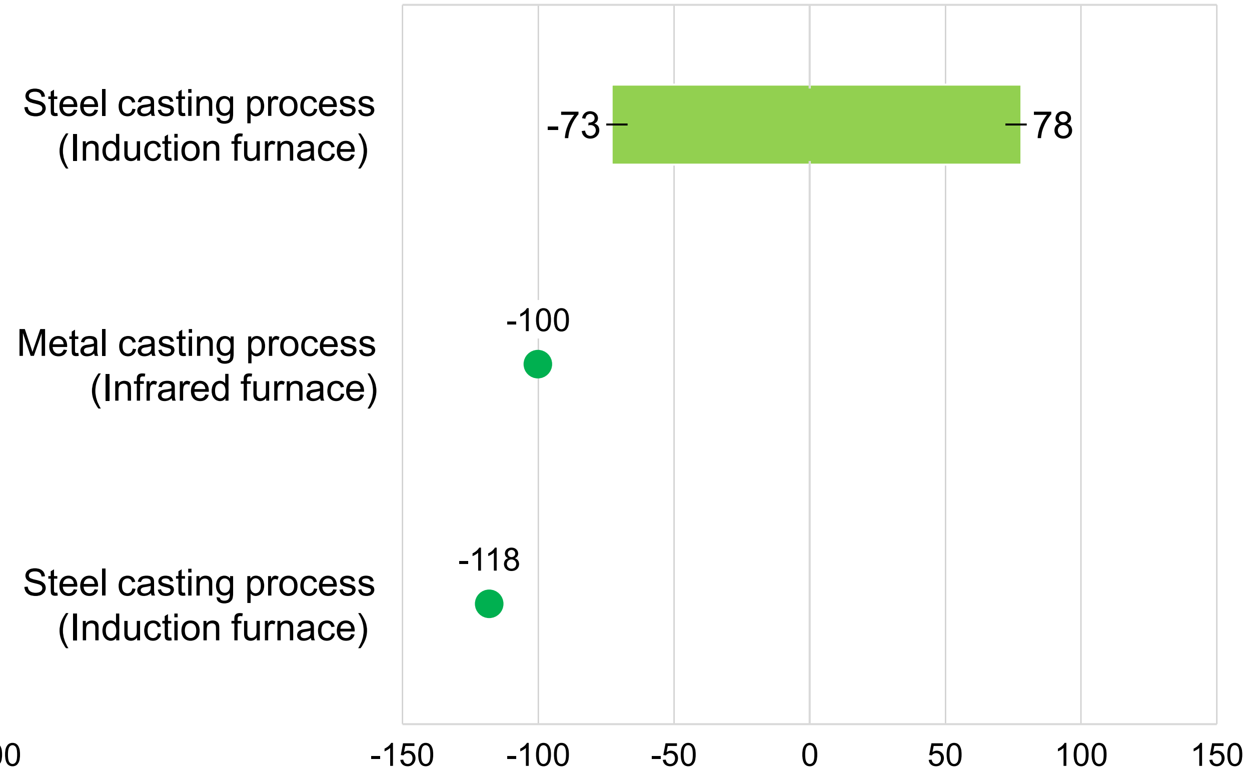
(5) Affordability – Electric heating – Installation cost and abatement cost are high for industries which require high temperatures

Installation cost, thousand USD



Source: Jadun, P., McMillan, C., Steinberg, D., Muratori, M., Vimmerstedt, L., and Mai, T. (2017)

Abatement costs per emission reduction, USD/tCO_2



Source: Oda, H., K. Okajima, and Y. Uchiyama (2008), SII (n.d.), MOE (2022c)

[Reference] Methodologies: Affordability

Methodology: Installation cost

1. The US National Renewable Energy Laboratory (NREL) has compiled information on the installation costs of electric heating by industry, based on the information in the database held by the US DOE's Industrial Assessment Centers. The above graph is based on the results of the study.

Source: Jadun, P., McMillan, C., Steinberg, D., Muratori, M., Vimmerstedt, L., and Mai, T. (2017)

Methodology: Abatement costs per emission reduction

- In Japan, a case study estimated the CO_2 reduction cost for casting at around USD78/tCO_2, though this may change depending on the price of the baseline fuel.
- When replacing fuel with electric heating for metal processing, the savings in fuel costs surpass the installation costs divided by its expected lifespan. Consequently, the abatement cost is negative.

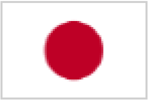
Source: Oda, H., K. Okajima, and Y. Uchiyama (2008), SII (n.d.), MOE (2022c)

(6) Reliability – Electric heating equipment is commercialised in the ASEAN region

Estimated commercialisation status

- TRL 10-11: Resistance heating, induction heating, infrared heating, and microwave heating
- Electric heating equipment is also being commercialised in the ASEAN region, with manufacturers of induction furnaces present in Vietnam.

Recent project examples

Project	Details
Vietnam's VAS GROUP, a steel manufacturer, uses induction furnaces in its manufacturing process 	• The VAS Group has actively introduced induction furnace systems to reduce CO_2 emissions. The smelting process at VAS Green Steel is continuously improving, with energy consumption reduced by 10%.
Subsidy project in Japan supporting the transition from cupola furnaces to high-frequency induction furnaces 	• In Japan, there have been cases in the past where electric heating has been used in processes such as casting and heating, and even more recently there have been cases where electric heating was introduced to improve energy efficiency and workability. • In a subsidy project run by the Ministry of the Environment Japan, subsidies were provided for projects to switch from cupolas to high-frequency induction furnaces in the transport machinery and equipment manufacturing industry. • In addition to reducing CO_2 emissions, the renewal has also improved the environment around the factory by reducing noise and odour, and has reduced the burden of maintenance.

Note:

1. Cupola is a furnace for melting cast iron (alloy of steel and carbon) in high temperature, coke is burnt as fuel of the cupola furnace.

Source: VAS Group (2024), MOE (2022c)

(7) Lock-in prevention – For decarbonisation, there is a need for higher efficiency in electric heating technology itself and grid decarbonisation

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Two paths exist for electric heating to be zero or near-zero emissions; – Path 1: Improving energy efficiency, through optimised operation control and effective use of waste heat. – Path 2: Shift to electricity generated from 100% renewable sources.
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Improving energy efficiency, through optimised operation control and effective use of waste heat. – Electric heating systems are generally energy efficient; however, they still waste some energy. The development of more efficient electric heating technologies is necessary, including optimised operation control, effective use of waste heat (e.g. thermal recovery, and cascade heat use). When energy efficiency increases, both electricity consumption and CO_2 emissions decrease. • Path 2: Shift to renewable energy – Most electricity in ASEAN countries is still generated from fossil fuels. It is necessary to shift to renewable energy. As the cost of renewable electricity tends to be lower, it is necessary to let this tendency accelerate. If the electricity used for electric heating comes from renewable sources, CO_2 emissions are reduced even further.

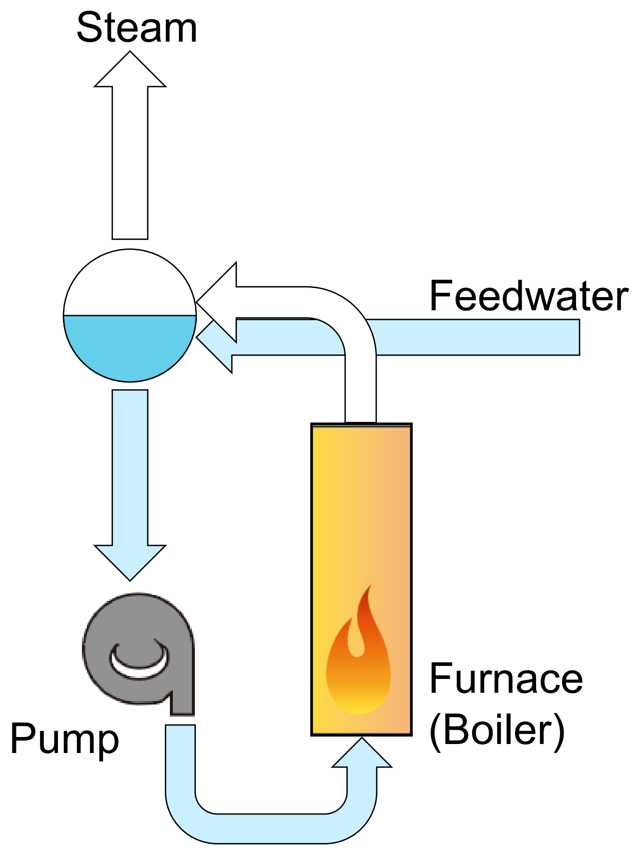
Source: ANRE (2024a), IRENA and ACE (2022)

(8)(9) DNSH/social considerations – Switching to electric heating reduces fuel use but increases electricity demand

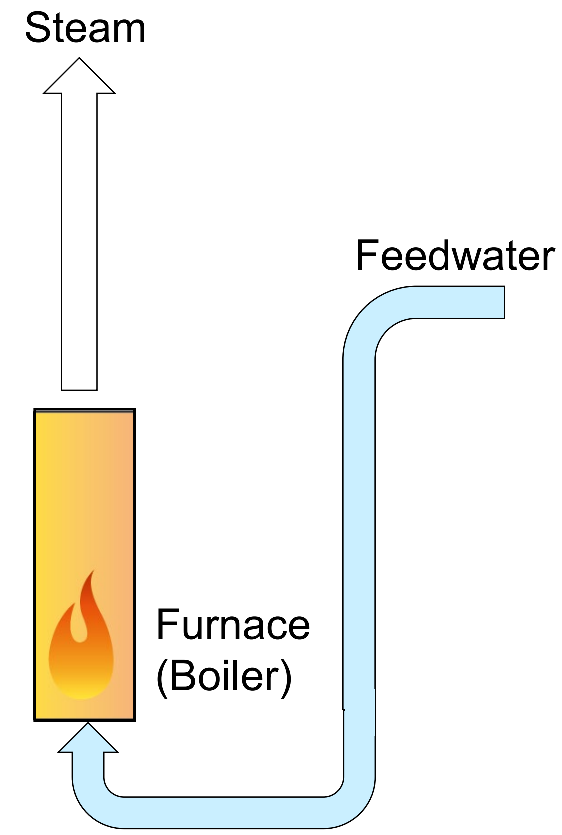
Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• Electric heating system does not burn fuels, so does not emit air pollutants such as NO_x and SO_x. NO_x and SO_x can cause acid rain, which can damage the ecosystem, but the electric heating will reduce damage of the acid rain. • Switching to electric heating lowers fuel use but increases electricity demand. If the electricity comes from fossil fuels, it can increase local pollution, such as NO_x. To avoid this, it's important to shift to renewable energy.
	Transition to circular economy	• Developing durable manufacturing technologies for electric heating systems is crucial to reducing resource use. For example, creating a more durable resistance heater that works at higher temperatures would not only increase its applications but also extend its lifespan.
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Electric heating systems release minimal heat and steam into the environment and emit no pollutants like NO_x, helping maintain a clean workplace. • Some electric heating systems produce electric waves (e.g. high frequency induction furnaces), requiring careful use and compliance with each country's regulations on electromagnetic emissions. • Companies must set guidelines and train operators to handle the electric heating system appropriately and HSE risks must be properly addressed.

Source: Expert interviews, MIC (2021)

(1) Small scale once-through boilers– Technology schematics and overview



Smoke tube boiler
(Forced circulation)



Once-through boiler

Source: Author created based on various literature

- A once-through boiler operates without a steam drum, consisting mainly of a heater and water tubes, where water enters from one end and steam exits from the other.
- The amount of water needed for once-through boiler is approximately 3 to 5% of conventional boilers, and therefore it can quickly produce steam.
- The efficiency of once-through boiler is 98% at maximum, which is roughly 8% higher than that of flue-gas and smoke tube boilers. Therefore, by installing once-through boilers, emissions can be reduced.
- The absence of components such as steam drums contributes to lowering capital investment costs and increasing start-up speed.

Source: Bui, N. H. (n.d.) Martech Boiler, UNCTCN (n.d.)

(2) Small scale once through boilers– Transition suitability assessment overview

Framework dimensions	Description
Contribution to energy transition	• The efficiency of once-through boiler is 98% at maximum, which is roughly 8% higher than that of flue-gas and smoke tube boilers. Therefore, by installing once-through boilers, emissions can be reduced. • Case studies show that by installing small scale once-through boilers, CO_2 emissions can be reduced by 10 to 19%.
Affordability	• Case studies show that the abatement costs range from USD14 to 37/tCO_2
Reliability	• TRL 9-10, Small-scale once-through boilers have been commercialised and are distributed globally.
Lock-in prevention considerations	• Path 1: Improving boiler efficiency • Path 2: Switching to renewable fuels • Path 3: Reducing CO_2 emissions by CCS
DNSH considerations	• Once-through boilers emit NO_x and CO in the fuel combustion process in the same way as the existing flue-tube boilers. Therefore, it is important to choose low NO_x specification (NO_x<25 ppm) models, which are already commercialised. • Utilisation of waste biomass as fuel could contribute to the transition to circular economy. • There should be a system in place to recycle retired small-scale once through boilers appropriately
Social considerations	• Compared to large boilers, the operation of small-scale once-through boilers is relatively easy. Therefore, it would be possible to employ engineers with a wide range of skill levels not just highly-skilled boiler management engineers. • The burden of cleaning the boiler (about once a month) is reduced by gasification of the fuel.

(3) ASEAN Taxonomy – Relevant technical screening criteria

Production of heating/cooling from renewable non-fossil gaseous and liquid fuels (1/2)

Eligibility	Climate Change Mitigation TSC	Details
Includes • Heating/cooling resulting from non-biological renewable non-fossil gaseous and liquid fuels only. • Heating/cooling resulting from a blend of non-biological renewable non-fossil gaseous and liquid fuels and biofuels. **Excludes** • Heating/cooling as part of co-generation • Heating/cooling resulting from bioenergy only.	**Tier 1 (Green)**	• Lifecycle GHG emissions < 28 gCO_2 -eq/MJ per unit of heating and/or cooling produced
	Tier 2 (Amber T2)	• Lifecycle GHG emissions < 65 gCO_2 -eq/MJ per unit of heating and/or cooling produced
	Tier 3 (Amber T3)	• No TSC available.
	TSC applicable to all Tiers	1. Anaerobic digestion of organic biowaste or sewage which is conducted at the site of fuel combustion must comply with the following: a. Implement monitoring and contingency plan to minimise methane leakage; b. Biogas produced onsite at a facility for the conduct of this Activity must be used only for this Activity or other Activities defined by the ASEAN Taxonomy, etc.; AND c. Any bio-waste that is used for anaerobic digestion is source segregated and collected separately. 2. For facilities that are equipped with CCUS, CO_2 from energy provision that is captured for underground storage, must be transported and stored in accordance with the TSC for Activities 000[010] and 000[020]

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

Production of heating/cooling from renewable non-fossil gaseous and liquid fuels (2/2)

Eligibility	Climate Change Mitigation TSC	Details
Includes • Heating/cooling resulting from non-biological renewable non-fossil gaseous and liquid fuels only. • Heating/cooling resulting from a blend of non-biological renewable non-fossil gaseous and liquid fuels and biofuels. **Excludes** • Heating/cooling as part of co-generation • Heating/cooling resulting from bioenergy only.	**Tier 1 (Green)**	• Lifecycle GHG emissions < 28 gCO_2 -eq/MJ per unit of heating and/or cooling produced
	Tier 2 (Amber T2)	• Lifecycle GHG emissions < 65 gCO_2 -eq/MJ per unit of heating and/or cooling produced
	Tier 3 (Amber T3)	• No TSC available.
	TSC applicable to all Tiers	3. The Activity meets either of the following criteria: a. at construction, measurement equipment for monitoring of physical emissions, such as methane leakage, is installed, or a leak detection and repair programme is introduced; b. at operation, physical measurement of methane emissions is reported, and leak is eliminate

Source: ASEAN Taxonomy Board (2024)

(3) ASEAN Taxonomy – Relevant technical screening criteria

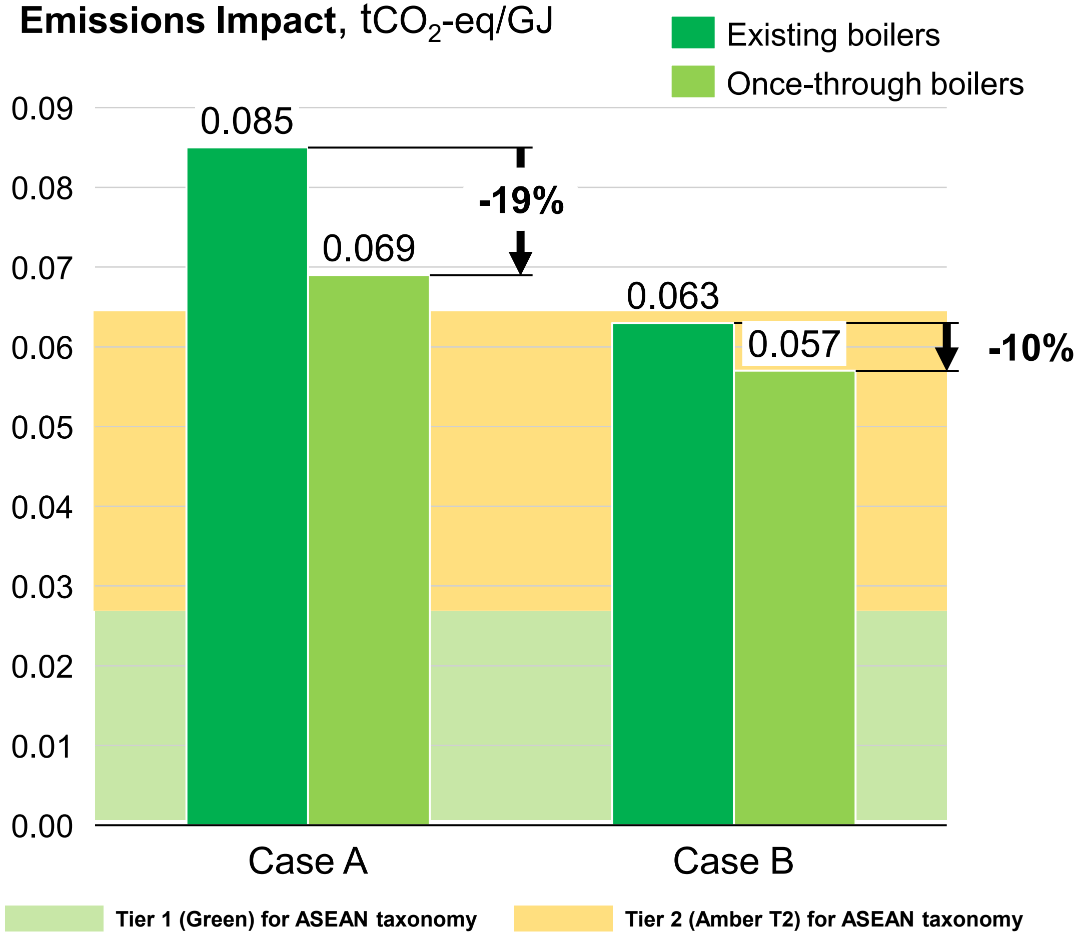
Production of heating/cooling from fossil gas

Eligibility	Climate Change Mitigation TSC	Details
Includes	**Tier 1 (Green)**	• Lifecycle GHG emissions < 28 gCO_2-eq/MJ per unit of heating and/or cooling produced
	Tier 2 (Amber T2)	• Lifecycle GHG emissions < 65 gCO_2-eq/MJ per unit of heating and/or cooling produced
	Tier 3 (Amber T3)	• No TSC available.
Excludes • Fossil heating/cooling as part of co-generation	**TSC applicable to all Tiers**	1. For facilities that are equipped with CCUS, CO_2 from energy provision that is captured for underground storage, must be transported and stored in accordance with the TSC for Activities 000[010] and 000[020]. 2. The Activity meets either of the following criteria: a. at construction, measurement equipment for monitoring of physical emissions, such as methane leakage is installed, or a leak detection and repair programme is introduced; OR b. at operation, physical measurement of methane emissions is reported, and leak is eliminated. 3. This Activity permits the storage of fossil gas, as long as it meets the thresholds shown, which are aligned with principles explained above in the bases for TSC setting.. This inclusion is subject to review and may be revised at the end of the first TSC Period.

Source: ASEAN Taxonomy Board (2024)

(4) Contribution to Energy Transition - Installing currently available small-scale once-through boilers can cut CO_2 emissions by approximately 10–19%

Emissions Impact, tCO_2-eq/GJ



Case:

A) Replace a heavy oil-fired flue gas tube boiler (efficiency: 81.6%, CO_2 emissions: 1,531tCO_2/year) with small once-through LPG boilers (efficiency: 86.7 to 87.1%, CO_2 emissions: 1,239tCO_2/year).

B) Replace the existing boilers (efficiency: 88%, energy type: city gas, CO_2 emissions:876tCO_2/year) with high efficiency small scale once-through boilers (efficiency: 98%, energy type: city gas, CO_2 emissions: 787tCO_2/year).

Comparison with ASEAN Taxonomy

There are two TSCs which are potentially applicable to small-scale once through boiler. Those TSCs set a threshold on lifecycle GHG emissions per heat generated.

Lifecycle GHG emissions would vary depending on many factors, e.g. distance and measure of fuel transport, lifetime of a boiler, the end-of-life processes etc. Therefore eligibility towards the ASEAN Taxonomy labelling should be assessed on a project-to-project basis.

The left graph uses the TSC for “production of heating/cooling from fossil gas”. However, since the ASEAN Taxonomy TSC is based on lifecycle GHG emissions, while this graph represents operational emissions only, a direct comparison is not available. The Tier1 and Tier2 ranges are provided for reference only.

Tier1 and Tier2 refers to Climate Change Mitigation TSC for Production of heating/cooling from fossil gas.

Source: J-Credit Scheme (n.d. a), MOE (2022b)

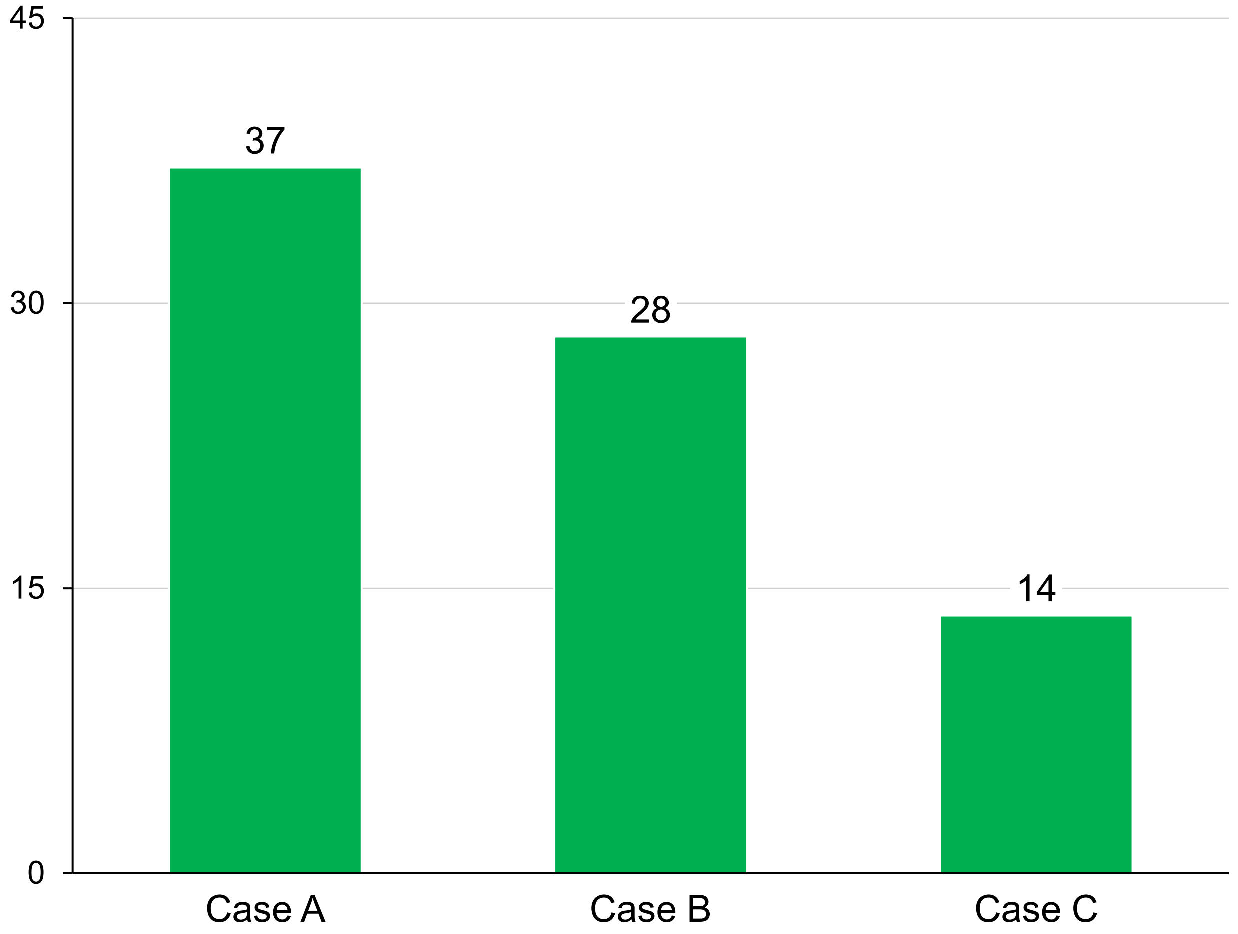
[Reference] Methodologies: Contribution to Energy Transition

Methodology: Emissions Impact	Note
1. Emission impacts include CO_2 reductions due to the fuel switching from heavy fuel oil to LPG.	• Emission impact is highly influenced by an existing boiler that a small-scale once through boiler is replacing, operating hours, utilisation capacity, etc. A general emission impact achieved by a small-scale once through boiler is therefore needs to be calculated on a case-by-case basis. • Compared to a flue-tube boiler, a once-through boiler consumes less water. Therefore, it takes less time to generate the required amount of steam, and it leads to energy savings.

Source: J-Credit Scheme (n.d. a), MOE (2022b)

(5) Affordability – Case studies show that the abatement costs range from USD14 – 37/tCO_2

Abatement costs per emission reduction, USD/tCO_2



- The figure shows the CO_2 abatement costs when installing once-through boilers instead of existing boilers. The data is based on the case studies in Japan.
- Boiler prices and possible emission reductions vary depending on operation, an existing boiler that a small scale once through boiler is replacing, operating hours a year etc. Thus abatement cost should be calculated on a case-by-case basis. The left was calculated based on the three cases below.
- Case:
  - A) Replace the existing boiler with a high-efficiency small scale once-through boiler in a food factory. (Energy type: heavy fuel oil, estimated CO_2 reduction: 232.4tCO_2/year)
  - B) Replace heavy fuel oil boilers with small scale once-through LNG boilers in a food factory. (Estimated CO_2 reduction: 287tCO_2/year)
  - C) Replace heavy fuel oil-fired steam boilers, mixed oil-fired steam boilers, and biomass oil-fired steam boilers with once-through gas-fired steam boilers in a chemical factory. (Estimated CO_2 reduction: 3,268tCO_2/year)

Source: MOE (2019), MOE (2022a), MOE (2024a)

[Reference] Methodologies: Affordability

Methodology: Abatement costs per emission reduction

1. Case B and C include emissions reductions by fuel-switching, which results in lower abatement costs.
2. . USD 1= JPY140, as of 13/09/2024

Source: MOE (2019), MOE (2022a), MOE (2024a)

(6) Reliability – Small-scale once-through boilers have been commercialised and are distributed internationally

Estimated commercialisation status

- Small scale once through boilers : TRL 9-10, Small scale once through boilers have been commercialised and are distributed globally.

Recent project examples

	Details
Introduction of small scale once through boiler at golf ball factory 	• A high efficiency (95%) once-through boiler has been installed to a golf ball factory in Indonesia. • By replacing the flue-tube boiler with the once-through boiler, GHG emissions were reduced by 181 tCO_2/year.
Introduction of high efficiency once through boiler at garment factory 	• High efficiency (98%) once-through boilers have been installed to replace the existing water tube boilers at a garment factory. • By replacing the boilers and switching fuel from coal to natural gas, GHG emissions were reduced by 2,665 tCO_2/ year.
Introduction of high efficiency once through boiler at food factory 	• A high efficiency once through boilers have been installed to replace the existing boilers at a food factory. • By replacing the boilers and switching fuel from coal to CNG[1] and LPG, GHG emissions were reduced by 7,361 tCO_2/ year.

Note:
1. CNG = compressed natural gas

Source: GEC (n.d. a)

(7) Lock-in prevention – Improving boiler efficiency, fuel switching, and adding CCS are paths for zero or near-zero emission

Framework dimensions	Considerations/ Key questions	Details
Lock-in prevention considerations	**What are the paths for the technology to be zero or near-zero emissions?**	• Three paths exist for small-scale once through boilers to be zero or near-zero emissions; – Path 1: Improving boiler efficiency – Path 2: Switching to renewable fuels – Path 3: Reducing CO_2 emissions by CCS
	What (lock-ins) may hinder the above paths to zero or near-zero emissions? Considerations include • Financial viability • Technological maturity • Sourcing and contracting	• Path 1: Improving boiler efficiency – The maximum efficiency of gas-fired boilers is around 98%. However, by installing economisers to recover latent heat, the efficiency can be 100% or above. Therefore, the development of latent heat recovery technology could improve boiler efficiency and reduce emissions. • Path 2: Switching to renewable fuels – Small-scale once-through boilers fuelled by renewable fuels such as biomass and H_2 are already commercialised. However, due to the insufficient supply of H_2 and its high cost, it is not yet widely used, except in plants that have H_2 byproducts. – Since H_2 emits more NO_x than LNG during the combustion process, technology development is required to reduce NO_x emissions. • Path 3: Reducing CO_2 emissions by CCS – There is an ongoing effort to redesign a small-scale once through boiler suited to CCS. Further R&D is needed to reduce cost of CCS. It is expensive to capture CO_2 in the exhaust gas from small scale once-through boilers. Therefore, technologies are being developed to increase the concentration of CO_2 in the exhaust gas and reduce recovery costs.

Source: UNCTCN (n.d.), Sumi, S. (2022), Nitto Denko (2023)

(8)(9) DNSH/social considerations–NO_x and CO emissions need consideration

Framework dimensions	Considerations/ Key questions	Details
DNSH considerations	**Protection of healthy ecosystems and biodiversity**	• Once-through boilers emit NO_x and CO in the fuel combustion process in the same way as the existing flue-tube boilers. Therefore, it is preferrable to choose low NO_x specification (NO_x<25 ppm) models, which are already in the market.
	Transition to circular economy	• Utilisation of waste cooking oil and biomethane generated in food processing plants, etc. as fuel for small scale once through boiler could contribute to the transition to circular economy. • There should be a system in place to recycle retired small-scale once through boilers appropriately
Social considerations	**Plans to mitigate the negative social impact of the technology**	• Compared to conventional boilers, such as smoke tube and flue-gas boilers, the management of small scale once-through boilers is relatively easy. Thus, the demand for highly-skilled engineers with specific qualifications might be negatively impacted. On the other hand, it can be said that there are more employment opportunities for engineers with varied levels of skills and experiences. • The burden of cleaning may be reduced by gasification of the fuel.

Source: UNCTCN (n.d.), Kikuchi. T. (2022)

How to use

Transition technologies for the end-use and industries sector

Building sub-sector

Transport sub-sector

Cement, concrete and glass sub-sector

Chemicals sub-sector

Iron & steel sub-sector

Industries cross-cutting sub-sector

Appendix

1 - Examples of AMS' technology introduction roadmap towards net zero emissions

2 - Examples of international aids towards decarbonisation of the industries and end-use sector in ASEAN

3 - Potential policy instruments that can support widespread deployment of transition technologies

Appendix-1

Examples of AMS' technology introduction roadmap towards net zero emissions

Thailand focuses on EE&C technologies to decarbonise the industry and building sectors, and fuel switching for the transport sector

Net zero GHG emission timeline for the end-use & industries sector[2]

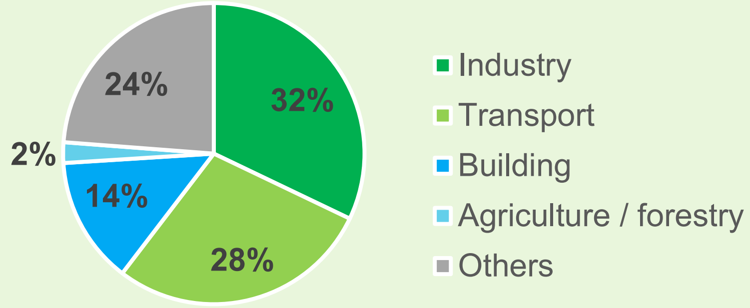
	2025	2030	2030 onwards
Industry	• Efficient lighting technologies • Efficient cooling technologies • Efficient motor technologies • Efficient boiler • IHPs • Renewable energy (biomass, biogas, solar, wind)	• Most efficient lighting technologies • Most efficient cooling technologies • Most efficient motor technologies • Most efficiency boiler • Clinker substitution • Substitution of refrigerant • Renewable energy (bioenergy; solar & wind with battery storage)	• Electric heating technologies • Green H_2 fuel • Most efficient electrical devices • Most efficient boiler • CCS, CCU & BECCS • Increased shared of renewable energy
Transport	• Efficient engine vehicles (gasoline & diesel) • Renewable energy • Electric train	• Phase down of ICEs • Most efficient ICEVs • Renewable energy • EVs	• Most efficient ICEVs with biofuels • High share of EVs • HFCV
Building	• Efficient lighting technologies • Air-conditioners COP-5	• Most efficient lighting technologies • Efficient office equipment • Efficient water heater, solar water heater • Air-conditioners COP-5 and COP-8 • Efficient heaters, efficient LPG stoves • Efficient refrigerators COP-5	• Most efficient electrical devices • Air-conditioners COP-8 • Efficient heaters • Maximum use of solar water heaters

Notes:

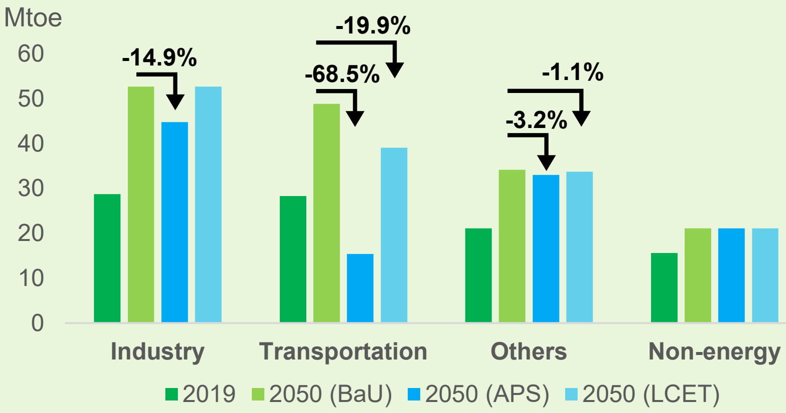
1. EE&C = Energy Efficiency and Conservation

Source: ONEP (2022), IEA (n.d. f), ERIA (2023a)

Total final energy consumption by sector (2022)[3]



Final energy demand forecast by sector, BaU, APS and LCET (2019-2050)[3]



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In the LCET scenario, energy consumption may be higher than in other scenarios; however, the deployment of new technologies leads to greater emission reductions.

Malaysia's transition roadmap highlights fuel switching and CCUS for the industry sector, electrification for the transport sector, and EE&C

Investment opportunities and impact of National Energy Transition Roadmap (NETR)'s Responsible Transition in the end-use and industries sectors[1]

	2030	2040	2050
Industry	**Fuel switching** • Establishment of 1 H_2 hub • 0.6B litres of biofuel and 500 MW of bioenergy	• Establishment of 2 additional H_2 hubs (until 2050) • 1.8B litres of biofuel and 460 MW of bioenergy	• Up to 2.5MTPA local green H_2 production • 3.5B litres of biofuel and 1,400 MW of bioenergy
Transport	**Green mobility** • 20% of four-wheel (4W) fleet as xEVs • 20% of two-wheel (2W) fleet electrified	• 50% of four-wheel (4W) fleet as xEVs • 50% of two-wheel (2W) fleet electrified	• 80% of four-wheel (4W) fleet as xEVs • 80% of two-wheel (2W) fleet electrified
Building	**Energy efficiency** • -RM 2B in smart devices installation* • -RM 2B retrofitting government building	• -RM 6B in smart devices installation* • -RM 7B retrofitting government building	• -RM 7B in smart devices installation*
CCUS	• 3 CCUS hubs • Up to 15 MTPA of storage capacity	• 1 carbon capture hub • 40 MTPA of storage capacity	• 2 additional carbon capture hubs • 80 MTPA of storage capacity

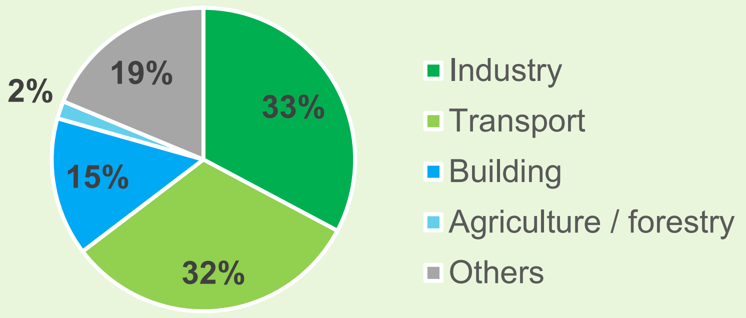
(*): includes investments in both the industry sector and the building sector

Notes:

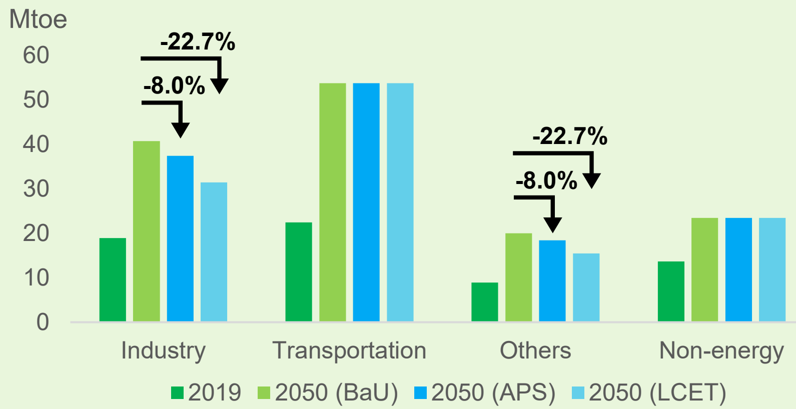
1. MTPA = Million Tons Per Annum

Source: Ministry of Economy, Malaysia (2023), IEA (n.d. c), ERIA (2023a)

Total final energy consumption by sector (2022)[2]



Final energy demand forecast by sector, BaU, APS and LCET (2019-2050)[3]



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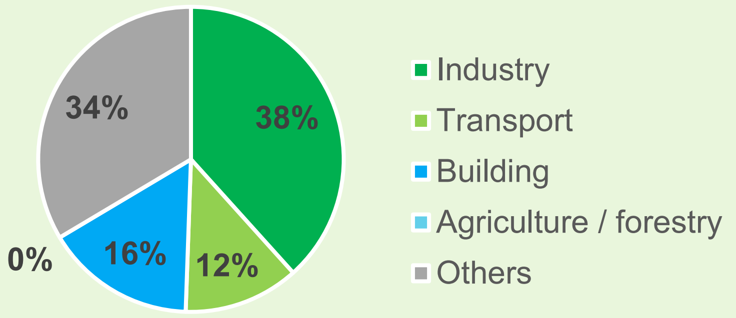
Singapore strives to decarbonise the transport sector through electrification and biofuels, along with EE&C measures for the other sectors

Key targets in Singapore Green Plan 2030 for the end-use and industries sectors[1]

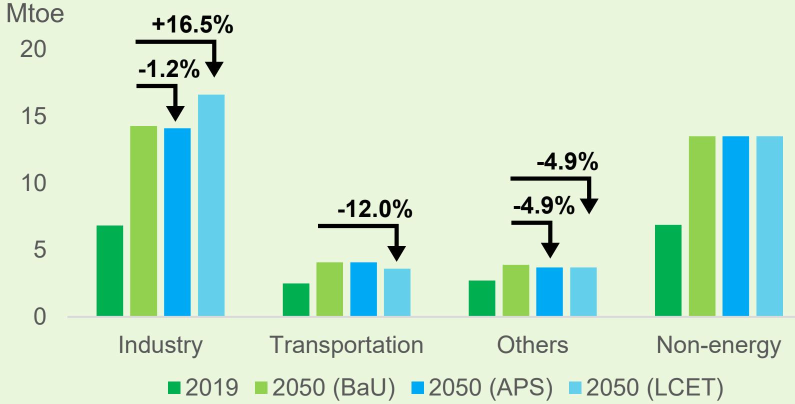
	2025	2030	2040
Industry	• Deploy 200 megawatt-hour of Energy Storage Systems to enhance grid resilience and support clean energy transition (achieved in 2022)	• Best-in-class power generation technology that meets emission standards and reduces carbon emissions	-
Transport	• New registrations of diesel cars and taxis to cease from 2025 • All Housing Development Board (HDB) towns to be EV ready with chargers at all HDB carparks by 2025 • All new airside light vehicles, forklifts and tractors at Changi Airport to be electric from 2025	• Achieve 75% mass public transport (rail and bus) peak-period modal share • EV buses to make up 50% of public bus fleet by 2030 • Existing diesel buses to be replaced with cleaner energy buses by 2040 • Expand rail network to 360km by early 2030s • Expand cycling path networks to -1,300km • All new car and taxi registrations to be of cleaner-energy models from 2030 • Deploy 60,000 EV charging points nationwide by 2030 • All new harbour craft operating in port waters to be fully electric, be capable of using B100 (pure biodiesel), or be compatible with net zero fuels from 2030	• Achieve more than 80% mass public transport (rail and bus) peak-period modal share • Public, active and shared transport modes to account for 9 in 10 of all peak-period journeys • All vehicles to run on cleaner energy by 2040 • All airside vehicles at Changi Airport to run on cleaner energy by 2040
Building	• Reduce energy consumption of desalination process from current 3.5kWh/m3 to 2kWh/m3 with R&D • Singapore's first integrated wastewater treatment facility to be 100% energy self-sufficient (Tuas Nexus)	• Green 80% of Singapore's buildings (by Gross Floor Area) by 2030 • 80% of new buildings (by Gross Floor Area) to be Super Low Energy buildings from 2030 • Best-in-class green buildings to see an 80% improvement in energy efficiency (over 2005 levels) by 2030 • Reduce energy consumption in existing HDB towns by 15%	

Source: MSE (n.d.), IEA (n.d. e) , ERIA (2023a)

Total final energy consumption by sector (2022)[2]



Final energy demand forecast by sector, BaU, APS and LCET (2019-2050)[3]



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In the LCET scenario, energy consumption may be higher than in other scenarios; however, the deployment of new technologies leads to greater emission reductions.

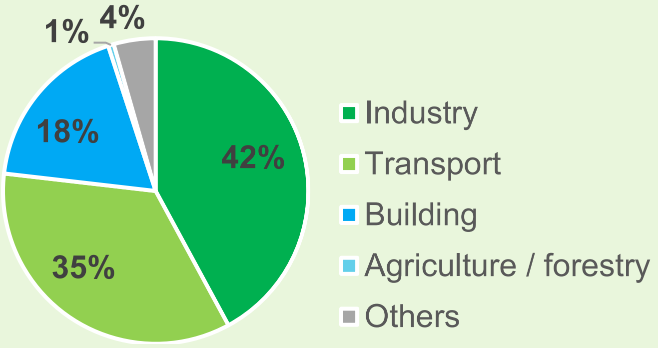
Indonesia plans to achieve net zero emissions through fuel switching of energy sources, and CCS/CCUS under certain conditions

Energy and Transportation Roadmap towards Net Zero Emission for the end-use and industry sectors[1]

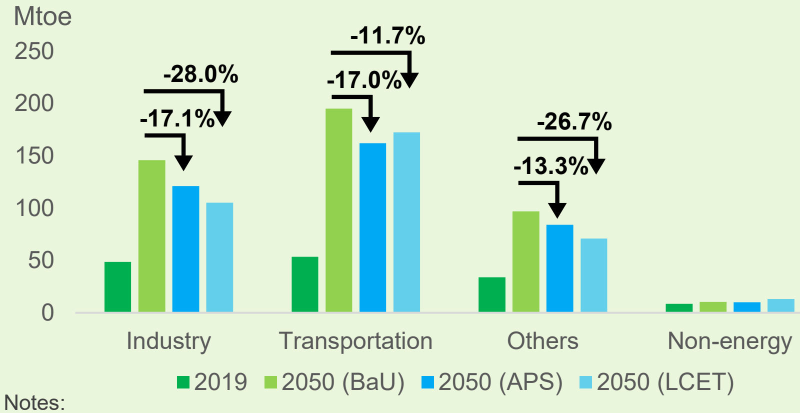
	2030	2040	2050	2060
Industry	• Development of coal-fired power plant (CFPP) replacement	• Retirement of CFPP (3 GW) • H_2 utilisation (332 MW) and battery utilisation (46 GW)	• Retirement of CFPP (31 GW) • H_2 utilisation (9 GW) and battery utilisation (151 GW)	• Retirement of CFPP (8 GW) • Retirement of gas & steam power plant (8 GW) • H_2 utilisation (52 MW) and battery utilisation (140 GW)
Transport	• 2 millions of cars and 13 million of motorcycles electrified	• 12.3 millions of cars and 105 million of motorcycles electrified • Gas fuel for 2 million cars	• 38.2 millions of cars and 205 million of motorcycles electrified • Gas fuel for 2.8 million cars	• 69.6 millions of cars and 229 million of motorcycles electrified
Building	• Decreasing of LPG • Induction stove for 18.2 million household • Gas network for 10 million houses	• Induction stove for 38.2 million household • Gas network for 20.3 million houses	• Induction stove for 48.2 million household • Gas network for 23.4 million houses	• Induction stove for 58 million household • Gas network for 23.9 million houses
CCUS (CO_2)	Innovative low-carbon technologies such as CCS/CCUS can be applied under certain conditions to fossil-based power plants to accelerate emission reductions towards a green transition and cleaner energy.			

Source: Syaifudin, N. (2023), IEA (n.d. b) , ERIA (2023a)

Total final energy consumption by sector (2022)[2]



Final energy demand forecast by sector, BaU, APS and LCET (2019-2050)[3]



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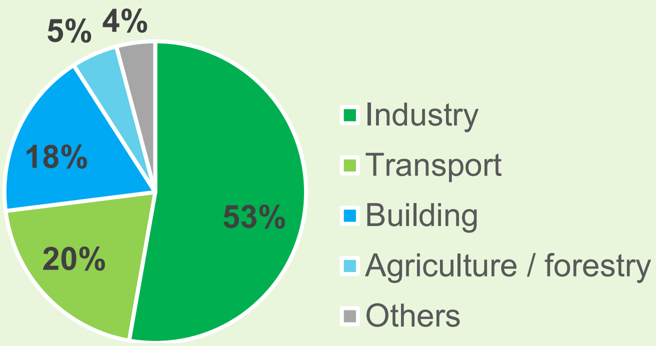
Viet Nam is adopting energy efficiency and fuel-switching measures for the industry sector while promoting green transition in the transport sector

Energy Transition Targets & Action Plans for end-use and industries sectors[1]

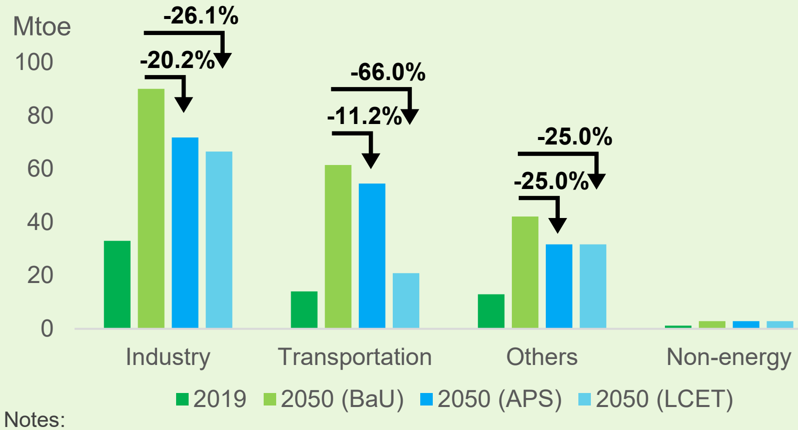
	Targets & action plans until 2030	2050 vision
Industry	**Energy efficiency** • Achieve energy saving rate of 8-10% compared to BaU scenario • Energy efficiency target by sector: • Cement: 10.89%- • Textile: 6.8%- • Chemical: 10%- • Steel: 5%-16.5% • Plastic: 21.55%- 24.81% • Beverage: 4.6%-8.44% • Pulp & paper: 9.9%- 18.48% **Fuel switching** • Develop clean energy centres to produce and use clean energy resources • Blue & green H_2 production capacity to reach 100 to 500 thousand tonnes per year	• 15-20% compared to BaU scenario • Blue & green H_2 production capacity to reach 10 to 20 million tonnes per year
Transport	**Green energy transition** • Promote the manufacturing, assembly, import and use of EVs • Expand in gasoline mixing, working toward 100% E5 gasoline for motorised road vehicles • Convert all railway vehicles to green energy and electricity • Encourage investment in green energy inland watercrafts • Replacement in buses – all new buses use electricity and clean energy • Step-by-step restriction and stop the use of vehicles using fossil fuels • Develop charging infrastructure nationwide; upgrade road, rail and port infrastructure (bus stops, rail stations, ports, etc.) to meet green criteria	• 100% motorised road vehicles, buses, taxis, trains and inland water vehicles (ships, boats) use electricity and green energy • 100% of transport equipment and infrastructure (bus stops, ports, etc.) use green energy
Building	**Energy efficiency** • 150 green building certifications • Strengthen energy management and energy auditing for energy users • Promote awareness of energy efficiency	• -

Source: Government Office, Vietnam (2022) , IEA (n.d. g) , ERIA (2023a)

Total final energy consumption by sector (2022)[2]



Final energy demand forecast by sector, BaU, APS and LCET (2019-2050)[3]



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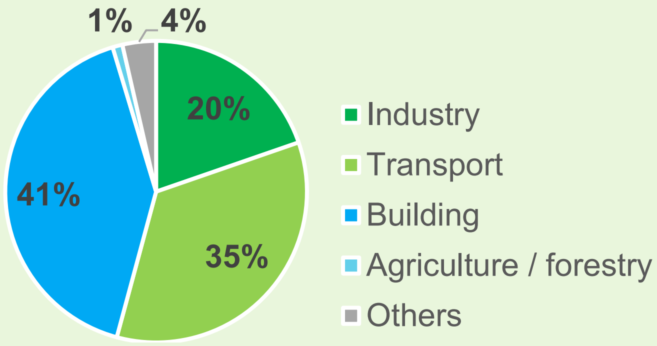
The Philippines aims to introduce various energy efficiency policies across the sectors, and develop production capacity for alternative fuels

Energy Road Maps for Transitioning to Reliable, Clean and Resilient Energy in the end-use and industries sectors[1]

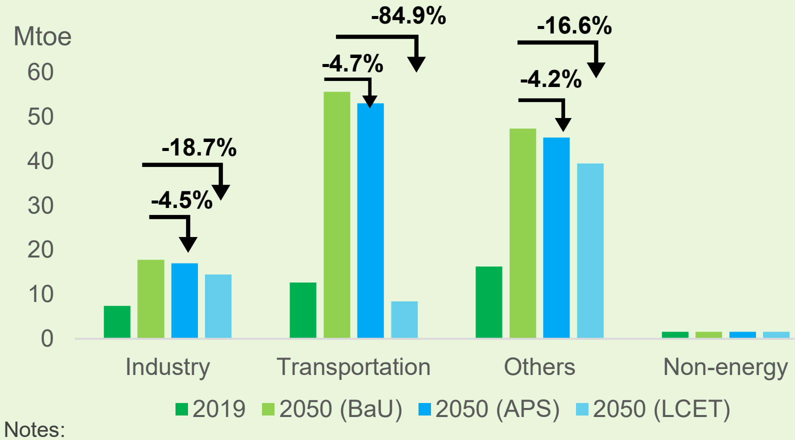
	Short term (-2024)	Medium term (2025-2028)	Long term (2029-2050)
Industry	**Energy Efficiency** • The Minimum Energy Performance for Products (MEPP) and Philippine Energy Labeling Program (PELP) for household appliances and industrial motors	• Establish MEPP for industrial devices	• 2050 objective: Measurable reduction in energy intensity and consumption per year vs BaU • Develop R&D capacity on EE&C
	Fuel switching • Conduct R&D, devise frameworks and strategies for H_2 development • Pilot demonstration on the production of alternative fuels (AFs)	• Develop support infrastructure for H_2 production • Develop supply chain & pilot programme of locally produced AFs	• 2050 objective: secured and stable supply of energy through technology-responsive energy sector • Mainstream the utilisation of locally produced AFs
Transport	**Energy Efficiency** • Develop minimum fuel efficiency and labelling programme for vehicles	• Create financial incentives for fuel-efficient vehicles	• -
	Electrification • Issue policies to support EV deployment • Conduct research & pilot programmes on EVs	• Strengthen and expand manufacturing of EVs for domestic market • Develop standards & conduct training on EV use, EV conversion and battery recycling	• Develop EV ecosystem • Utilise 100% renewables to power EV • Support R&D in battery research & EV technology
Building	**Energy Efficiency** • Adopt the Guidelines for Energy Conserving Design of Buildings • Expand MEPP and PELP for household appliances and industrial motors	• Establish Building Energy Efficiency Indices for government and commercial buildings • Develop a building energy code for low rise residential buildings	• Develop energy efficiency projects in low-income neighbourhood • Develop R&D capacity on EE&C

Source: Department of Energy, Phillipines (2023) , IEA (n.d. d) , ERIA (2023a)

Total final energy consumption by sector (2022)[2]



Final energy demand forecast by sector, BaU, APS and LCET (2019-2050)[3]



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Appendix-2

Examples of international aids towards decarbonisation of the industries and end-use sector in ASEAN

International aid towards energy transition in ASEAN

Industry sector - IFC provides finance to an Indonesian steel company

- In September 2024, International Finance Corporation (IFC)※1 announced a loan to PT Gunung Raja Paksi Tbk (hereinafter referred to as GRP)※2, a leading Indonesian steel maker. The financial support will contribute to increasing low-carbon steel production in Indonesia, cutting GHG emissions and helping to achieve the country's climate objectives.
- IFC will provide GRP with up to USD60 million. GRP will utilise the financing to expand low-carbon flat steel production by using the EAF technology. The financial assistance is expected to enhance GRP's capability to recycle scrap metals and produce high-quality steel. Furthermore, emissions are estimated to be reduced by more than half in comparison to the global average for steel production.

	Details
Donour	International Finance Corporation
Country	Indonesia
Target sector	Industry (specifically steel sector)
Programme name	N/A (press release: "IFC Promotes Decarbonization of Indonesia's Steel Sector with Investment in Gunung Raja Paksi")
Financing type	Loan
Total fund value	Up to USD 60 million
Emissions avoided	Specific value of potential emission avoidance is not indicated, but more than half of emissions will be cut compared to the global average for steel production

Notes:
1. International Finance Corporation (IFC) is a member of the World Bank Group and the largest global development institution with the focus on the private sector in emerging economies
2. PT Gunung Raja Paksi Tbk (GRP) is a member of Gunung Steel Group, one of the largest steel firms in Indonesia, established in 1970 in North Sumatra.

Source: IFC (2024)

International aid towards energy transition in ASEAN

Industry sector - ADB Leads USD135 Million Climate Finance Initiative to Promote Electric Mobility in Vietnam

Project name: "Viet Nam: VinFast Electric Mobility Green Loan Project"

- In 2022, the Asian Development Bank (ADB) assembled a USD135 million financing package for VinFast[1]. This funding is designated for the production of Vietnam's first fully electric public bus fleet and the establishment of the nation's initial EV charging network.
- The assistance is intended to support Vietnam's goal of attaining net-zero GHG emissions and expanding its high-tech manufacturing sectors.

	Details
Donour	Asian Development Bank
Country	Vietnam
Target sector	Transport
Programme name	Viet Nam: VinFast Electric Mobility Green Loan Project
Financing type	Loan and Grant
Total fund value	USD135 million *For fund/grant sources, see table on the right
Emissions avoided	The VinFast e-buses, funded by this climate financing, are expected to reduce Viet Nam's GHG emissions by an estimated 155,000 tonnes over their operating life and help the country fulfill its commitments to the Paris Agreement on Climate Change.

Fund/grant sources

Facility	Fund Source
Grant	Climate Innovation and Development Fund
Loan	Ordinary capital resources, Australia, Clean Technology Fund
B-Loan	Other

Note:
1. VinFast Trading and Production Joint Stock Company is Viet Nam's first domestic car and e-vehicle manufacturer, developing its own cars for the domestic and international markets.

Source: ADB (2022), ADB (2024a)

International aid towards energy transition in ASEAN

Industry sector - ADB Leads USD135 Million Climate Finance Initiative to Promote Electric Mobility in Vietnam

Project name: “Viet Nam: VinFast Electric Mobility Green Loan Project”

- To meet the requirements of the VinFast Electric Mobility Green Loan Project, VinFast is obligated to implement a Livelihood Restoration Plan (LRP) for individuals affected by the construction of its production plants, charging stations, and other facilities.
- The plan includes components such as compensation for land acquisitions and vocational training for those who lost their jobs due to the construction activities.

Photo: Disclose and consultation LRP to affected households by VinFast employee

Photo: VinFast employee work with English centre on vocational training

Photo: VinFast employee work with local authorities on education development programme

Source: ADB (2024a)

Appendix-3

Potential policy instruments that can support widespread deployment of transition technologies

Recommended policies for introduction of transition technologies

Carbon pricing

Carbon pricing is an essential tool to internalise the external costs of GHG emissions, promoting cleaner technologies and energy efficiency. It ensures that emitters bear the social costs of their activities, thereby incentivising reductions.

	Carbon tax	Emissions Trading Scheme
Overview	A carbon tax directly sets a price on carbon by defining a tax rate on GHG emissions or the carbon content of fossil fuels. This method provides a clear economic signal to emitters to reduce their carbon footprint. Fuel taxes are a form of carbon tax.	An emissions trading scheme (ETS) sets a cap on overall emissions while allowing entities to buy and sell allowances. This market-driven approach helps achieve emission reductions at the lowest possible cost.
Technologies in TLP that benefit from the policy/regulation	**All technologies**	
Barriers to deployment	Transition technologies often require higher implementation cost compared to conventional technologies, which may discourage technology users from implementing these technologies.	
How those policies would accelerate deployment of transition technologies	Carbon pricing policies increase the operating cost of technologies with higher GHG emissions and provide financial incentive to implement technologies with less GHG emissions. Increasing the price of carbon overtime is effective for incentivising early adoption of transition and green technologies.	

Recommended policies for introduction of transition technologies

Carbon pricing

Carbon pricing is an essential tool to internalize the external costs of GHG emissions, promoting cleaner technologies and energy efficiency. It ensures that emitters bear the social costs of their activities, thereby incentivizing reductions.

	Carbon tax	Emissions Trading Scheme
Example cases in ASEAN	 In Singapore, the government implemented a carbon tax in 2019, with a rate of 5 Singapore dollars per tonne of CO_2e, which is set to increase over time to motivate companies to adopt sustainable practices and technologies.	 In 2023, Indonesia launched a mandatory and intensity-based ETS in the power sector. It only covers coal fired power plants in the first phase and then the coverage is planned to expand in later phases.

Source: National Climate Change Secretariat Singapore (n.d.), International Carbon Action Partnership (2023)

Recommended policies for introduction of transition technologies

Performance standards

Performance standards set regulatory thresholds to ensure technology and infrastructure meet minimum energy efficiency and environmental performance levels, driving advancements in cleaner technologies.

	MEPS	Performance labelling	Building codes
Overview	MEPS establish mandatory efficiency levels for energy-consuming products, reducing energy consumption and environmental impact across various sectors.	Performance labelling provides consumers with information on the energy efficiency and environmental impact of products, empowering them to make informed decisions and encouraging manufacturers to improve product performance.	Building codes set standards for construction and retrofitting, ensuring that buildings are energy-efficient and environmentally sustainable while providing comfort and safety for occupants.
Technologies on TLP that benefit from the policy/regulation	**Heat pumps, Fuel combustion co-generation, Fuel cell co-generation, HEMS, HFCV, BEV, PHEV, FFV**		**Heat pumps, Fuel combustion co-generation, Fuel cell co-generation, HEMS**
Barriers to deployment	Conventional alternatives to these advanced technologies often exhibit lower energy efficiency, resulting in higher emissions. However, without access to relevant information, users are often unable to see the differences in energy efficiency between conventional and more efficient technologies. As a manufacturer, developing lower emission technologies often require investment, which needs to be justified by conditions such as the technology user's preference and regulation.		
How those policies would accelerate deployment of transition technologies	Mandating a certain environmental performance support the development of transition technology by manufacturers. By providing information on the energy efficiency of those technologies, which allows users to make comparisons, users are able to make better-informed decisions. Many countries implement performance standards. Unifying these standards may also help to send clear messages to the manufacturers.		

Recommended policies for introduction of transition technologies

Performance standards

Performance standards set regulatory thresholds to ensure technology and infrastructure meet minimum energy efficiency and environmental performance levels, driving advancements in cleaner technologies.

	MEPS	Performance labelling	Building codes
Example cases in ASEAN	 Singapore implemented MEPS for household appliances in 2011. Since then, the standards have been tightened and more technologies were added.	 Thailand's Electricity Generating Authority of Thailand (EGAT) has been implementing the energy efficiency label No. 5 for over 30 years. EGAT has reported that more than 470 million appliances have been labelled, and 20 million tonnes of CO_2 emission reduction was achieved.	 The Philippines Green Building Code integrates energy efficiency and environmental sustainability requirements into the building approval process to enhance resource utilisation.

Source: NEA (n.d.), EGAT (2024), DPWH (2015)

Recommended policies for introduction of transition technologies

Investment subsidies

Investment subsidies, such as grants, tax credits, and financing programmes, lower the financial barriers to adopting advanced technologies, accelerating the transition toward sustainable practices.

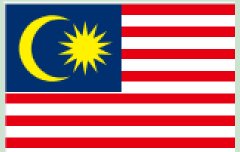
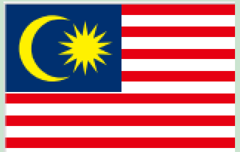
	Grants and rebates	Tax credits	Low-interest loans and financing programmes
Overview	Grants and rebates reduce the upfront costs for individuals and businesses to adopt energy-efficient technologies.	Tax credits offer financial incentives by allowing deductions from the total tax liability for investments in sustainable technologies and practices, promoting widespread adoption.	Low-interest loans and financing programs help reduce the cost of capital for sustainable investments, ensuring long-term financial viability and encouraging adoption.
Technologies on TLP that benefit from the policy/regulation	**All technologies. Particularly relevant for the technologies which require a large capital investment for deployment, e.g. Carbon capture, LNG-fuelled ships, Biofuel-fuelled ships, etc.**		
Barriers to deployment	Transition technologies often require higher implementation cost compared to conventional technologies, which may discourage technology users from implementing these technologies.		
How those policies would accelerate deployment of transition technologies	In addition to covering the technology cost, covering the cost for assessments to implement technologies, as in the example of Enhanced Industry Energy Efficiency Grant in Singapore, can be effective for assisting companies to make the decision to implement sustainable practices.		

Source: NEA (2023)

Recommended policies for introduction of transition technologies

Investment subsidies

Investment subsidies, such as grants, tax credits, and financing programmes, lower the financial barriers to adopting advanced technologies, accelerating the transition toward sustainable practices.

	Grants and rebates	Tax credits	Low-interest loans and financing programs
Example cases in ASEAN	 Singapore's Enhanced Industry Energy Efficiency Grant offers financial support for companies to invest in energy efficient technologies or equipment. It also supports initiatives, such as implementing energy management information systems and conducting energy assessments.	 In Malaysia, the Green Investment Tax Allowance allows companies investing in green technology projects to claim a tax allowance. The Green Income Tax Exemption offers income tax exemptions to companies involved in green technology services and systems.	 Malaysia's Green Technology Financing Scheme (GTFS) is a loan programme which supports projects in energy, manufacturing, transport, building, waste and water sector.

Source: NEA (2023), MGTC (n.d. a), MGTC (n.d. b)

Recommended policies for introduction of transition technologies

Infrastructure development

Developing infrastructure such as stable utility supply systems and vehicle charging/refuelling stations is crucial for supporting the wide adoption of clean technologies and ensuring sustained progress.

	Stable utility supply	Charging/refuelling stations
Overview	Ensuring a stable and reliable utility supply especially for electric power supports the consistent operation of sustainable technologies and contributes to overall economic stability and growth.	Expanding the network of charging and refuelling stations is essential for promoting the adoption of alternative fuel vehicles and other methods of transportation.
Technologies on TLP that benefit from the policy/regulation	**Heat pumps, Fuel cell co-generation, Fuel combustion co-generation EAF, Electric heating**	**BEV, PHEV/HFCV, LNG-fuelled ship, Biofuel/Ammonia-fuelled ship**
Barriers to deployment	Adoption of technologies requiring grid electricity relies on stable and reliable electricity supply.	One bottleneck for adoption of electric and H_2 vehicles is the underdeveloped charging station networks. Same can be said about ships using alternative fuels requiring bunkering facilities.
How those policies would accelerate deployment of transition technologies	Providing reliable power supply infrastructure will reduce risks for individuals and businesses adopting technologies.	Providing the infrastructure such as charging stations and bunkering stations could boost the adoption of these technologies.

Recommended policies for introduction of transition technologies

Infrastructure development

Developing infrastructure such as stable utility supply systems and vehicle charging stations is crucial for supporting the wide adoption of clean technologies and ensuring sustained progress.

	Stable utility supply	Charging/refuelling stations
Example cases in ASEAN	 Singapore's grid modernisation efforts focus on grid resilience and integration of renewable energy, ensuring consistent supply and accommodating future technological advancements	 In 2021 the Government of Singapore announced a target to deploy 60,000 EV charging points by 2030.

Source: LTA (n.a.), EMA (2024b)

Recommended policies for introduction of transition technologies

R&D support

Investments in R&D are vital for technological innovation and the discovery of new solutions to environmental and energy challenges. Public and private collaboration enhances the impact of these efforts.

	Public investment in research	Public-Private Partnerships
Overview	Government funding for research in end-use technologies accelerates the development of advanced solutions in areas like building automation, industrial processes, and clean transportation.	Public-private partnerships combine resources and expertise to advance R&D in end-use sectors, fostering the commercialization of innovative and energy-efficient technologies.
Technologies on TLP that benefit from the policy/regulation	**Ammonia fueled ship, Production of chemicals using captured CO_2, DRI, Carbon capture, Large scale IHPs**	
Barriers to deployment	Technologies with lower TRLs require further investment in research or demonstration.	
How those policies would accelerate deployment of transition technologies	Even for technologies with higher TRLs, support for technological development and demonstration could contribute to increasing the performance or bringing down cost, leading to increased adoption of technologies.	

Recommended policies for introduction of transition technologies

R&D support

Investments in R&D are vital for technological innovation and the discovery of new solutions to environmental and energy challenges. Public and private collaboration enhances the impact of these efforts.

	Public investment in research	Public-Private Partnerships
Example cases in ASEAN	 Under the Research, Innovation, and Enterprise 2020 Plan, Singapore's government has committed 19 billion Singapore dollars over 2016 to 2020 in research and innovation. One of the four technology domains is Urban Solutions and Sustainability.	  The Philippines' Public Private Partnership Center manages various initiatives and projects across sectors, including energy and infrastructure. Thailand's National Energy Technology Center carry out R&D in energy technologies with public and private partners.

Source: MTI (2016), Public-Private Partnership Centre, Philippines (n.d.), National Science and Technology Development Agency (2019)

Recommended policies for introduction of transition technologies

Biofuel mandate

A biofuel mandate requires a certain percentage of biofuel to be blended with traditional fossil fuels, reducing reliance on non-renewable energy sources and lowering GHG emissions.

	Biofuel mandate
Overview	ASEAN Member States are increasingly adopting biofuel mandates. Indonesia, Malaysia, the Philippines, and Thailand have implemented large-scale biofuel blending programmes, whilst Viet Nam and the Lao People's Democratic Republic are in the process of doing so as of 2020.
Technologies on TLP that benefit from the policy/regulation	**Biofuel fuelled ship, FFV, Lower emission fuel fueled equipment, Fuel combustion co-generation (using biofuels)**
Barriers to deployment	Technologies using biofuels often require additional technology development, resulting in higher cost.
How those policies would accelerate deployment of transition technologies	Biofuel mandates send a clear message to technology manufacturers from the government to utilise biofuel, ensuring technology commercialisation. Countries implementing biofuel mandates are gradually increasing the percentage of biofuels, which help manufacturers make the decisions for early technology development.

Source: ACE (2024)

Recommended policies for introduction of transition technologies

Biofuel mandate

A biofuel mandate requires a certain percentage of biofuel to be blended with traditional fossil fuels, reducing reliance on non-renewable energy sources and lowering GHG emissions.

	Biofuel mandate
Example cases in ASEAN	 Indonesia implements a mandatory biodiesel blending program (B35), requiring a 35% blend of biodiesel with diesel fuel, aiming to boost domestic biodiesel production and reduce fossil fuel dependence. The blending levels of biodiesel has been increasing continuously from 2.5% in 2008, and the country plans to increase it further.

Source: ACE (2024)

Recommended policies for introduction of transition technologies

Sustainability certificate mandate on biofuels

Sustainability certificate mandate on biofuels require suppliers to produce biofuels in a sustainable manner which comply with the sustainability standards such as the Roundtable on Sustainable Palm Oil (RSPO) and the International Sustainability and Carbn Certification (ISCC). Additionally national certification schemes ensure environmental and social sustainability, enhancing market access for certified biofuel producers.

	Sustainability certificate mandate on biofuels
Example cases in ASEAN	 Indonesia has established the Indonesian Sustainable Palm Oil (ISPO) certification, a mandatory scheme aimed at enhancing the sustainability of palm oil production.

Source: ACE (2024)

List of Contributors

List of contributors (1/3)

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Alphabetical order

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Alphabetical order

List of Acronyms and Abbreviation

List of acronyms and abbreviations (1/13)

4E	Energy Efficient End-Use Equipment Technology Collaboration Programme, IEA
AC	Air conditioner
ACE	ASEAN Centre for Energy
ADB	Asian Development Bank
AER	Annual efficiency ratio
AFs	Alternative fuels
AI	Artificial intelligence
AMS	ASEAN Member States
ANRE	Agency for Natural Resources and Energy, Japan
APS	Announced pledges scenario
APS	Alternative policy scenario
ASEAN	Association of Southeast Asian Nations

List of acronyms and abbreviations (2/13)

ASHP	Air-source heat pump
BaU	Business as usual
BECCS	Bioenergy with carbon capture and storage
BECCU	Bioenergy with carbon capture and utilisation
BEV	Battery electric vehicle
BF	Blast furnace
BF-BOF	Blast furnace-basic oxygen furnace
BOF	Basic oxygen furnace
CaCO3	Calcium carbonate
CaO	Calcium oxide
CAPEX	Capital expenditure
CBI	Climate Bond Initiative

List of acronyms and abbreviations (3/13)

CCS	Carbon caputre and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
CFD	Computational fluid dynamics
CFPP	Coal-fired power plant
CH4	Methane
CHP	Combined heat and power
CNG	Compressed natural gas
COP	Coefficient of Performance
CWC	COGEN World Coalition
DAC	Direct air capture
DNSH	Do no significant harm

List of acronyms and abbreviations (4/13)

DOE	United States Department of Energy
DR	Demand response
DRI	Direct reduced iron
EAF	Electric arc furnace
EC	Essential criteria
ECM	Electronic control module
EE&C	Energy efficiency and conservation
EEDI	Energy efficiency design index
EER	Energy efficiency ratio
EEXI	Energy efficiency existing ship index
EGR	Exhaust gas recirculation
EHPA	European Heat Pump Association

List of acronyms and abbreviations (5/13)

EOs	Environmental objectives
EPA	United States Environmental Protection Agency
ERIA	Economic Research Institute for ASEAN and East Asia
ETS	Emissions trading scheme
EU	European Union
EV	Electric vehicle
FC CHP	Fuel cell CHP
FF	Foundation Framework of the ASEAN Taxonomy
FFV	Flex fuel vehicle
F-gas	Fluorinated gas
GCCSI	Global CCS Institute
GEC	Global Environment Centre Foundation, Japan

List of acronyms and abbreviations (6/13)

GHG	Greenhouse gas
GNR	Getting the Numbers Right database
GSHP	Ground-source heat pump
GWP	Global warming potential
HEMS	Home energy management system
HEV	Hybrid vehicle
HFC	Hydrofluorocarbons
HFCV	Hydrogen fuel cell vehicle
HFO	Hydrofluoroolefin
HP	Heat pump
HPC	Heat Pump Centre, IEA
HPTCJ	Heat Pump & Thermal Storage Technology center of Japan

List of acronyms and abbreviations (7/13)

HSE	Health, safety, and environment
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
IE	Institute of Energy, Vietnam
IEA	International Energy Agency
IEA NZE	International Energy Agency's Net Zero Emissions by 2050 Scenari
IFC	International Finance Corporation
IHP	Industrial heat pump
IMO	International Maritime Organization
IoT	Internet of things
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency

List of acronyms and abbreviations (8/13)

JADA	Japan Automobile Dealers Association
JICA	Japan International Cooperation Agency
JST	Japan Science and Technology Agency
LCA	Life-cycle assessment
LCET	Low-carbon energy transition
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LWA	Light weight aggergates
MCFC	Molten carbonate fuel cell
MEPS	Minimum energy performance standard
METI	Ministry of Economy, Trade and Industry, Japan
MGO	Marine gas oil

List of acronyms and abbreviations (9/13)

MHEV	Mild hybrid electric vehicle
MI	Methanol Institute
MSRP	Manufacturer’s suggested retail price
N2O	Nitrous oxide
NEDO	New Energy and Industrial Technology Development Organization, Japan
NEEP	Northeast Energy Efficiency Partnerships, the U.S.
NETL	National Energy Technology Laboratory, the U.S.
Nox	Nitrogen oxides
NREL	National Renewable Energy Laboratory, the U.S.
NSP	New suspension preheater
NWA	Normal weight aggregates
NYSERDA	New York State Energy Research and Development Authority

List of acronyms and abbreviations (10/13)

O&M	Operation and maintenance
OECD	Organisation for Economic Co-operation and Development
OFFO	Oil Fuel Fund Office, Thailand
OPEX	Operationg expenditure
PAFC	Phosphoric acid fuel cell
PCBs	Polychlorinated biphenyls
PE	Polyethylene
PEFC	Proton-exchange membrane fuel cell
PFAS	Polyfluoroalkyl substances
PHEV	Plug-in hybrid vehicle
POM	Polyoxymethylene
PP	Polypropene

List of acronyms and abbreviations (11/13)

PS	Plus Standard of the ASEAN Taxonomy
R&D	Research and development
RCA	Recycled concrete aggregates
RMT	Remedial measures to transition
RNG	Renewable natural gas
SA	Social aspect
SEAISI	South East Asia Iron and Steel Institute
SMR	Steam methane reforming
SOFC	Solid-oxide fuel cell
SOx	Sulfur oxide
TLP	Technology List and Perspectives
TRL	Technology List and Perspectives for Transition Finance in Asia

List of acronyms and abbreviations (12/13)

TSC	Technical screening criteria
TTW	Tank-to-wheel
TVA	Tennessee Valley Authority
U4E	United for Efficiency, United Nations Environmental Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
VAT	Value added tax
VRE	Variable renewable energy sources
WEF	World Economic Forum
WHR	Waste heat recovery
WRI	World Resources Institute

List of acronyms and abbreviations (13/13)

WS	Wholesale price
WSHP	Water-source heat pump
WTT	Well-to-tank
WTW	Well-to-wheel

Units of measure (1/5)

DWT	Deadweight tonnage
gCO_2/km	Gram of carbon dioxide per kilometre
gCO_2/MJ	Gram of carbon dioxide per megajoule
gCO_2/t-km	Gram of carbon dioxide per tonne kilometre
gCO_2-eq/gH_2	Gram of carbon dioxide equivalent per gram of hydrogen
gCO_2-eq/km	Gram of carbon dioxide equivalent per kilometre
gCO_2-eq/kWh	Gram of carbon dioxide equivalent per kilowatt hour
gCO_2-eq/MJ	Gram of carbon dioxide equivalent per megajoule
gCO_2-eq/v-km	Gram of carbon dioxide equivalent per vehicle kilometre
gH_2/km	Gram of hydrogen per kilometre
GJ	Gigajoule
GT	Gross tonnage

Units of measure (2/5)

GW	Gigawatt
$kgCO_2$	Kilogram of carbon dioxide
$kgCO_2$/GJ	Kilogram of carbon dioxide per gigajoule
$kgCO_2$/kWh	Kilogram of carbon dioxide per kilowatt hour
$kgCO_2$/MWh	Kilogram of carbon dioxide per megawatt hour
$kgCO_2$/TJ	Kilogram of carbon dioxide per terajoule
$kgCO_2$-eq/kWh	Kilogram of carbon dioxide equivalent per kilowatt hour
$kgCO_2$-eq/tonne-km	Kilogram of carbon dioxide equivalent per tonne kilometre
kJ/kg	Kilojoule per kilogram
kW	Kilowatt
kWh	Kilowatt hour
m^3N/h	Normal cubic meter per hour

Units of measure (3/5)

MJ	Megajoule
MJ/t-clinker	Megajoule per tonne of clinker
MJ/tCO_2	Megajoule per tonne of carbon dioxide
MMBtu	Metric million British thermal unit
MPa	Megapascal
Mtoe	Million tonnes of oil equivalent
MTPA	Million tons per annum
MW	Megawatt
MWh	Megawatt hour
ppm	Parts per million
t	Tonne
t methanol	Tonne of methanol

Units of measure (4/5)

tCO_2	Tonne of carbon dioxide
tCO_2/t-clinker	Tonne of carbon dioxide per tonne of clinker
tCO_2/t-steel	Tonne of carbon dioxide per tonne of steel
tCO_2/year	Tonne of carbon dioxide per year
tCO_2-eq	Tonne of carbon dioxide equivalent
tCO_2-eq/GJ	Tonne of carbon dioxide equivalent per gigajoule
tCO_2-eq/kWh	Tonne of carbon dioxide equivalent per kilowatt hour
TEU	Twenty-foot equivalent unit
tH_2	Tonne of hydrogen
TWh	Terawatt hour
USD/t methanol	US dollar per tonne of methanol
USD/t-cement	US dollar per tonne of cement

Units of measure (5/5)

USD/t-clinker	US dollar per tonne of clinker
USD/tCO_2-eq	US dollar per tonne of carbon dioxide equivalent
USD/t-steel	US dollar per tonne of steel

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