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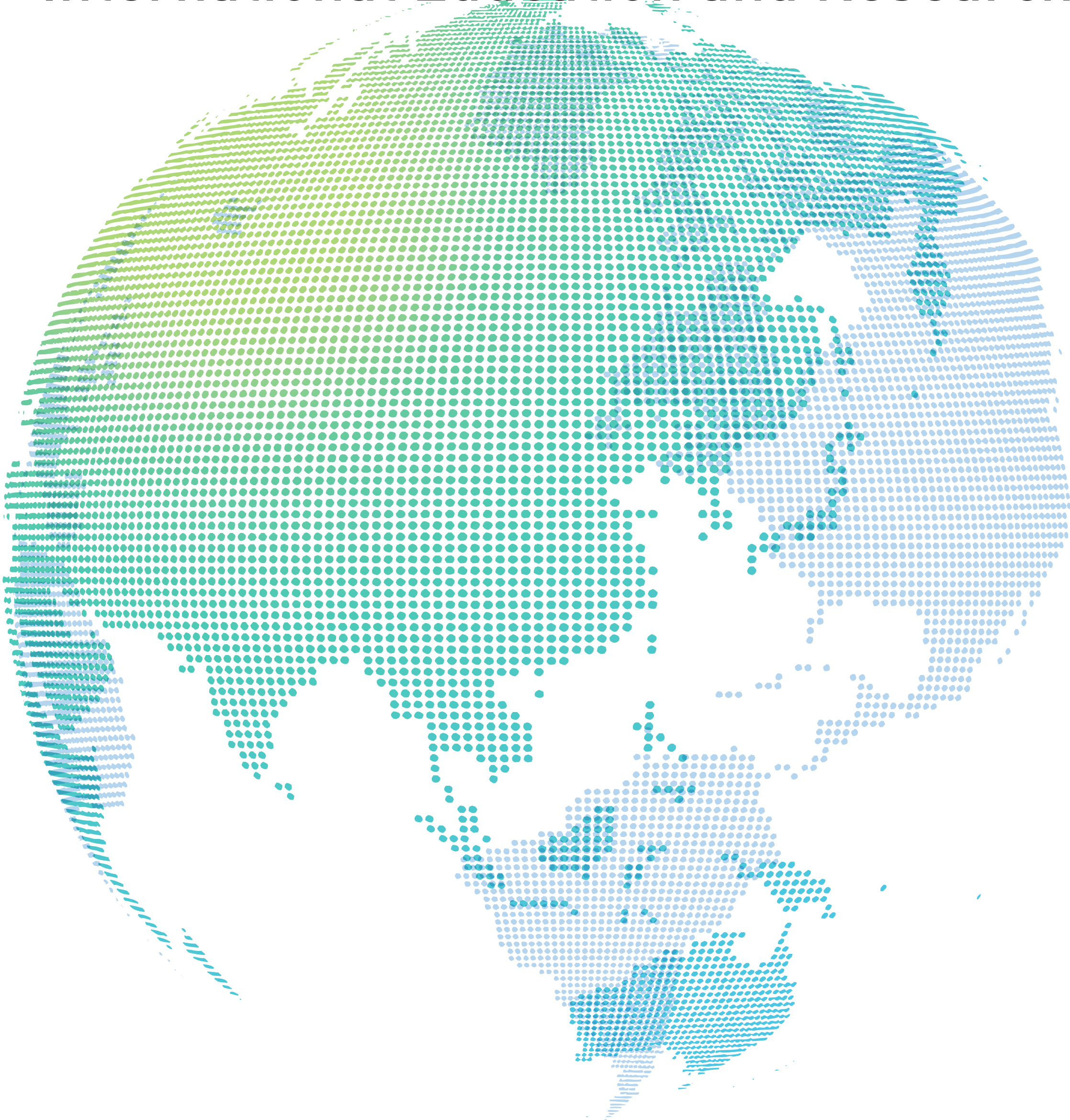

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ASEAN Power Pathways to 2050: E3ME-FTT Model Projections

Shinya KATO[1), Pim VERCOULEN[2), Jeong Won KIM[3), Yongsung CHO[4), Xu HAN[5), and Soocheol LEE[1)

1) Faculty of Economics, Meijo University
2) Cambridge Econometrics
3) Energy Studies Institute, National University of Singapore
4) Department of Food and Resource Economics, Korea University
5) Graduate School of Economics, Kyoto University

Abstract

ASEAN's power sector faces the hard task of cutting fossil dependence. Using the macro-econometric E3ME-FTT model calibrated to the IEEJ 2023 Outlook, we project outcomes under four pathways. The Reference (REF) and Current Technology Trajectory (CTT) cases yield only modest renewable gains by 2050. By contrast, the Nationally Determined Contribution (NDC) and Ambitious (AMB) cases deliver large increases, with renewables supplying about 85% and 93% of electricity, respectively. NDC combines a domestic ETS with subsidies for CCS, wind, and solar, plus feed-in tariffs; AMB further tightens additions of new fossil capacity. Model results indicate that, although employment could fall in fossil-fuel industries, higher clean-energy investment can raise ASEAN-wide GDP. Given the peninsular and archipelagic geography of many member states, policies also attend to grid stability and access, not only climate mitigation. These findings underscore the importance of coherent policy packages and credible near-term power plans to steer the transition.

Keywords：ASEAN・Power sector・Renewable energy・Nationally Determined Contribution (NDC)・E3ME-FTT model

1. Introduction

1.1 Background

The Association of Southeast Asian Nations (ASEAN) is a regional economic union likely to experience rapid growth in the near future, accompanied by significant increases in energy consumption and associated carbon dioxide emissions (IEEJ, 2022). Although ASEAN's share of global greenhouse gas emissions was only 5% in 2022, absent mitigation efforts, future growth is expected to be environmentally significant.

In recent years, most ASEAN Member States (AMS) have announced carbon-neutrality targets to be achieved around the middle of this century (UNFCCC, 2024). Given these countries' reliance on fossil energy and their economic growth trajectories, the path to carbon neutrality is steep (IEA, 2022a; IEEJ, 2022; Lau, 2023). Beyond domestic efforts, cooperation and support from countries with carbon-free technologies and financing—such as Japan, China, and South Korea—will also be important.

Achieving carbon neutrality requires economy-wide decarbonization, with particular urgency in the power sector. This study therefore focuses on the power sector because (i) it offers large and immediate emissions reductions through generation and investment choices, (ii) low-carbon power technologies are already mature and increasingly cost-competitive, and (iii) power-sector decarbonization is a prerequisite for electrifying other sectors and reducing their emissions. Mature low-carbon alternatives in electricity are rapidly outcompeting incumbent carbon-intensive technologies in deployment and cost (IEA, 2024), and a decarbonized grid can accelerate electrification in other sectors.

Across ASEAN, net-zero pledges and updated NDCs are increasingly complemented by power-sector policies that prioritise rapid renewable deployment and grid enabling conditions, alongside a gradual shift away from unabated coal. At the regional level, the ASEAN Plan of Action for Energy Cooperation (APAEC) 2026–2030 sets an aspirational target of 45% renewables in installed power capacity by 2030 (ACE, 2025). Indonesia's Enhanced NDC raises its 2030 mitigation target to 31.89% (unconditional) and 43.20% (conditional) below BAU, and the JETP CIPP further articulates a conditional pathway with power-sector emissions peaking by 2030 (≤290 $MtCO_2$) and reaching net zero by 2050 (Government of Indonesia, 2022; JETP Secretariat and Working Groups, 2023). Malaysia's National Energy Transition Roadmap (NETR) outlines a "Responsible Transition" pathway targeting 70% renewables in installed capacity by 2050, providing policy context for the scenarios analysed in this paper (Ministry of Economy Malaysia, 2024).

However, under current policies, power-sector decarbonization is unlikely (IEA, 2022a; IEEJ, 2022). Policy support and enforcement—carbon pricing, subsidies, and, in some cases, regulations on fossil power generation (e.g., phase-outs)—are needed to spur power producers to invest in and adopt decarbonization technologies.

1.2 Literature review

According to the IPCC (2023), achieving carbon neutrality on a global scale requires significant reductions in fossil-fuel usage in the power sector, adoption of carbon capture and storage (CCS), carbon-free power systems, widespread electrification, and energy conservation and efficiency improvements. Furthermore, the cost of reducing CO_2 emissions by one ton is under $20 for solar and wind energy, energy efficiency improvements, and methane emission reductions (from coal mining, oil and gas, and waste), contributing significantly to emission reductions. However, it is acknowledged that achieving net-zero CO_2 emissions from the industrial sector is challenging. Nevertheless, coordinated actions across the entire value chain, including demand management, energy and material efficiency, emission reductions, and transformations in production processes, can make this possible.

Regarding the decarbonization of the power sector in ASEAN, Lau (2023) argues that coal and natural gas have historically dominated ASEAN's power sector, accounting for 77% of the electricity generation in 2019. To achieve net zero by 2050, AMS need to decarbonize the power sector over the next 30 years.

Regarding the importance of climate change measures in AMS, the Asian Development Bank (ADB) estimates that if climate change is not mitigated, major industries such as agriculture, tourism, and fisheries, as well as human health and labor productivity in AMS, will be severely impacted (Raitzer et al., 2016). This could lead to an 11% reduction in GDP in the region by the end of the century, with AMS potentially suffering greater losses than most other regions worldwide.

Given the significance of climate change impacts in AMS, recent years have seen modelling analyses on decarbonization targeting these nations. The IEA (IEA, 2023) utilized the GEC (Global Energy and Climate) model, a bottom-up technology selection model, to simulate the pathway to decarbonization in ASEAN countries up to 2050. Assuming a GDP growth rate of 3.8% from 2020 to 2050, and analyzing the Announced Pledges Scenario (APS) from the World Energy Outlook 2022 (IEA, 2022a), it is estimated that the total energy supply will grow at an annual rate of 1.5%, with CO_2 emissions peaking around 2030 and subsequently decreasing at an average annual rate of −1.7%, achieving carbon neutrality by 2050. The importance of decarbonizing the power sector through an increased share of renewable energy is also highlighted. Similarly, Kimura et al. (2022) and IEEJ (2022) utilized the IEEJ-NE (Institute of Energy Economics, Japan-New Earth) model Otsuki et al. (2019, 2022), a bottom-up technology selection model, to conduct similar simulations, outlining the pathway to decarbonization in AMS centered on electrification and the transition to renewable energy sources. The former investigated the optimal configuration under the constraints of Net-Zero, while the latter produces energy system outlooks in a "Reference" and "Advanced technologies scenario". Phoumin et al. (2021) applied the bottom-up Low Emissions Analysis Platform (LEAP) software tool and adapted it to the case of the ASEAN power generation sector. They exposed the LEAP platform to various power generation configurations, though not per se with full decarbonization in mind. IRENA and ACE (2022) investigated various decarbonization scenarios focusing on renewable energy, using the REmap toolkit, which includes PLEXOS to estimate long-term power capacity planning. Lastly, the IEA (2022b) also published decarbonization pathways specific to the case of ASEAN, building on their inhouse developed scenarios using the GEC model (IEA, 2023).

From the studies above, we selected the scenarios that are publicly available and somewhat similar to the AMB (Ambitious) scenario displayed in this study, but we note substantial differences in scenario design as well. Most of the aforementioned studies investigated economy-wide decarbonization while in this study we limited ourselves to the power sector alone. This means that, depending on the scenario inputs, assumptions, and methodology, other studies show significant increases in electricity demand due to electrification of e.g. road transport. In this study, electricity demand is affected by electricity prices and sectoral output. Impacts on the latter only occur through indirect effects of the scenario inputs. The selected scenarios of the selected studies are displayed in **Table 1**.

In contrast, in a study performed by the ASEAN Centre for Energy (ACE) and Gesellschaft für Internationale Zusammenarbeit (GIZ) (2022) the LEAP model was used to simulate the decarbonization pathway for AMS up to 2050. The simulation results indicate that the total investment required for decarbonization from 2021 to 2050 amounts to $726 billion under the APS, with 77% of this investment directed towards renewable energy.

Furthermore, analyses focusing on the power sector using the E3ME model, which is also utilized in this study, include

Table 1 Overview and description of the selected scenarios of selected studies for comparison

Source	Scenario	Model	Brief description
Kimura et al. (2022)	CN2050/2060 (Carbon neutral by 2050 or 2060, depending on national pledges)	IEEJ-NE	"CN2050/2060 reflects nationally declared carbon-neutral target years and considers natural carbon sinks in Indonesia, Malaysia, Myanmar, Thailand and Viet Nam based on discussions with each country."
IEEJ (2022)	Advanced Technology Scenario	IEEJ-NE	"In the Advanced Technologies Scenario, measures to maximize the reduction of carbon dioxide (CO_2) emissions and to ensure energy security will be enhanced with consideration given to their application opportunities and acceptability to society. Each country and region will actively implement aggressive energy efficiency and decarbonization policies that contribute to securing a stable energy supply, enhancing climate change measures, and accelerating the development and introduction of innovative technologies globally."
Phoumin et al. (2021)	APS (Alternative policy scenario)	LEAP	"The APS refers to Alternative Policy Scenario and assumes that states will increase more efficient final energy consumption, more efficient power generation, a higher share of renewables, and the introduction of nuclear power plants, based on each AMS government policy. The assumptions used in the APS are described in the table below."
IEA (2022b)	SDS (Sustainable development scenario)	GEC	"In the SDS, CO_2 emissions drop to zero around 2070 and there are rapid reductions in non-CO_2 emissions. The 1.5℃ level is exceeded in the early 2030s and the rise in temperature peaks at just under 1.7℃ around 2050. The SDS is in line with the Paris Agreement objective of 'holding the increase in the global average temperature to well below 2℃'."
IRENA and ACE (2022)	TES (Transforming Energy Scenario)	REmap and PLEXOS	"The TES describes an energy pathway based largely on currently available and competitive low and zero carbon technologies. It is characterized largely by renewable energy expansion and energy efficiency."
	1.5-S 90% (consistent with achieving 1.5C global warming, with a 90% uptake of renewables in the power sector by 2050)		"The 1.5-S is a more ambitious energy pathway, and outlines options to further reduce CO_2 emissions in the energy system in challenging sectors. It largely follows the WETO scenario aiming to reach net-zero emissions globally by 2050."
	1.5-S 100% (consistent with achieving 1.5C global warming, with a 100% uptake of renewables in the power sector by 2050)		

Source: Author's summary

those by Pollitt (2020) and Lee et al. (2022). Pollitt (2020) predicts that if China achieves carbon neutrality, cumulative CO_2 emissions will decrease by approximately 215 Gt, and China's GDP will increase by about 5% over the next decade. This is attributed to increased investments in the power sector, technological advancements related to coal phase-out, and the promotion of fuel substitution. Lee et al. (2022) estimate the macroeconomic impacts of Japan achieving carbon neutrality by 2050 and how Japan's energy mix will change. The results indicate that, assuming the decommissioning of nuclear power plants by 2040, about 90% of the energy mix in 2050 will consist of renewable energy. GDP is projected to increase by 4.0–4.5% compared to the baseline scenario, and employment is expected to increase by 1.5–2.0%, demonstrating the potential for simultaneous achievement of decarbonization and economic growth.

1.3 Purpose of this study

In this study, we will investigate announced policies using the Nationally Determined Contribution (NDC) documents (UNFCCC, 2024) and policy documents specific to the respective domestic power sectors (ACE, 2023). Using the E3ME-FTT model, we can enter the interpretation of the announced policies to investigate the impact on technology uptake, emissions, and macro-economic consequences. E3ME-FTT is a simulation model, which can yield substantially different results when compared to optimization models (Mercure et al., 2019). Simulation models have so far rarely been used to investigate decarbonization of the power sector in the ASEAN context, however, as mentioned in the previous section, various studies have been conducted using optimization models (e.g. (Phoumin et al., 2021; Kimura et al., 2022; Matsumoto and Phoumin, 2022; IEEJ, 2022)). Finally, Barbrook-Johnson et al. (2024) argue that energy models built on optimization and cost-benefit analysis, while useful, are not suitable for policy appraisal and they suggest a shift away from such models for policy appraisal purposes.

The E3ME-FTT model will be used to investigate whether the policies mentioned in NDC documents are sufficient to meet the renewable energy targets. In addition, we will expose the ASEAN power systems to a more stringent set of policies to investigate what the decarbonization potential is and how much investment is required to achieve such decarbonization. Though, the aim is not to seek economy-wide decarbonization. This study focusses on quantitative impacts on technology diffusion, CO_2 emissions, and upfront investment costs in the power sector, while also showing macroeconomic impacts. The main questions this study seeks to answer are:

- Are the NDC policies sufficient to achieve renewable energy and emission targets in the power sector?
- What are the economic impacts of an isolated transition in the ASEAN power sectors?
- What level of investments are required to achieve Net-Zero in the ASEAN power sectors?

2. Analysis Method

2.1 Brief description of E3ME-FTT

Here, we use the E3ME-FTT model to explore the impacts of various policy packages on the ASEAN economies. The E3ME-FTT framework combines macro-econometrics based on the post-Keynesian school of thought (E3ME) with technology diffusion models based on evolutionary economics theory (FTT). For a more detailed description of the econometric equations and the economic accounting framework within E3ME, we refer to the E3ME model manual (Cambridge Econometrics, 2022). In brief, E3ME is grounded in empirically derived relationships between macroeconomic indicators, based on long time series data. The model covers the whole globe divided into 71 regions and 70/43 sectors in European/non-European regions.

It utilizes a system of econometric equations to track economic activity undertaken by persons, households, firms and other groups in society, and how it affects other agents. Through the economic structure, E3ME includes various feedback loops affecting effective demand: Interaction between sectors; an income loop; an investment loop; and a trade loop. This is illustrated in **Figure 1**.

Figure 1 Illustration of the economic structure as represented in E3ME
Source: Cambridge Econometrics

E3ME-FTT differs from most other macro-economic modelling (or Integrated Assessment Models (AIMs)) frameworks. Mercure, et al. (Mercure et al., 2019) reviewed the various economic and energy/technology modelling approaches and described why different approaches can lead due to the simulation approach, rather than applying optimization routines and restrictive assumptions as found in many other macro-economic models. Most other models start from the premise that economies operate in equilibrium, that prices and wages adjust to clear markets, and assume a fixed supply of money. In the E3ME-FTT framework, none of the aforementioned assumptions are included. Instead, under-utilized capacity can be activated through policy, prices and wages can be sticky, and money is created through lending.

The world is divided into 71 regions of which major economies and EU member states are represented individually. The ASEAN community of nations is subdivided into 3 regions; Indonesia and Malaysia are represented individually, while all other AMS are represented as a single aggregate region. The time horizon for this study runs from 2020 to 2050. Finally, FTT: Power includes 24 different power generation technologies. However, the model does not include hydrogen mixing as an option by default due to a lack of a hydrogen supply module.

We use E3ME-FTT because it directly matches our aims: E3ME quantifies economy-wide impacts of NDC policy packages (via demand, investment and trade feedbacks), while FTT: Power simulates policy-driven decarbonization of the electricity mix through technology diffusion and competition. Their integration allows us to link power-sector transitions to macroeconomic outcomes for ASEAN over 2020–2050 in a consistent framework.

2.2 Theoretical background of FTT: Power

FTT: Power is coupled bidirectionally with the macro-econometric model E3ME. E3ME endogenously determines electricity demand as the broader economy evolves—for example through changes in prices and sectoral activity—while FTT: Power determines the technological configuration of electricity supply consistent with that demand. The supply module represents technology diffusion as a path-dependent process: today's fleet composition influences tomorrow's choices, costs respond to the economic environment (notably energy and carbon prices), and learning-by-doing reduces costs as cumulative capacity grows, including spillovers across related technologies. The initial formulation of the FTT family is described in Mercure (2012), with a concise overview of recent developments in Nijsse et al. (2023), and the mathematical justification for the Lotka-Volterra diffusion framework provided in Mercure (2015).

Investment decisions are based on levelised cost of electricity (LCOE), which aggregates all relevant lifetime costs—upfront investment, operations and maintenance, fuel, and carbon costs—discounted over time. In FTT: Power these cost components are represented as distributions rather than single point values, allowing uncertainty to propagate into LCOE estimates. Policies act directly on these components: investment subsidies lower initial outlays; carbon prices increase running costs for carbon-intensive technologies; and movements in fuel and electricity prices alter operational economics. As deployment expands, cumulative capacity updates the model's learning relationships, so that future cost projections embody learning-by-doing and associated technology spillovers.

Pairwise comparisons of technology-specific LCOE then translate into probabilistic investor preferences via a binary-logit representation. Larger, more certain cost advantages yield stronger preferences; small or uncertain advantages yield weaker ones. These preferences feed a Lotka-Volterra-type substitution mechanism that shifts market shares gradually over time. Substitution depends on retirements of incumbent plant (age-based survival), feasible build rates and lead times of alternatives, and the degree of incumbency—capturing bottlenecks when new technologies and their supply chains are not yet fully established. In this way, market shares evolve incrementally rather than jumping discontinuously, reflecting observed frictions in technology transitions (Mercure, 2015).

System operation and variability are handled using a residual load-duration curve (RLDC) framework parameterized following Ueckerdt et al. (2017). This provides, for a given technology mix, indicative levels of curtailment of variable renewables, requirements for short- and long-term storage, and achievable load factors for dispatchable technologies. The dispatch process itself is mimicked as a matching problem between technologies and load bands. Technologies "bid" for suitable load ranges according to their marginal costs and technical suitability (e.g., base-load versus peak), while load bands "accept" bids depending on how full they already are, prioritizing system reliability rather than pure cost minimization. An iterative matching routine inspired by the Gale-Shapley algorithm (Gale and Shapley, 1962) allocates remaining capacity to unfilled load bands until the stack is satisfied.

In summary, E3ME determines how much electricity is demanded, while FTT: Power determines with which technologies it is supplied over time. Costs respond to policy and learning; investors choose probabilistically under uncertainty; fleets turn over gradually subject to retirements and build constraints; and operational feasibility is respected through RLDC-based flexibility and a reliability-oriented dispatch heuristic. **Figure 2** summarizes the resulting flow of information within FTT: Power.

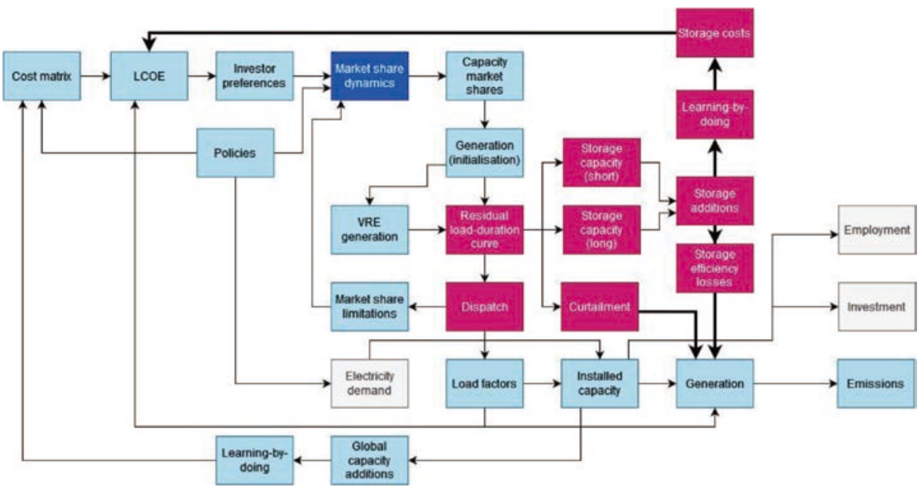

Figure 2 Illustration of the flow of information inside FTT: Power

Source: University of Exeter and Cambridge Econometrics

3. Scenario Design

In this study we seek to expose the ASEAN power sectors to various policy environments in order to investigate the impact of such policies on renewable technology diffusion. The reference scenario (REF) is calibrated to the reference scenario in the IEEJ 2023 Outlook (IEEJ, 2022). Calibration applies to macro-economic indicators and energy consumption projections. In the REF scenario, FTT: Power is not used to determine technology diffusion endogenously; instead it is fed to the model exogenously while keeping the accounting part enabled. We also investigate a scenario where FTT: Power simulates

Table 2 Overview of scenarios considered in this study

Scenario	Abbr.	Region	Policy context
Reference	REF	All	Fully calibrated to the IEEJ 2023 Outlook (macro-economic variables and power sector configuration). No further policies included.
Current technology trajectory scenario	CTT	All	Only macro-economic indicators are calibrated to the IEEJ 2023 Outlook. Nuclear power is based on IEEJ 2023 Outlook and entered as an exogenous input, where applicable. No further policies included.
Nationally determined contribution scenario	NDC	Indonesia	Includes policies based on NDC and domestic power sector policy documents. Implementation of a domestic ETS (see **Figure 3**). Subsidies on upfront investment for CCS applications (25%), wind power (50%), and solar PV (10%). Feed-in-Tariffs on wind power and solar PV. Charcoal co-firing in coal power plants (up to 20% on energy basis by 2030; constant after) Follow the Indonesia Electricity Supply Business Plan (RUPTL) in the short-term (2021–2030)
		Malaysia	Nuclear power is based on IEEJ 2023 Outlook and entered as an exogenous input. No ETS or carbon tax mentioned in NDC documents. Subsidies on upfront investment for CCS applications (25%), wind power (50%), and solar PV (10%). Feed-in-Tariffs on wind power and solar PV. Follow the Malaysia Renewable Energy Roadmap (MREP) in the short-term (2021–2039)
		Rest of ASEAN	Nuclear power is based on IEEJ 2023 Outlook and entered as an exogenous input. No ETS or carbon tax mentioned in NDC documents. Subsidies on upfront investment for CCS applications (25%), wind power (50%), and solar PV (10%). Feed-in-Tariffs on wind power and solar PV. Follow an aggregate version of the various roadmaps provided by individual countries
Ambitious scenario	AMB	Indonesia	Implementation of a domestic ETS (see **Figure 3**). Subsidies on upfront investment for CCS applications (25%), wind power (50%), and solar PV (10%). Feed-in-Tariffs on wind power and solar PV. Phase-out regulations on new fossil-fuel power plant capacities from 2025 onwards. Charcoal co-firing in coal power plants (up to 20% on energy basis by 2030; constant after)
		Malaysia	Nuclear power is based on IEEJ 2023 Outlook and entered as an exogenous input. Implementation of a domestic ETS (see **Figure 3**). Subsidies on upfront investment for CCS applications (25%), wind power (50%), and solar PV (10%). Feed-in-Tariffs on wind power and solar PV. Phase-out regulations on new fossil-fuel power plant capacities from 2025 onwards.
		Rest of ASEAN	Nuclear power is based on IEEJ 2023 Outlook and entered as an exogenous input. Implementation of a domestic ETS (see **Figure 3**). Subsidies on upfront investment for CCS applications (25%), wind power (50%), and solar PV (10%). Feed-in-Tariffs on wind power and solar PV. Phase-out regulations on new fossil-fuel power plant capacities from 2025 onwards.

Source: Authors' summary

technology diffusion endogenously in order to compare to the REF scenario. This is called the current technology trajectory (CTT) scenario. Comparing REF and CTT isolates the effect of endogenous technology diffusion on the evolution of the power mix and related economic outcomes. In this paper, "technology diffusion" refers to changes over time in the uptake of specific generation technologies (i.e., installed capacity and generation shares across coal, gas, oil, hydro, solar PV, wind, biomass, geothermal, and other technologies represented in FTT: Power).

Then, we made interpretations of the policy options mentioned in the NDC documents and built a detailed policy package. These scenarios also include capacity plans as published policy documents related to the power sector. Finally, a more ambitious policy package is developed to test how far decarbonization can reach (abbreviated AMB). **Table 2** provides an overview.

All policies are exclusively applied to the power sector, with the exception of carbon prices, for which it would likely apply wider. **Figure 3** displays the carbon prices used in this study. Only Indonesia has explicitly announced to implement an emission trading scheme and hence why it is the only country to apply an ETS in the NDC scenario. The more ambitious scenario includes higher carbon price projections for each of the AMS.

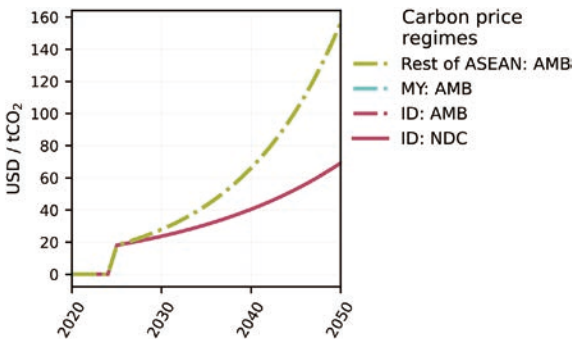

Figure 3 Exogenous carbon price projections (nominal) included in the scenarios

Note: The projections for each of the countries in the AMB scenario overlap. MY: AMB is overlapping with Rest of ASEAN: AMB, and ID: AMB is overlapping with ID: NDC. MY refers to Malaysia, and ID refers to Indonesia.

Source: Created by authors based on the E3ME model analysis results

ACE (2023) reviewed each country's power generation outlook and renewable energy targets. The targets abide by various definitions: renewable energy share of total primary energy, total final energy, total installed capacity, or total electricity generation. Given that the countries within the "Rest of ASEAN" group did not formulate RE targets along a uniform metric, we cannot evaluate a weighted aggregate target. Indonesia has set its target in relation to the total capacity addition over the period from 2021 and 2022. Malaysia and the whole of ASEAN have targets in relation to the total installed capacity by a given year. This is summarized in **Table 3**.

Table 3 Renewable target pledges

Region	Year	RE target
Indonesia	2030	51.6% of capacity addition between 2021–2030
Malaysia	2025	31% of installed power capacity
	2035	40% of installed power capacity
ASEAN	2030	35% of installed power capacity

Source: Authors

4. Analysis Results

4.1 Estimation of power generation technologies

According to the IEEJ 2023 Outlook (REF scenario, see **Figure 4**), the ASEAN community of nations remains reliant on fossil-fuels for its power generation. Without additional policy support, Indonesia and Malaysia rely on domestic supply of coal and natural gas respectively. The share of renewables in the generation profile across all AMS hover between 23–27% over the whole time period. Under the current technology trajectory (CTT) scenario, similar diffusion trends are noted. Like the REF scenario, a 29% generation share is attributed to renewables in 2030. However, towards the end of the timeline (around 2040) uptake of renewables starts to take off, indicating the existence of a positive tipping point. By 2050, this yields a 40% share of renewables in the generation profile. In both the REF and CTT scenarios, Malaysia remains behind with a renewable share of 18% and 11% by 2030 and a 19% and 22% share by 2050 respectively. Indonesia also performs slightly worse than the ASEAN average, with a renewable share of 23% and 21% by 2030 and a 27% and 26% share by 2050 in the REF and CTT scenarios respectively.

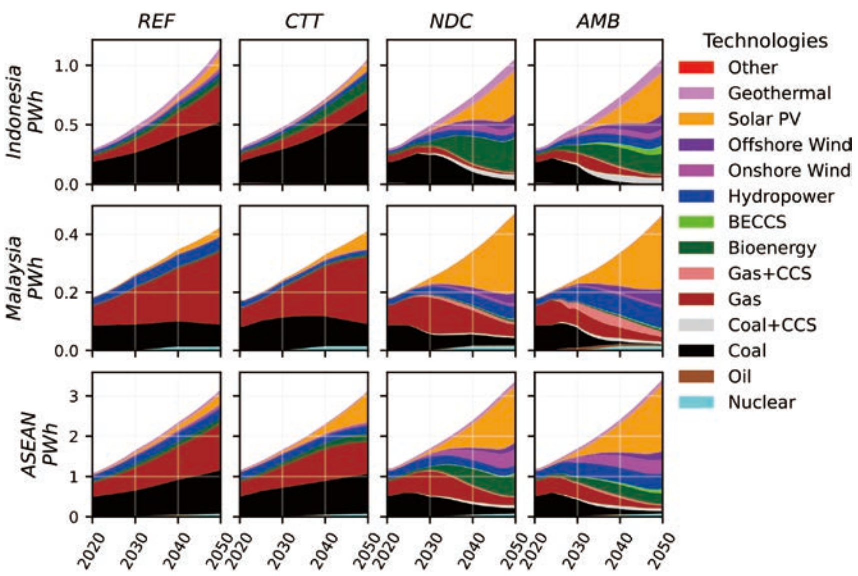

Figure 4 Generation by technology in PWh. Shown individually for Indonesia and Malaysia and for ASEAN as a whole

Note: In REF, Gas and Coal remain dominant, while in AMB, Solar PV and Hydropower expand significantly. These results do not explicitly show the impact of charcoal blending in coal power plants.

Source: Created by authors based on the E3ME model analysis results

Policies in the NDC and AMB scenarios can bring the tipping point forward in time. The NDC scenario indeed shows increased uptake of solar PV in all regions, biobased technologies in Indonesia and the Rest of ASEAN, and wind power in the Rest of ASEAN. The stronger renewable uptake in the NDC scenario is mainly driven by the combined effect of (i) carbon pricing/ETS-type measures that penalise fossil generation and shift investment and dispatch toward low-carbon options, and (ii) renewable support such as feed-in tariffs (FITs) that improve project economics—especially for solar PV, resulting in higher PV broadly, more bio-based generation in Indonesia and the Rest of ASEAN, and stronger wind uptake in the Rest of ASEAN. This results in a renewable generation share of 33% (including charcoal co-firing; not shown in **Figure 4**) by 2030, and a share of 85% by 2050 across all AMS. Indonesia is outperforming over other AMS in the NDC scenario (39% renewable share by 2030 and 93% renewable share by 2050), whilst Malaysia remains behind (24% by 2030 and 79% by 2050). This can be attributed to some degree to the Malaysia Renewable Energy Roadmap, which describes a continued reliance on coal power.

Under the AMB scenario, the short- to medium-term outlook as presented in the power sector roadmap documents is forfeited. Gas-based power can therefore be phased out at a greater rate in Malaysia. The phase-out regulations on new capacity additions of fossil-fueled power plants also help to create space for renewable technologies to diffuse into, which is evident across the whole ASEAN. Renewable generation shares increase from 54% in 2030 to 92% in 2050.

Furthermore, it is noteworthy to state that Malaysia sees some uptake of offshore wind power despite the country's limited access to offshore areas with high wind speeds. In E3ME-FTT, offshore wind is represented at the national level and the model does not resolve detailed geographic siting constraints. The offshore wind uptake in Malaysia should therefore be read as an indicative substitution when solar PV approaches its technical limit and fossil additions are constrained in the NDC/AMB scenarios. If real-world site constraints are binding, offshore wind would be lower and the modelled generation would be met by other low-carbon options instead.

Both the NDC and AMB scenarios show substantial changes to the total electricity generated compared to the REF scenario. This is driven by two parts: responses in electricity demand, and additional generation needs due to storage losses (when conventional storage is insufficient) and curtailment. Indonesia shows an overall decrease in both the NDC and AMB scenarios, a carbon price is implemented in Indonesia which increases energy prices depending on their emission intensity. The dominant response is to lower energy demand rather than energy substitution. This will be discussed in more detail in section 4.5. Malaysia, and ASEAN overall show increased generation levels due to storage losses and curtailment.

Table 4 displays the RE targets and the outcome in each of the scenarios. In the REF and CTT scenarios, none of the RE targets are met as the power systems remain to be dominated by fossil-fueled technologies. However, all targets are met under the NDC and AMB scenarios, with the exception of the 2025 target in Malaysia. The 2025 target is missed because there is simply not enough time for the policies to adequately change investment decisions. Between the NDC and AMB scenarios, the latter typically overshoots the target by some margin (at least 5% greater than the target).

Table 4 Overview of renewable generation targets and the renewable energy levels attained in the respective scenarios

Region	Year	RE target	RE% achieved			
			REF	CTT	NDC	AMB
Indonesia	2030	51.60% of capacity addition between 2021–2030	35.4%	29.1%	56.5%	63.5%
Malaysia	2025	31% of installed power capacity	20.6%	21.4%	22.5%	24.4%
	2035	40% of installed power capacity	20.3%	21.1%	42.8%	47.7%
ASEAN	2030	35% of installed power capacity	26.9%	30.1%	45.8%	57.4%

Source: Created by authors based on the E3ME model analysis results

4.2 Estimation of primary energy demand in power sector

Primary energy demand for electricity generation responds to the diffusion of technologies (see **Figure 5**). A continued reliance on fossil-fuels is noted in the REF and CTT scenarios. Using primary energy conversion factors in accordance with the IEA, the share of renewable primary energy demand follows an increasing trend in line with uptake of e.g. solar PV and wind power, however, the shares are smaller than in the generation profile due to the primary energy conversion factors. For example, using coal to generate electricity converts only 33% of the primary energy potential to electricity.

In the NDC and AMB scenarios a strong shift to renewables in the primary energy demand profile is noted. Total primary energy demand in Indonesia is reduced by a third and by a half by 2050 in the respective scenarios, while the remainder primary energy demand is predominantly biomass. Malaysia still relies to a moderate degree on fossil-fuels, however, a large

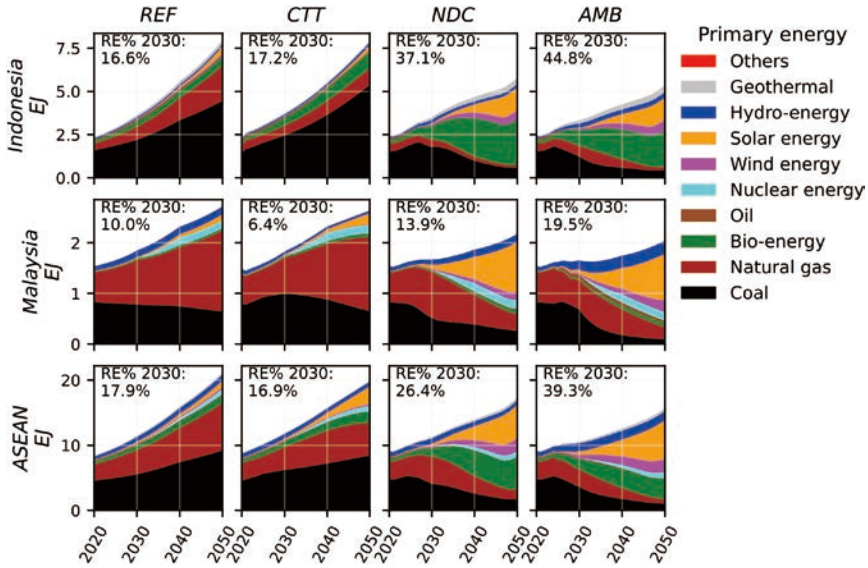

Figure 5 Primary energy demand by energy type in EJ. Shown individually for Indonesia and Malaysia and for ASEAN as a whole

Note: In REF, natural gas and coal are the dominant sources, whereas in AMB, solar power and bioenergy expand, while natural gas declines. These results do not explicitly show abated fossil-fuel demand.

Source: Created by authors based on the E3ME model analysis results

portion feeds into fossil-fueled power plants with CCS applications.

4.3 Estimation of CO_2 emissions in power sector

Direct CO_2 emissions in the REF and CTT scenarios continue to rise sharply in line with increased electricity demand and continued dominance of fossil-fueled power plants (see **Figure 6**). The endogenous FTT scenario (CTT) displays a slightly greater reliance on coal power and therefore shows higher emissions compared to the REF in 2030. However, by 2050, the push towards renewables starts to take off everywhere except in Indonesia. This leads to 25.6% lower emissions between the two scenarios. See **Figure 6** and **Table 5**.

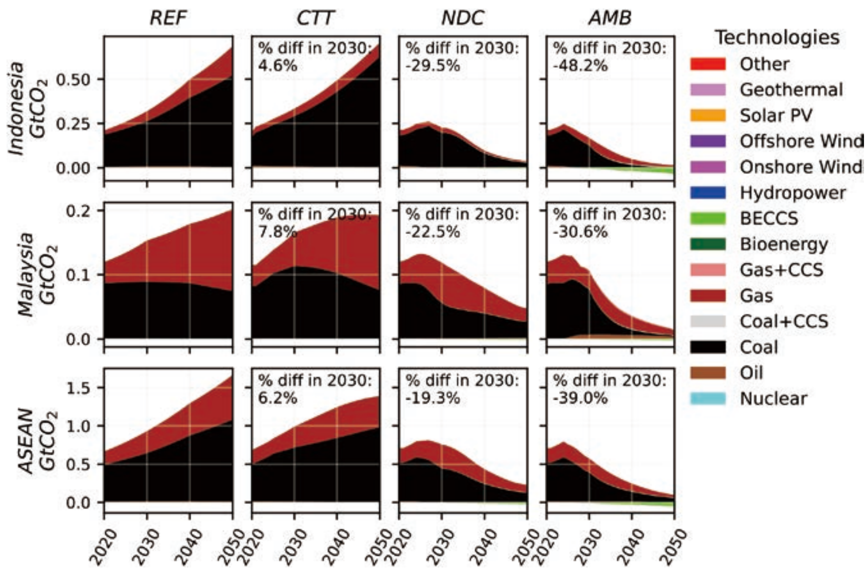

Figure 6 Direct CO_2 emissions by technology in $GtCO_2$. Shown individually for Indonesia and Malaysia and for ASEAN as a whole.

Note: In all scenarios, coal and natural gas account for the largest shares.

Source: Created by authors based on the E3ME model analysis results

Table 5 Direct CO_2 emissions in scenario in 2030 and 2050 relative to the REF scenario in the same year.

Direct CO_2 emission difference to REF (%)	CTT	NDC	AMB	CTT	NDC	AMB
	2030			2050		
Indonesia	+4.6	−29.5	−48.2	+2.9	−95	−103.2
Malaysia	+7.8	−22.5	−30.6	−4.9	−76.9	−94.2
All of ASEAN	+6.2	−19.3	−39	−25.6	−89	−97.8

Source: Created by authors based on the E3ME model analysis results

The uptake of renewables is pushed forwards via policies in the NDC and AMB scenarios. Additional uptake of renewable technologies replaces fossil-fuels and therefore also affect direct CO_2 emissions. By 2030, the NDC policies reduce emissions by 19.3% across all of ASEAN compared to the REF scenario. Emissions are reduced by 39% in the AMB scenario. Indonesia shows the greatest decline in emissions (95% and 103.2% reduction in the NDC and AMB scenarios resp. compared to the REF scenario in 2050) as it has sufficient potential for renewable alternatives. Malaysia has less potential for biobased energy sources and wind power and therefore needs to rely more on CCS applications to reduce emissions (76.9% and 94.2% reduction in the NDC and AMB scenarios resp compared to the REF scenario in 2050). The combined emission reduction across all ASEAN power sectors by 2050 is 89% in the NDC scenario and 97.8% in the AMB scenario.

4.4 Estimation of upfront investment requirements

Expanding power generation capacity requires investments, which is displayed in **Figure 7**. The investment portfolio in the REF and CTT scenarios remains focused on thermal power generation, more so in the latter scenario than the former. Nuclear power investments occur in Malaysia, and in the Rest of ASEAN group (Thailand and Viet Nam), which follows IEEJ projections across all scenarios (IEEJ, 2022). Overall, both scenarios show a lot of overlap. The portfolios start to diverge heavily in the NDC and AMB scenarios as investment decisions start to gravitate towards various forms of renewables. Renewables are typically more CAPEX heavy rather than OPEX heavy, increasing the investment needs. By 2050, investments into unabated fossil-fueled power plants in the AMB scenarios are practically removed.

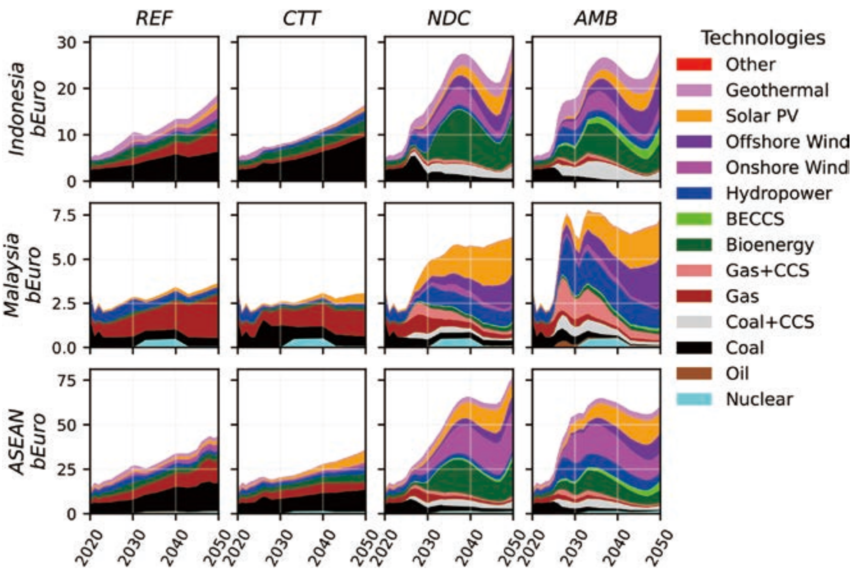

Figure 7 Upfront investment requirements by technology in billion 2010 Euro. Shown individually for Indonesia and Malaysia and for ASEAN as a whole.

Note: In AMB, the shares of solar PV, onshore wind, offshore wind, and hydropower are relatively large.
Source: Created by authors based on the E3ME model analysis results

Overall, decarbonizing the ASEAN power sector would require substantial investments between 2025 and 2050 (see **Table 6**). The NDC and AMB scenarios require a cumulative investment of 1388 and 1458 billion 2010 Euro. This is mostly driven by investments in additional renewable technologies. This is 70% and 79% higher than the investment needs in the REF scenario, which sits at 815 billion 2010 Euro. In the CTT scenario, we find that the ASEAN region requires 680 billion 2010 Euro investment for the same period to maintain current diffusion trajectories. The difference is largely due to lower geothermal and wind uptake (both capital intensive technologies) relative to the REF scenario. In relative terms, Malaysia sees the largest increase; investment more than double in the AMB scenario compared to the REF scenario.

Table 6 Total cumulative investment needs in power generation technologies between 2025 and 2050.

Cumulative investment in billion (2010 price of Euro)	REF	CTT	NDC	AMB
Indonesia	319	282	559	577
Malaysia	78	72	136	176
All of ASEAN	815	680	1388	1458

Source: Created by authors based on the E3ME model analysis results

4.5 Estimation of electricity prices

Up to 2040, electricity prices in the CTT scenario move approximately in line with the REF scenario in Indonesia and Malaysia (see **Figure 8**). Only towards the end of the time horizon deviations are observed. Malaysia and the Rest of ASEAN see a decline in electricity prices due to additional uptake of cheap solar PV (and wind power in the case of Rest of ASEAN). Indonesia sees an increase in electricity prices due to a slightly increased reliance on bio-based technologies compared to the REF scenario, which do not benefit from the same level of learning potential as other renewable alternatives. In addition, bio-based technologies suffer a slight efficiency penalty relative to fossil-fuel alternatives. Across all AMS, electricity prices decline towards the end of the time horizon.

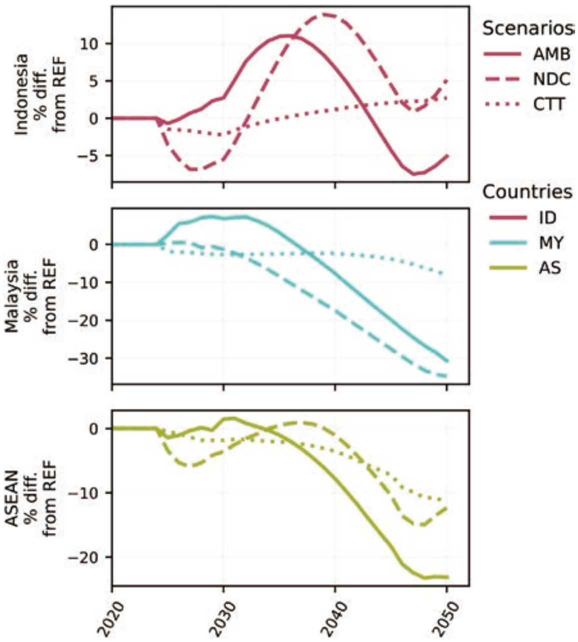

Figure 8 Electricity prices as a% difference from the reference scenario. Shown individually for Indonesia and Malaysia and for ASEAN as a whole.

Source: Created by authors based on the E3ME model analysis results

The NDC scenario equally shows varied impacts across the countries. Initially, electricity prices in Indonesia decrease to a minimum around 2030, followed by an increase which peaks around 2042. By 2050, electricity prices come down to levels slightly above the REF scenario. This behavior can be attributed to the relative contribution of more expensive bio-based energy technologies versus cheap solar PV. Malaysia sees a gradual reduction of electricity prices over the whole timeline, which reaches a limit as solar PV uptake encroaches on its potential deployment. Overall, across all AMS, electricity prices were simulated to decline considerably. This effect is reinforced in the AMB scenario. The largest driver is increased uptake of solar PV in Indonesia. Malaysia sees slightly higher electricity prices in the AMB scenario due to a greater reliance on CCS applications and wind power to further reduce emissions. The limited wind energy potential is represented by quickly declining capacity factors (Mercure and Salas, 2013), which negatively impacts the electricity price.

Electricity prices in E3ME-FTT reflect the evolving generation mix simulated with FTT: Power (24 generation technologies) and are shaped by scenario-specific policies together with common techno-economic constraints, including technology-specific deployment limits (e.g., solar PV saturation) and resource-related capacity-factor assumptions (e.g., declining wind capacity factors at higher penetration). Across scenarios, the technology set and constraint structure are held constant; the main differences are whether the power mix is imposed exogenously (REF) or evolves endogenously through diffusion and policy incentives (CTT, NDC, AMB). The price trajectories below should therefore be interpreted as changes in the marginal mix—most notably increased low-cost solar PV versus greater reliance on higher-cost options such as bio-based generation and CCS—under these stated assumptions.

4.6 Estimation of macroeconomic impacts

Macro-economic effects of the policy scenarios have many facets to them. Invoking a transition in the power sector through policies leads to additional investments as shown in section 4.4, which propagate through the economic channels within the system of national accounts in the ASEAN economies. Additional investments can lead to additional job creation and can, through increased disposable income, lead to increased consumer spending. However, consumer spending is also affected by price levels. In turn, price levels are affected by electricity price developments which also invokes changes

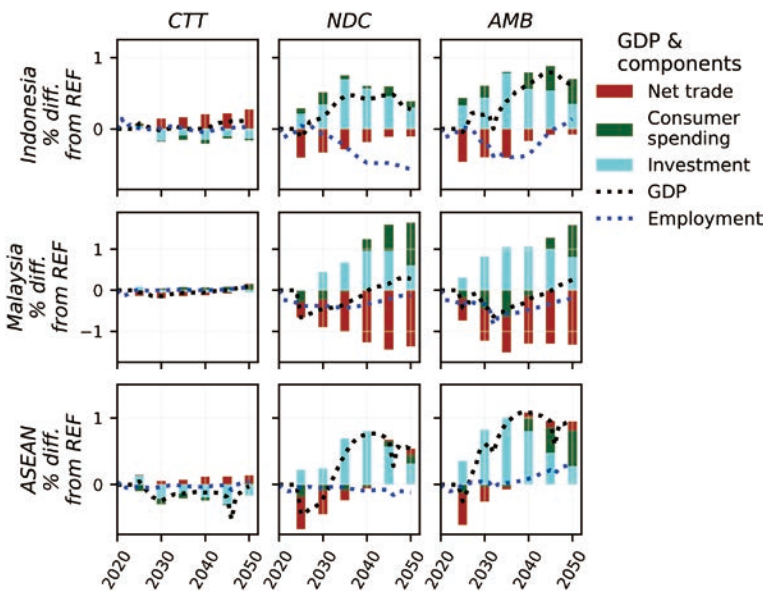

Figure 9 GDP and employment impacts by components for each scenario relative to the REF scenario

Note: The bars represent the weight of each GDP component relative to the overall GDP impact. Results are shown individually for Indonesia and Malaysia, and for ASEAN as a whole. GDP tends to increase more than employment compared with REF.

Source: Created by authors based on the E3ME model analysis results

to other industry prices depending on the degree of each sector's electrification. Carbon prices can lead to an increase in industrial prices depending on each sector's emission intensity and ETS coverage.

The net GDP impacts, and the contribution of its components are illustrated in **Figure 9**. In line with expectations, the CTT scenario does not show large deviations from the REF scenario. However, impacts become more diverse when considering the NDC scenario. In each region an increase in investment is noted, positively contributing to GDP. However, fossil-fuel producing countries such as Indonesia and Malaysia are negatively impacted due to decreased position of their net trade balance. As an aggregate country group, the Rest of ASEAN is a mix of countries which on average are reliant on energy imports and therefore stand to gain from a transition in the power sector, hence why overall ASEAN results on net trade towards the end of the time horizon are positive while negative impacts in Indonesia and Malaysia dominate initially.

Jobs related to the fossil-fuel industry are also negatively impacted by a transition which is visible in Indonesia and Malaysia in both the NDC and AMB scenarios. Indonesia in the AMB scenario also shows the impact of reduced electricity prices on job creation and consumer spending, especially when compared to the NDC scenario, where Indonesia is exposed to higher electricity prices by 2050.

Overall and across all AMS, GDP impacts are positive by 2050, but some negative impacts may occur in the initial phase of the transition. Malaysia is the main exception as positive effects are almost completely negated by negative effects.

5. Conclusion

Here, we simulate multiple scenarios of ASEAN power-sector decarbonization and their economic consequences using the E3ME-FTT model. If the REF scenario—aligned with IEEJ (2022) projections—materializes, grid emission intensity in ASEAN will not decline, hindering decarbonization via electrification. In the CTT scenario, reliance on fossil-fuels remains similar to REF; however, signs of a positive tipping point toward (variable) renewables emerge around 2040 in most ASEAN countries. Policies can target such tipping points to accelerate technology uptake (e.g., solar PV) (Nijsse et al., 2023).

Indeed, the NDC and AMB scenarios show that policies advance the tipping point toward solar PV and other renewables across all AMS. In both scenarios, RE targets beyond 2025 are achieved; in fact, the AMB scenario over-achieves. Malaysia is the only country missing its 2025 target, reflecting the short window for policies to affect investment decisions and continued short-term reliance on coal. With additional renewables, power-sector emissions fall by 89.0% in NDC vs. REF in 2050 and by 97.8% in AMB.

We find that large-scale transitions in NDC and AMB are feasible and can yield positive GDP effects overall, though regional differences exist. Gains are driven mainly by investment stimuli in low-carbon technologies and along their value chains, typically creating jobs; these gains can be offset by lower export volumes and inflationary effects. In both scenarios, Malaysia and Indonesia lose trade volumes, predominantly linked to fossil-fuel trade.

The required investment stimulus for large-scale decarbonization is substantial. Achieving it could require €1,458 billion (2010 prices) between 2025 and 2050—an additional €643 billion relative to REF. This estimate excludes storage investments (which are represented in the model) and grid reinforcement (not represented); needs would rise with further end-use electrification.

The investment numbers indicate the scale of capital required for the power transition. E3ME-FTT estimates macroeconomic impacts assuming this investment can be mobilised; it does not model country-specific fiscal and financial constraints. In practice, implementation requires credible financing and risk-reduction mechanisms (e.g., stable auctions/PPAs (Power Purchase Agreement), concessional or blended finance, guarantees, and public funding for grids and other enabling infrastructure).

Models have limits. FTT: Power excludes hydrogen-based technologies and co-firing of hydrogen/ammonia (biomass co-firing is included), largely because the E3ME model lacks a hydrogen supply module. Hence, hydrogen/ammonia-consuming technologies are outside scope. Moreover, E3ME-FTT does not model each AMS individually. Although Indonesia and Malaysia account for roughly half of electricity generation, aggregation error remains possible.

Comparing Indonesia's GDP impacts in NDC vs. AMB highlights the importance of electricity prices. In FTT: Power, prices are a generation-share-weighted average of LCOE. While LCOE for variable renewables includes curtailment and storage costs, grid infrastructure costs—potentially material in these scenarios—are not included. For example, in AMB we diverge from the Malaysia Renewable Energy Roadmap's limited plant-deployment outlook; the roadmap's emphasis on reliable supply in remote areas would entail significant grid-strengthening investments. FTT: Power is also constrained by the RLDC framework, which uses coarse geographic regions that effectively assume a "copper-plate" system (i.e., free power flows).

Unlike many macroeconomic models, E3ME does not adopt the loanable-funds approach (Pollitt and Mercure, 2018). Credit creation via lending is possible in both the model and reality (Mcleay et al., 2014), yet the model remains agnostic about the financial consequences of stimulus and technology decisions. Access to finance is approximated via interest rates, which influence choices depending on the ratio of upfront capital to operating costs. In the ASEAN context, finance access is a known constraint (ASEAN Secretariat, 2015). Future work will improve this aspect of the FTT framework.

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Simplified Approach to Improving the Performance of Recycled Aggregate Concrete

Yasuhiro Dosho, Dr[1)], Duc Nguyen Anh, Dr[2)]

1)Professor, Department of Environmental Technology, Faculty of Science and Technology, Meijo University, 1-501 Shiogamaguchi, Tempaku Ward, Nagoya City, 468-8502, Japan;
dosho@meijo-u.ac.jp
2)Department of Road and Bridge Engineering, Faculty of Civil Engineering, Vietnam Maritime University, 484 Lach Tray, Le Chan Ward, Hai Phong City, Vietnam
ducna.ctt@vimaru.edu.vn

Abstract

Recycled aggregate concrete (RAC) is an effective use of concrete waste, but its performance is often inferior to that of normal concrete, which limits its applicability. The performance of RAC can be improved through supplementary cementitious materials (SCMs); however, introducing SCMs complicates the concrete manufacturing process at plants that lack adequate storage resources. Therefore, this study investigated the feasibility of improving the performance of RAC by utilizing established cements that already contain SCMs, such as fly ash and ground granulated blast-furnace slag. RAC samples were produced using different classes of recycled coarse aggregate (Class M and Class L) and four types of cement (ordinary portland cement, portland fly ash cement Type B, portland blast-furnace slag cement Type B, and ecocement) to evaluate the combinations and recycled aggregate replacement ratios that resulted in improved performance. The aim of this study was to develop a simplified manufacturing method that promotes the use of recycled aggregates and environmentally friendly cements to realize a high-performance and low-carbon concrete with both excellent resource recyclability and economic efficiency.

Keywords：recycled aggregate concrete; recycled coarse aggregate; supplementary cementitious materials; mix proportion; concrete performance

1. Introduction

In October 2020, the Japanese government announced its objective of achieving carbon neutrality by 2050 and reducing greenhouse gas emissions to zero [1]. The manufacturing industry accounts for 35% of CO_2 emissions in Japan of which ceramics and mineral products comprise 17.4%, and the cement industry has the largest share. CO_2 emissions are inevitably generated during the cement manufacturing process, which involves the calcination of limestone ($CaCO_3$) via decarboxylation ($CaCO_3 \rightarrow CaO + CO_2$). To reach the high temperatures of 1450°C required for the calcination process, fossil fuels such as coal are widely used, which further contribute to CO_2 emissions [2].

Table 1 presents the CO_2 emission intensities of various types of cement along with life cycle inventory (LCI) data [3] published annually by the Japan Cement Association. The production of 1 ton of ordinary portland cement (N) produces more than 700 kg of CO_2. The amount of CO_2 emissions can be reduced by blending cement with supplementary cementitious materials (SCMs) such as fly ash (FA) or ground granulated blast-furnace slag (GGBFS) that also possess cementitious properties. The most versatile blended cements are portland fly ash cement Type B (FB), which contains >10 and ≤20 mass% FA, and portland blast-furnace slag cement Type B (BB), which contains >30 and ≤60 mass% GGBFS. Meanwhile, ecocement (E) mainly comprises ash from the incineration of municipal solid waste and sewage sludge and was first produced in Ichihara City, Chiba Prefecture in 2001 after which it was standardized by the Japanese Industrial Standards (JIS) in July 2002. Although the applications of E are limited owing to its relatively high chloride ion content, each ton of E produced recycles ≥500 kg of waste resources (reference: N = 480 kg, actual results for FY2023 [4]) [5].

Table 1 CO_2 emission intensities and energy input of various types of cement

Cement type	CO_2 emission intensity (kg-CO_2/t)	Energy input (GJ/t)
N (JIS R 5210)	741.3 [3]	3.40 [5]
FB (JIS R 5213)	612.9 [3]	3.02 [5]
BB (JIS R 5211)	423.3 [3]	2.28 [5]
E (JIS R 5214)	803.0 [5]	6.40 [5]

Cement is primarily used in concrete, so an effective approach to reduce CO_2 emissions is to implement measures targeting both concrete and cement as a single entity. Concrete is the second-most consumed material after water and is fundamental to modern urban environments. About 4 billion tons of cement was produced globally in 2024 [6] compared with about 131 million tons in 1950 [7].

Concrete is extremely durable and can last for hundreds of years. As old concrete structures are demolished, large volumes of waste are generated that can also last for centuries. Billions of tons of waste concrete enter the construction and demolition waste stream each year on a global scale, and the amount is still rapidly increasing because of continuous urbanization and redevelopment activities in many countries. Even though available data exhibit substantial geographical variation, it is estimated that 50%–90% of waste concrete is recycled as aggregates [8]. In Japan, the Ministry of Land, Infrastructure, Transport and Tourism conducted a survey in fiscal year 2018 and reported that 74.4 million tons of construction waste are produced annually, most of which is recycled in compliance with related laws and ordinances. Concrete accounts for 36.9 million tons of the total construction waste. Although 99.3% of the concrete waste is recycled, the most common use is as roadbed material or backfill [9]. However, the demand for roadbed material is not expected to increase owing to the declining construction of new roads [9]. Thus, new uses for concrete waste are needed. Meanwhile, concrete waste also contains harmful trace elements originating from cement such as hexavalent chromium and lead that may leach into the environment when fine powder (diameter ≤ 5 mm) is subjected to wetting [10]. Therefore, decreasing the amount of fine powder during the recycling of concrete waste may help reduce the environmental risks of soil contamination.

The most promising alternative use of concrete waste is in recycled aggregate concrete (RAC) where the concrete waste is recycled as aggregate for new concrete. In particular, recycled aggregate (RA) Class L can be manufactured using a simplified method and offers excellent cost-effectiveness [11]. As shown in Figure 1, RA can also be used to adsorb CO_2 in an aggregate yard via a forced carbonation method [12]. The effectiveness of the CO_2 adsorption increases with the amount of original mortar and paste attached to the RA. The adsorbed CO_2 is then capsulated and fixed in RAC through standard

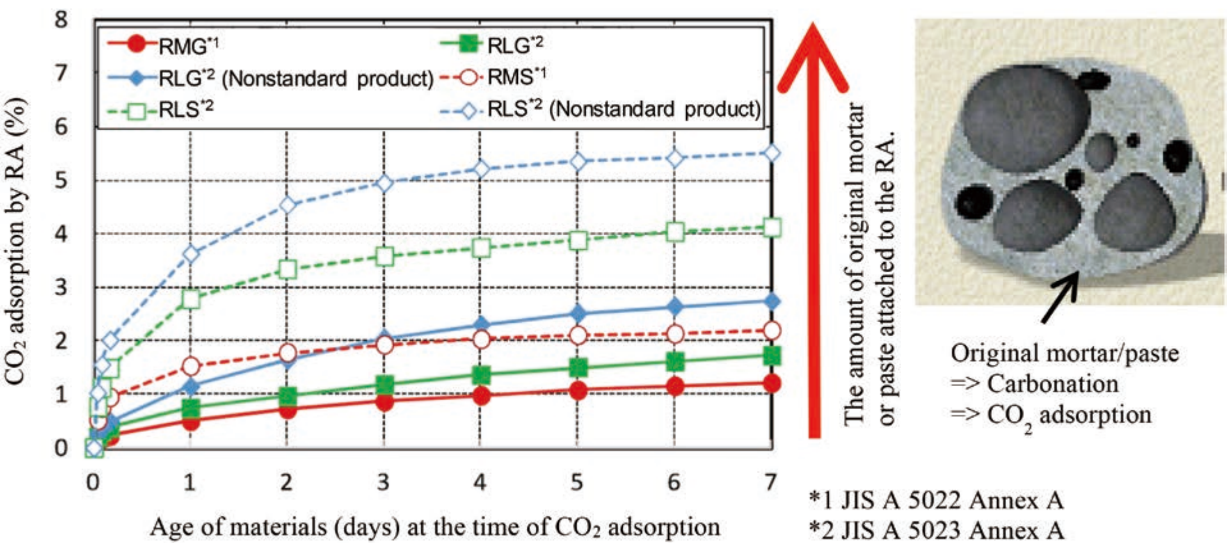

Fig. 1 CO_2 adsorption by RA (modified from [12]) concrete manufacturing methods. The potential wider adoption of RAC led to the establishment of the ISO 18985:2025 standard to regulate its use [13]. However, while the presence of the original mortar and cement paste in the RA is necessary for CO_2 adsorption, it can also degrade the performance of the resulting RAC.

The authors previously demonstrated that FA and GGBFS can effectively improve the performance of RAC [14]. However, increasing the number of SCMs can make it difficult for concrete plants without available storage silos to respond in a timely and stable manner to various orders [15]. Therefore, rather than use SCMs directly, this study investigated whether the performance of RAC could be improved by employing established cements that already contain these SCMs. Concrete samples were produced using various types of RA and four different types of cement to determine how different combinations and RA replacement ratios affect the performance.

The aim of this study was to develop a simplified manufacturing method that promotes the use of RA and environmentally friendly cement to realize a high-performance and low-carbon concrete with excellent resource recyclability and economic efficiency.

2. Current status of RAC in Japan

Table 2 presents the history of standards for RAC in Japan. JIS A 5021, JIS A 5022, and JIS A 5023 were established in 2005–2007 to regulate the performance of RAC [16]. In 2018, the Ministry of Land, Infrastructure, Transport and Tourism investigated the usage and performance of RAC [9]. They found that RAC recycled 119000 tons of waste concrete, which was approximately twice the amount recorded in 2012 (55000 tons) but remained small relative to the total amount of concrete waste. The total amount of recycled concrete comprised 64000 tons of RAC Class H (to be used in structural and nonstructural members [17]), 50000 tons of RAC Class M standard type (to be used in structural and nonstructural members unaffected by drying shrinkage [17]) and frost-resistant type (to be used in structural and nonstructural members unaffected by drying shrinkage and frost damage [17]), and 5000 tons of RAC Class L (for use in nonstructural members without reinforcement [17]). The use of RAC Class M increased by 48000 tons compared with 2012. In 2018, JIS A 5022 was revised based on recommendations from the Architectural Institute of Japan (AIJ) [18] to stipulate that RA class L can be mixed with normal aggregate to produce RAC Class M [18]. In 2022, JASS 5 [19] was revised to include environmental considerations (resource recycling, low carbon performance, and environmental safety) as performance requirements for reinforced concrete, including the use of byproducts such as RA.

Table 2 History of standards for RAC in Japan

Year	Main trends
2005	Establishment of JIS A 5021 (Recycled aggregate for concrete-class H)
2006	Establishment of JIS A 5023 (Recycled concrete using recycled aggregate class L)
2007	Establishment of JIS A 5022 (Recycled concrete using recycled aggregate class M)
2009	Revision of “Japanese Architectural Standard Specification JASS 5 Reinforced concrete work” (JASS 5) [16]. New provisions in Section 28 of JASS 5 “Recycled aggregate concrete.”
2011	Revision of JIS A 5021
2012	Revision of JIS A 5022 and JIS A 5023
2014	Publication of “Recommendation for mix design, production and construction practice of concrete with recycled concrete aggregate” [17] by the Architectural Institute of Japan (AIJ).
2018	Revision of JIS A 5021, JIS A 5022 (Recycled aggregate concrete-Class M) and JIS A 5023 (Recycled aggregate concrete-Class L). Revision of JASS 5 in Section 28 “Recycled aggregate concrete” [18].
2022	Revision of JASS 5 [19].
2024	Revision of JIS A 5021, JIS A 5022 and JIS A 5023

Table 3 lists the RAC classes and types based on different combinations of coarse and fine aggregates [19]. The RAC classes are based on the quality of the coarse aggregate. Each RAC Class can be further divided into two types based on whether the fine aggregate is normal (Type 1) or either partially or fully RA (Type 2). This study focused on RAC Class M Type 1, in which the coarse aggregate is either fully recycled coarse aggregate (RG) Class M (RMG) or normal coarse aggregate mixed with <50% RG Class L (RLG), and the fine aggregate is normal fine aggregate.

Figure 2 shows the actual shipments of RAC by class [20]. The total volume of RAC peaked at approximately 110000 m^3 in 2006 but fell to 34000–52000 m^3/year in 2019–2021, which is approximately 30%–50% of the total volume in 2006. Of the cumulative total of 945636 m^3, 39410 m^3 (4%) was RAC Class H, 478934 m^3 (51%) was RAC Class M, and 427493 m^3 (45%) was RAC Class L. Even at its 2006 peak, RAC accounted for only 0.2% of the total amount of ready-mixed concrete shipped in 2024 (65963396 m^3) [21]. Thus, the impact of the standard revisions listed in Table 2 on RAC shipment volumes remains unclear present.

Table 3 RAC types and combinations of coarse and fine aggregates [19]

RAC	Coarse aggregate	Fine aggregate
RAC Class H Type 1	All or part of the coarse aggregate is RG-Class H (RHG)	Normal fine aggregate
RAC Class H Type 2	All or part of the coarse aggregate is RHG Normal coarse aggregate	All or part of the fine aggregate is recycled fine aggregate Class-H
RAC Class M Type 1*1	All or part of the coarse aggregate is RG class M (RMG) Part of the coarse aggregate is RG class L (RLG) (replacement ratio of ≤ 50%)*2	Normal fine aggregate
RAC Class M Type 2	All or part of the coarse aggregate is RMG	All or part of the fine aggregate is recycled fine aggregate class M (RMS) Part of the fine aggregate is recycled fine aggregate class L (RLS) (replacement ratio of ≤ 30%)*2
	Part of the coarse aggregate is RLG (replacement ratio of ≤ 50%)*2	All or part of the fine aggregate is RMS Part of the fine aggregate is RLS (replacement ratio of ≤ 30%)*2
	Normal coarse aggregate	All or part of the fine aggregate is RMS Part of the fine aggregate is RLS (replacement ratio of ≤ 50%)*2

*1 Standard products and freeze-resistant products are available.
*2 Satisfies the specifications of RA class L and impurity content of RA class M.

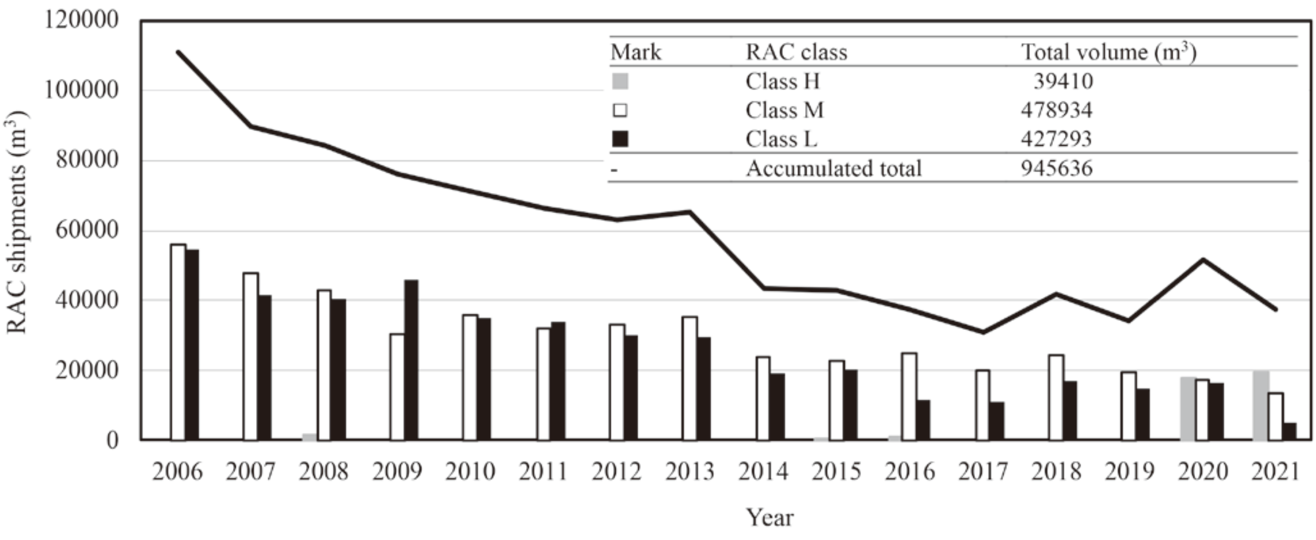

Fig. 2 RAC shipments by type in Japan [20]

3. Materials and methods

3.1 Materials

Four types of cement were used: N, FB, BB, and E. Table 4 lists the main characteristics of these cements. For normal fine aggregates, river sand (NS) was used. For normal coarse aggregates, hard sandstone (NG) and limestone (LG) were used. Air-entraining and water-reducing admixture (high-performance type), and air-entraining admixture were used as chemical admixtures.

Table 4 Main characteristics of cements

Item		**N***1		**FB***1		**BB***1		**E***1
Density (g/cm^3)		3.16	3.16	2.97	2.97	3.04	3.04	3.15
Blaine fineness (cm^2/g)		3270	3320	3670	3670	3620	3770	4100
Set	Water amount (%)	27.7	27.7	27.7	28.1	29.4	29.1	27.3
	Start (hour–min)	2–15	2–11	2–13	2–35	2–45	2–50	2–38
	Finish (hour–min)	3–32	3–31	3–41	3–50	4–11	4–42	4–00
Stability	Compaction method	Good	Good	Good	Good	Good	Good	Good
Compressive strength (N/mm^2)	3 days	30.9	32.9	27.3	27.7	22.1	22.8	29.8
	7 days	47.5	48.1	37.5	38.5	36.3	37.6	42.9
	28 days	64.1	62.4	58.1	58.1	64.2	64.8	58.1
Heat of hydration (J/g)	7 days	339	330	-	-	-	-	-
	28 days	389	388	-	-	-	-	-
Chemical composition (%)	MgO	1.46	1.41	1.04	1.04	3.41	3.53	1.55
	SO_3	2.18	2.23	1.86	1.92	2.10	2.08	3.31
	Ignition loss	2.23	2.27	1.20	1.18	1.88	1.88	2.50
	Total alkali	0.49	0.54	-	-	-	-	0.57
	Cl^-	0.011	0.015	0.015	0.014	0.007	0.012	0.044
Chloride ion residual rate: α		-	-	-	-	-	-	0.24*2
Admixture content (mass%)		-	-	15–17	15–17	40–45	40–45	-

*1 Average value *2 Maximum value

For recycled coarse aggregates, RLG_1, RLG_2, and RMG were produced with sizes of 20–5 mm. Table 5 presents an overview of the RGs produced at three plants (A, B, and C). RLG_1 was produced using original concrete for which the application and original aggregate type were unknown at Plant A. The original concrete was used to produce recycled crushed stone with sizes of 40–0 mm, which was then crushed using a fixed-type jaw crusher and divided using a fixed-type screen into RLG_1 and recycled fine aggregate. RLG_2 was produced using original concrete with unknown application and aggregate type at Plant B. After the original concrete was pre-crushed to approximately the size of a human head, it was further crushed using a fixed-type jaw crusher and divided using a fixed-type screen into RLG_2 and recycled fine aggregate. RMG was produced at Plant C using original concrete from a hospital building, although the original aggregate type was unknown. RMG was manufactured using the gravity concentration method [22].

Table 5 Overview of RGs

Original concrete		**Type of recycled aggregate**	**Plant**	**Production method**
Application	**Original aggregate**			
Building	Unknown	RLG_1	A	Recycled crushed stone: crushing and classifying
Unknown	Unknown	RLG_2	B	Crush to head-size of concrete waste: crushing and classifying
Hospital building	Unknown	RMG	C	Gravity concentration method [22]

Table 6 presents the main characteristics of the aggregates. RLG_1 and RLG_2 exhibited water absorption values of 6.42%–6.48%, fines content of 1.35%, and impurity content of 0.31 mass%, satisfying the requirements of JIS A 5023 Annex A. RMG had an oven-dry density of 2.40 g/cm^3, water absorption of 3.63%, fines content of 1.76%, and impurity content of 0.13 mass%, satisfying the requirements of JIS A 5022 Annex A. The alkali–silica reactivity classifications were B (not tested) for RLG_1 and RLG_2 and A (harmless) for RMG, as determined according to JIS A 1145 and JIS A 5021.

Table 6 Main characteristics of aggregates

Item		Test method	NS*1	NG*2	LG*3	RLG_1	RLG_2	RMG
Density in oven-dry condition (g/cm^3)		JIS A 1109	2.55–2.59	2.54–2.68	2.69	2.30	2.21	2.40
Water absorption (%)		JIS A 1110	1.57–1.72	0.43–1.48	0.41	6.42	6.48	3.63
Fineness modulus (FM)		JIS A 1102	2.50–2.57	6.65–6.87	6.77	6.77	6.54	6.92
Content of materials finer than 75-μm sieve (%)		JIS A 1103	3.2–3.5	1.3	0.3	1.4	1.6	1.8
Solid content in aggregate (%)		JIS A 1104	63.7–64.8	58.7–64.2	61.5	60.1	60.2	63.6
Solid content of particle shape classification (%)		JIS A 5005	-	56.1–58.4	61.2	59.8	-	61.8
Chloride content (%)		JIS A 5002	-	-	-	0.030	-	0.002
		JIS A 5023	-	-	-	-	0.020	-
Alkali–silica reactivity*4		JIS A 1145	-	-	-	-	-	A*5
		JIS A 5021	-	-	-	B*6	B*6	-
Amount of contained impurities (mass%)	A	JIS A 5022 JIS A 5023	-	-	-	0.16	1.17	0.03
	B					0.09	0.08	0.05
	C					0.02	0.05	0
	D					0	0	0
	E					0	0	0.02
	F					0.04	0.02	0
	G					0	0.01	0.03
	Total					0.31	1.33	0.13

*1: Sand from Ibi river. *2: Crushed hard sandstone from Kasugai. *3: Crushed limestone from Fujiwara. *4: Classification according to alkali–silica reactivity, as specified in JIS A 5308 Annex A. *5: Classified as "A" because it was determined to be harmless based on the alkali–silica reactivity test (JIS A 1145). *6: Classified as "B" because the samples were not subjected to the alkali–silica reactivity test.

3.2 Mix proportions

Table 7 lists the mix proportions of the 41 concrete samples prepared using the different types of cement, normal coarse aggregate, and recycled coarse aggregate. In addition, three water–binder ratios (W/B) were considered (i.e., 45%, 55%, and 65%) along with three replacement ratios for the recycled coarse aggregate (i.e., 0%, 50%, and 100%). These replacement ratios were selected based on JASS 5, which specifies an upper limit of 50% for RLG when used in structural members [19], whereas a replacement ratio of 100% is assumed for RMG in structural applications. However, concrete using LG was tested with recycled aggregate replacement ratios of 0% and 50%, and W/B of 45%, 55%, and 65% to evaluate the influence of different kinds of normal coarse aggregates with RAC. Concrete using BB cement was tested with RG replacement ratios of 0%, 50%, and 100% and only W/B of 55% to assess the effects of the cement and replacement ratio. Because E exhibits properties similar to N, concrete using E had RG replacement ratios of 0% and 50% with W/B of 55% only. The mix proportion for RAC involved replacing only the recycled coarse aggregate in the mix proportion of the normal concrete under the same conditions (i.e., W/B, s/a, quantity of material per unit volume of concrete). This explains the presence of −1 (e.g., NNSNG-55-1) and −2 (e.g., NNSNG-55-2) for some test samples of the normal concrete.

The target slump of the concrete samples was set to 18 ± 2.5 cm, and the target air content was set to 4.5% ± 1.5%. The chemical admixtures included an air-entraining and water-reducing admixture made from modified lignin sulfonate compound and polycarboxylic acid compound complex added at 1.0% of the cement mass and an air-entraining admixture made from a resin-based anionic surfactant added at 0.05%–0.10% of the cement mass. The unit water contents of FB and BB were reduced

Table 7 Mix proportions

Sample	Cement type	Replacement ratio of RG	W/B (%)	s/a (%)	Unit weight (kg/m^3)							
					W	C	NS	NG	LG	RLG$_1$	RLG$_2$	RMG
NNSNG-45	N	0	45	43.1	185	411	715	968	-	-	-	-
NNSNGRLG$_1$50-45		50						484	-	446	-	-
NNSNG-55-1		0	55	45.8	180	327	798	968	-	-	-	-
NNSNG-55-2				44.3			782	1006	-	-	-	-
NNSNGRLG$_1$50-55		50		45.8			798	484	-	446	-	-
NNSNGRLG$_2$50-55				44.3			782	503	-	-	440	-
NNSRLG$_1$100-55		100		45.8			798	-	-	892	-	-
NNSRLG$_2$100-55				44.3			782	-	-	-	879	-
NNSNG-65		0	65	48.3	176	271	868	952	-	-	-	-
NNSNGRLG$_1$50-65		50						476	-	439	-	-
NNSLG-45		0	45	41.1	181	402	689	-	1030	-	-	-
NNSLGRLG$_1$50-45		50						-	514	467	-	-
NNSLG-55		0	55	43.3	180	327	754	-	1030	-	-	-
NNSLGRLG$_1$50-55		50						-	514	467	-	-
NNSLG-65		0	65	45.9	176	271	824	-	1013	-	-	-
NNSLGRLG$_1$50-65		50						-	506	459	-	-
NNSNG-45		0	45	38.8	185	441	642	1010	-	-	-	-
NNSNGRMG50-45		50						506	-	-	-	486
NNSNG-55		0	55	39.7	180	327	692	1044	-	-	-	-
NNSNGRMG50-55		50						522	-	-	-	502
NNSRMG100-55		100						-	-	-	-	1004
NNSNG-65		0	65	43.4	176	271	780	1010	-	-	-	-
NNSNGRMG50-65		50						506	-	-	-	486
FBNSNG-45	FB	0	45	43.7	176	391	733	968	-	-	-	-
FBNSNGRLG$_1$50-45		50						484	-	446	-	-
FBNSRLG$_1$100-45		100						-	-	892	-	-
FBNSNG-55-1		0	55	46.4	171	311	816	-	-	-	-	-
FBNSNG-55-2				44.9			803	1006	-	-	-	-
FBNSNGRLG$_1$50-55		50		46.4			816	484	-	446	-	-
FBNSNGRLG$_2$50-55				44.9			803	503	-	-	440	-
FBNSRLG$_1$100-55		100		46.4			816	-	-	892	-	-
FBNSNG-65		0	65	48.7	169	260	881	952	-	-	-	-
FBNSNGRLG$_1$50-65		50						476	-	439	-	-
FBNSRLG$_1$100-65		100						-	-	877	-	-
BBNSNG-55-1	BB	0	55	46.3	173	315	813	968	-	-	-	-
BBNSNG-55-2				44.9			801	1006	-	-	-	-
BBNSNGRLG$_1$50-55		50		46.3			813	484	-	446	-	-
BBNSNGRLG$_2$50-55				44.9			801	503	-		440	-
BBNSRLG$_1$100-55		100		46.3			813	-	-	892	-	-
ENSNG-55	E	0	55	45.8	180	327	795	968	-	-	-	-
ENSNGRLG$_1$50-55		50						484	-	446	-	-

by −5% and −4%, respectively, relative to N in accordance with recommendations from the AIJ [5].

3.3 Methods

Table 8 summarizes the properties measured for the concrete samples and the test methods. The slump, air content, density, concrete temperature, and chloride ion content were measured for fresh samples. The chloride ion content was calculated as the equation (1).

Table 8 Test items and methods

Item			Method	Note
Fresh properties	Slump		JIS A 1101	-
	Air content		JIS A 1128	
	Density		JIS A 1116	
	Concrete temperature		JIS A 1156	
	Chloride ion content	Normal concrete	JASS 5 T-502	Ion-selective electrode method
		RAC and RAC used E	JIS A 5022, JIS A 5023	Calculated using Equation (1)
Hardened properties	Compressive strength		JIS A 1108	At 4 and13 weeks
	Static modulus of elasticity		JIS A 1149	
	Length change rate (drying shrinkage)		JIS A 1129-3	-
	Accelerated carbonation		JIS A 1153	-
	Freezing and thawing		JIS A 1148	Method A

$$C_0 = \frac{C_1 \times W_1}{100} + \frac{3}{4} \times \frac{C_L \times W_L}{100} + \frac{1}{4} \times \frac{C_H \times W_H}{100} + \frac{3}{4} \times \frac{C_M \times W_M}{100} + \alpha \times \frac{C_2 \times W_2}{100} \qquad (1)$$

C_0 is the chloride ion content of RAC Class M or RAC Class L (kg/m^3),
C_1 is the chloride ion content of fresh concrete (%),
W_1 is the unit water content specified in the mix proportion (kg/m^3),
C_L is the chloride ion content of RA Class L (%) × 0.607*,
W_L is the amount of RA Class L used in the mix proportion (kg/ m^3),
C_H is the chloride ion content in RA Class H (%) × 0.607*,
W_H is the amount of RA Class H used in the mix proportion (kg/m^3),
C_M is the chloride ion content in RA Class M (%) × 0.607*,
W_M is the amount of RA Class M used in the mix proportion (kg/m^3),
α is the chloride-ion residual rate from JIS R 5214 (0 except for E),
C_2 is the chloride ion content in E (%), and W_2 is the unit cement content specified in the mix proportion (kg/m^3).
*The coefficient of 0.607 was selected to converting NaCl to the Cl equivalent:
0.607 = Cl molecular weight (35.45) ÷ NaCl molecular weight (58.44).

The compressive strength, static modulus of elasticity, length change (drying shrinkage), accelerated carbonation depth, and durability factor were measured for the hardened samples. Concrete samples were prepared by following JIS A 1138, and hardened concrete samples were prepared by following JIS A 1132. Cylindrical samples with a diameter of 100 mm and height of 200 mm were used to test the compressive strength and static modulus of elasticity. After demolding the next day, the samples were cured under standard conditions until the prescribed age was reached. Six samples were tested for each age (28, 91 days), and the average value was recorded. The static modulus of elasticity was measured by using a compressometer. Three samples with dimensions of 100 mm × 100 mm × 400 mm were used for the drying shrinkage, accelerated carbonation, and freezing and thawing tests. Three samples were used for each test, and the average value was recorded.

For the drying shrinkage test, the samples were kept moist in a room at 20°C ± 2°C. After demolding, they were cured under standard conditions for 7 days and were then stored in a humidity chamber at a constant temperature of 20°C ± 2°C and relative humidity of 60% ± 5% until the prescribed age was reached for measurement.

For the accelerated carbonation tests, after demolding the samples were placed in water at a temperature of 20°C ± 2°C for 4 weeks. They were then kept in a humidity chamber at a constant temperature of 20°C ± 2°C and relative humidity of 60% ± 5% for another 4 weeks. The accelerated carbonation test was conducted under the conditions of a temperature of 20°C ± 2°C, relative humidity of 60% ± 5%, and CO_2 concentration of 5% ± 0.2%.

For the freezing and thawing tests, samples were demolded, cured under standard conditions until 4 weeks of age, and then subjected to freezing and thawing cycles until the prescribed age for measurements.

4. Results

4.1 Fresh properties

Table 9 summarizes the fresh properties of the concrete samples.

4.1.1. Slump and air content

FBNSRLG$_1$100–65 (W/B: 65%, cement: FB, RLG$_1$ replacement ratio: 100%) had a slump of 10.5 cm, which was substantially below the target value. Thus, the type and volume of chemical admixture needed to be adjusted in this case. For all other samples, the target values for the slump and air content were satisfied. The aggregate modification factor was 0.4%–0.5% at the 50% replacement ratio and 0.6% at the 100% replacement ratio for RLG. The aggregate modification factor was 0.3% at the 50% replacement ratio and 0.5% at the 100% replacement ratio for RMG.

4.1.2. Density

The density of RAC tended to decrease as the RG replacement ratio increased. This is because RG had a lower density than the normal coarse aggregate owing to the adhesion of original mortar or cement paste.

4.1.3. Concrete temperature

Samples were prepared according to JIS A 1138 from mid-July to mid-December of the following year. The concrete temperatures varied because mixing was partially conducted outdoors. However, all samples had temperatures of 8.4°C–30.1°C and thus stayed below 35°C. The RG replacement ratio had no effect on the concrete temperature.

4.1.4. Chloride ion content

As per JIS A 5022 and JIS A 5023, the chloride ion content was calculated under the assumption that 25% of the total chloride ion content of RMG and RLG in addition to 100% of the chloride ion content of the cement would leach into water. The results demonstrated that the chloride ion content of all samples satisfied the limit of 0.30 kg/m^3 set by JIS A 5308 although it increased with the replacement ratio.

4.2 Hardened properties

4.2.1. Compressive strength

Figure 3 illustrates the compressive strengths of the concrete samples. For samples using RLG$_1$, the compressive strength tended to decrease as the replacement ratio increased. The type of cement influenced the development of the compressive strength: FB and BB resulted in greater long-term strength than N whereas E had nearly equal strength [19]. With N, the 4-week compressive strength tended to decrease as the replacement ratio increased. With FB, the 13-week compressive

Table 9 Fresh properties of concrete samples*1

Sample	Slump (cm)	Air content*2 (%)	Density (kg/m^3)	Temperature (°C)	Chloride ion content (kg/m^3)*3
NNSNG-45	20.5	5.6	2263	18.0	0.07
NNSNGRLG$_1$50-45	19.0	5.0 (0.4)	2230	17.4	0.13 (0.035)
NNSNG-55-1	20.0	5.4	2244	18.6	0.05
NNSNG-55-2	20.5	5.5	2397	25.9	0.02
NNSNGRLG$_1$50-55	20.5	4.9 (0.5)	2260	18.8	0.12 (0.031)
NNSNGRLG$_2$50-55	20.5	4.3 (0.7)	2299	22.6	0.09 (0.026)
NNSRLG$_1$100-55	20.0	4.5 (0.6)	2180	18.2	0.18 (0.033)
NNSRLG$_2$100-55	19.5	5.3 (0.7)	2173	22.8	0.14 (0.031)
NNSNG-65	20.0	4.4	2261	18.7	0.03
NNSNGRLG$_1$50-65	17.5	5.2 (0.4)	2180	18.6	0.09 (0.018)
NNSLG-45	20.5	4.0	2214	12.5	0.03
NNSLGRLG$_1$50-45	20.5	5.1 (0.4)	2199	12.7	0.07 (0.003)
NNSLG-55	20.5	4.4	2343	20.0	0.05
NNSLGRLG$_1$50-55	20.0	4.9 (0.5)	2261	20.2	0.12 (0.032)
NNSLG-65	20.0	5.3	2306	18.5	0.04
NNSLGRLG$_1$50-65	20.0	4.9 (0.5)	2273	14.2	0.09 (0.014)
NNSNG-45	20.5	5.6	2286	23.8	0.08
NNSNGRMG50-45	19.5	4.4 (0.3)	2290	24.2	0.07 (0.039)
NNSNG-55	20.5	5.9	2274	26.6	0.03
NNSNGRMG50-55	20.0	5.2, 5.6 (0.3)	2225, 2240	23.0, 23.3	0.05 (0.028)
NNSRMG100-55	19.0, 19.5	4.0, 5.3 (0.5)	2254, 2280	24.4, 24.9	0.05 (0.025)
NNSNG-65	20.0	5.8	2230	23.7	0.04
NNSNGRMG50-65	18.0	5.1, 5.2 (0.3)	2247, 2307	23.5, 23.6	0.06 (0.034)
FBNSNG-45	20.0	3.6	2377	28.2	0.03
FBNSNGRLG$_1$50-45	20.0	4.5 (0.4)	2274	21.1	0.06 (0.003)
FBNSRLG$_1$100-45	18.0	3.7 (0.6)	2289	20.5	0.12 (0.013)
FBNSNG-55-1	17.0, 18.0	3.3, 5.8	2300, 2376	24.9	0.03
FBNSNG-55-2	20.5	5.2	2371	25.3	0.01
FBNSNGRLG$_1$50-55	16.0	3.3 (0.4)	2310	22.1	0.06 (0.004)
FBNSNGRLG$_2$50-55	20.5	4.6 (0.6)	2310	19.2	0.06 (0.013)
FBNSRLG$_1$100-55	18.5	3.8 (0.6)	2243	22.3	0.12 (0.007)
FBNSNG-65	18.5	4.0	2351	19.3	0.03
FBNSNGRLG$_1$50-65	16.5	4.2 (0.4)	2279	20.8	0.06 (0.004)
FBNSRLG$_1$100-65	10.5	4.4 (0.6)	2223	19.7	0.12 (0.004)
BBNSNG-55-1	18.0, 19.0	5.9, 6.0	2281, 2289	26.1, 26.7	0.04
BBNSNG-55-2	19.5	4.4	2340	25.4	0.02
BBNSNGRLG$_1$50-55	18.0	4.5 (0.4)	2243	20.4	0.06 (0.016)
BBNSNGRLG$_2$50-55	19.0	5.2 (0.4)	2350	24.8	0.06 (0.012)
BBNSRLG$_1$100-55	17.0	5.1 (0.6)	2244	22.3	0.12 (0.020)
ENSNG-55	18.5, 19.5	5.8, 5.9	2200, 2287	27.1	0.10
ENSNGRLG$_1$50-55	19.5	4.8 (0.4)	2236	14.1	0.14 (0.026)

*1 Including cases where measurements were performed twice simultaneously.
*2 Aggregate correction factor is provided in brackets. Further, it is omitted if the threshold is less than 0.1%.
*3 The value in brackets indicates the value of C_1 in Equation (1).

strength exceeded 50 N/mm^2 for all samples with a W/B of 45%. However, at W/B of ≥55%, the effect of the replacement ratio was subtle. With BB, the 13-week compressive strength decreased as the replacement ratio was increased although only at a W/B of 55%. A similar trend was observed with E regarding the 4-week compressive strength.

For samples using LG as the normal coarse aggregate, the effect of the replacement ratio was unclear because the compressive strength was less than 50 N/mm^2 even at a W/B of 45%. These results may have been influenced by the coarse aggregate strength [23]. The replacement ratio had no effect on the 4- and 13-week compressive strengths of concrete samples using RMG.

4.2.2. Static modulus of elasticity

Figure 3 shows that the replacement ratio affected the static modulus of elasticity for concrete samples using RLG_1, particularly at 13 weeks for samples using FB and BB as the cement and at 4 weeks for samples using E and N as the cement. The replacement ratio barely affected the static modulus of elasticity of concrete samples using RMG. Between the normal coarse aggregates, the static modulus of elasticity tended to be higher with LG than with NG when N was used as the binder, which agrees with previous results [19]. These results indicate that mixing LG with RLG effectively improves the static modulus of elasticity of RAC. The static modulus of elasticity (Young's modulus) can be evaluated by using the following equation (2) from JASS 5 [19]:

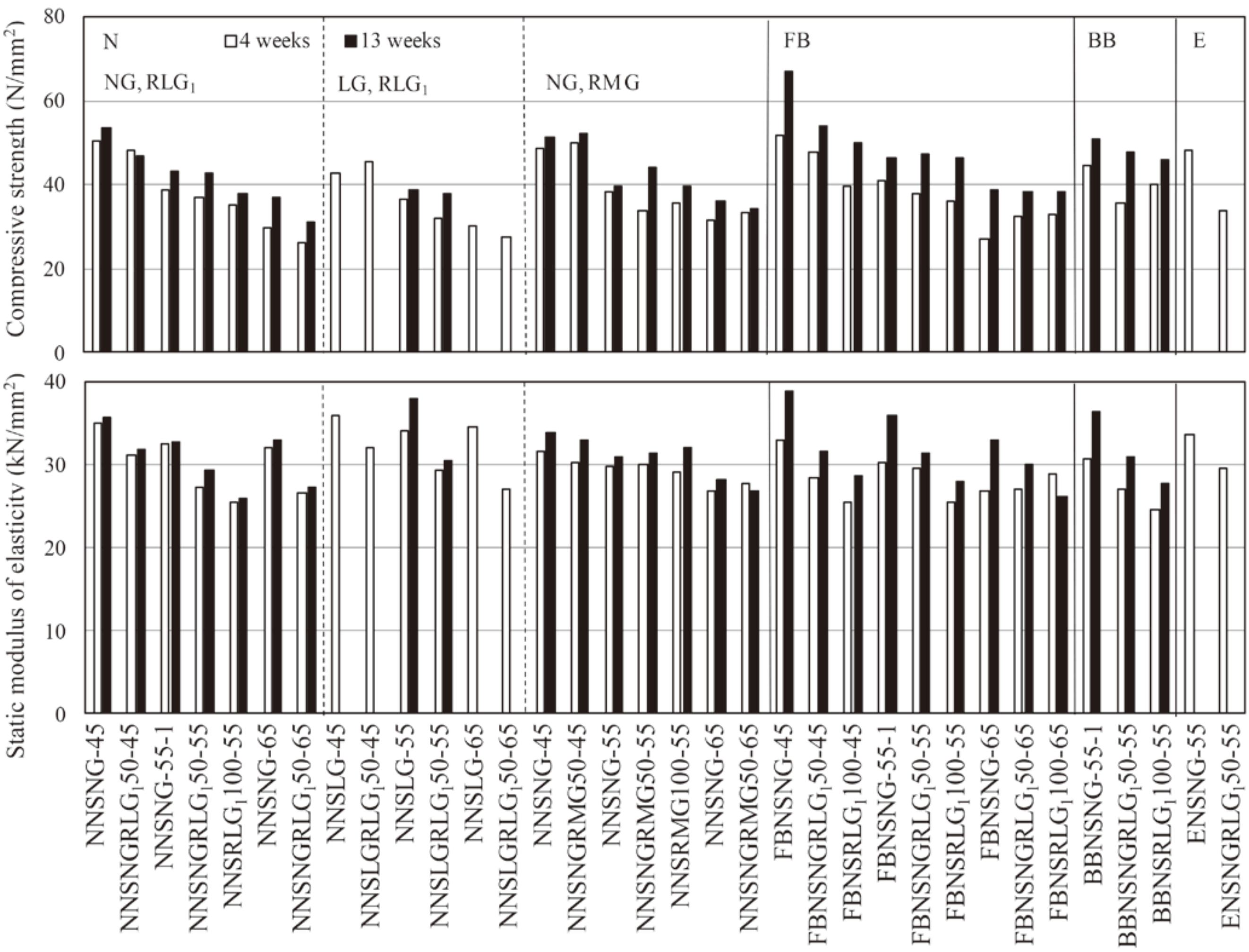

Fig. 3 Compressive strength and static modulus of elasticity of concrete samples

$$E = k_1 \times k_2 \times 3.35 \times 10^4 \times \left(\frac{\gamma}{2.4}\right)^2 \times \left(\frac{\sigma_B}{60}\right)^{1/3} \quad (2)$$

where

E is the Young's modulus (N/mm^2),

k_1 is the modification factor determined by the type of coarse aggregate (1.2 for LG, 1.0 for NG, and 1.0 for no admixture),

k_2 is the modification factor determined by the type of admixture (1.1 for FA (FB), 0.95 for GGBFS (BB), and 1.0 for no admixture (N, E)),

γ is the density of concrete (t/m^3),

σ_B is the compressive strength of concrete (N/mm^2), and B is the concrete age (4 weeks).

The accuracy of this equation is reported to be within ±20% of the actual value. The air-dry density of the concrete was measured from samples used for drying shrinkage after 3 months (i.e., 13 weeks) of storage.

Figure 4 illustrates the relationship between the compressive strength and Young's modulus for the concrete samples according to the coarse aggregate type, cement type, and replacement ratio. The measured static modulus of elasticity was within −10% to +22% of the value estimated from equation (2) except for NNSNG-65, which was within +31%. Overall, however, the values were generally within ±20%, which corresponds with expectations [19].

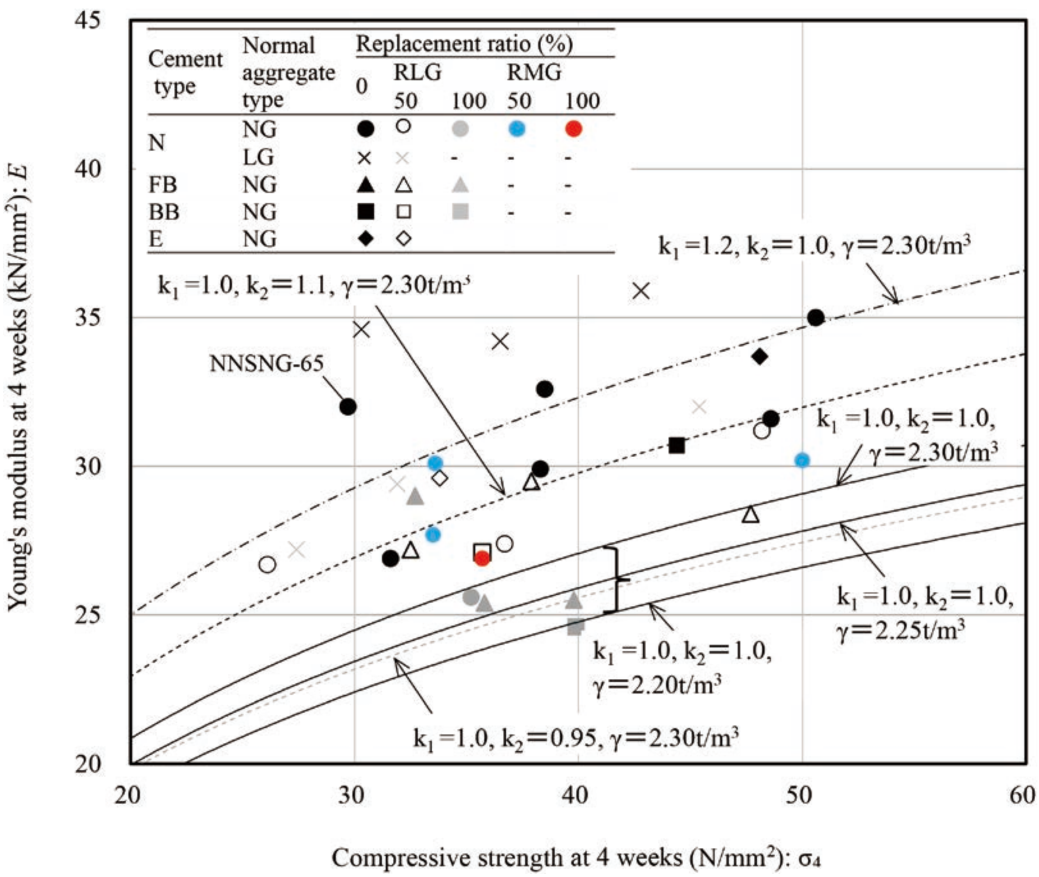

Fig. 4 Relationship between the compressive strength and Young's modulus

4.2.3. Drying shrinkage

Figure 5 shows that the replacement ratio affected the drying shrinkage of concrete samples using RLG_1. $BBNSNGRLG_1$50–55 and $NNSRLG_1$100–55 both exceeded the target value of 8×10^{-4} set by JASS 5 [19]. Conversely, the replacement ratio had little effect on the drying shrinkage of concrete samples using RMG, which remained at <8 × 10^{-4} even at a 100% replacement ratio. When RLG_1 was mixed with LG, the maximum drying shrinkage was 6 × 10^{-4} even at a replacement ratio of 50%. This may be because concrete using crushed limestone generally has little drying shrinkage [24]. When comparing $NNSNGRLG_1$50–45 and $NNSLGRLG_1$50–45 with a W/B of 45% and a high-water content per unit volume at N, the study obtained reductions of approximately 2 × 10^{-4}. Overall, the effect of the cement type was unclear. However, concrete samples using W/B of 55% and 100% replacement ratio for RLG_1 with different types of cement ($NNSRLG_1$100–55, $FBNSRLG_1$100–55, and $BBNSRLG_1$100–55) had drying shrinkages of 10 × 10^{-4}, 8 × 10^{-4}, and 8 × 10^{-4}, respectively. These concrete samples had water contents per unit volumes of 180, 171, and 173 kg/m^3, respectively, which suggests that the reduced water content per unit volume owing to the use of blended cement influenced the drying shrinkage.

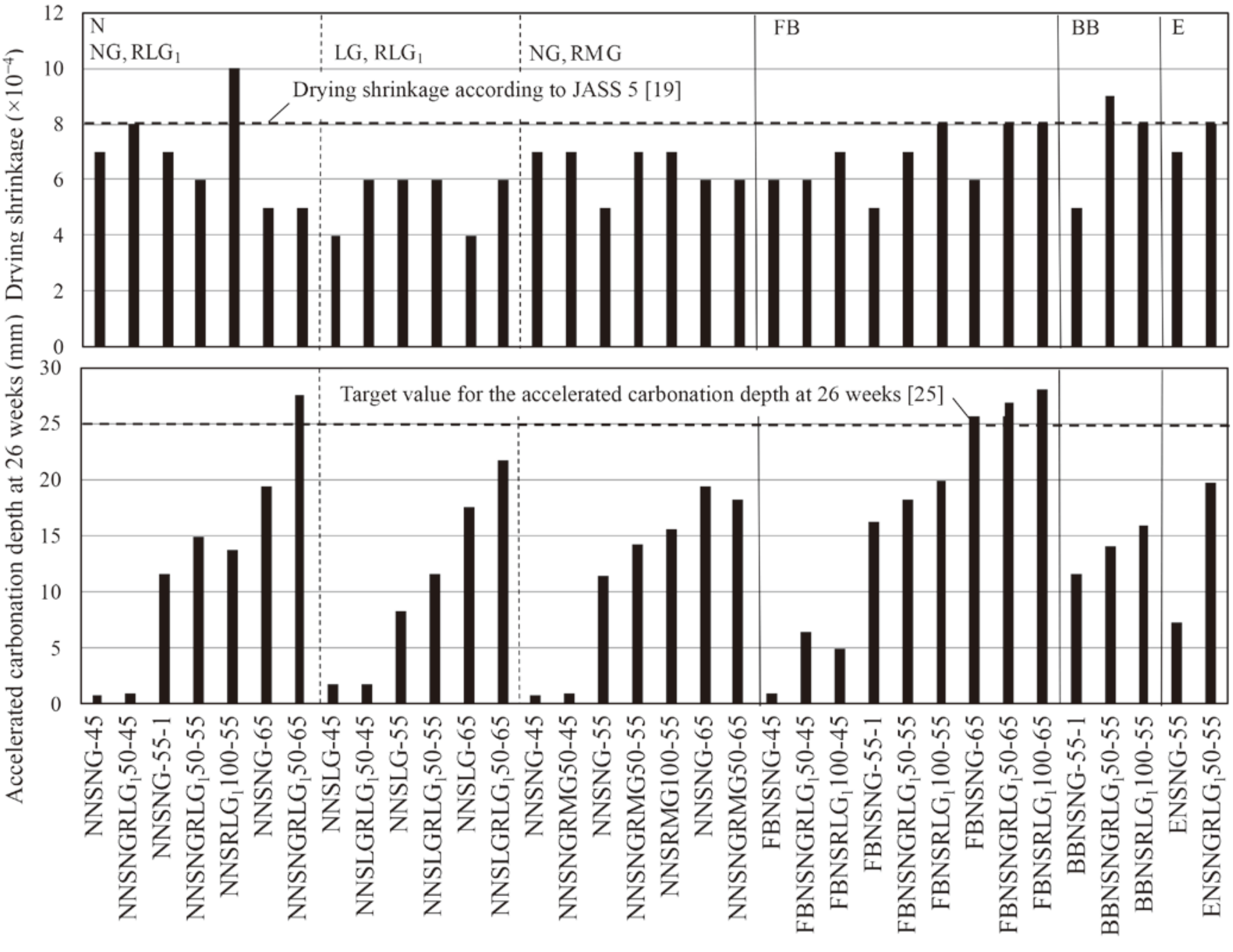

Fig. 5 Drying shrinkage and accelerated carbonation depth of concrete samples

4.2.4. Accelerated carbonation

Figure 5 shows that the accelerated carbonation depth was most affected by the W/B with little progress at W/B of 45%. However, at W/B of 65%, $NNSNGRLG_1$50–65 exceeded the target of <25 mm for highly durable concrete [25]. The replacement ratio clearly affected the accelerated carbonation depth in concrete samples using RLG_1 and with a W/B of ≥55%. The W/B affected the accelerated carbon depth in concrete samples using RMG, but the effect of the replacement ratio was less evident at W/B of ≥55% W/B. Among cement types, the accelerated carbonation depth increased with FB, which agrees with previous results [26].

Figure 6 shows the relationship between the compressive strength of concrete samples and the accelerated carbonation depth. A strong correlation was observed for all cement types, which indicates that the target quality can be achieved by increasing the compressive strength (i.e., by reducing the W/B). However, BB was used as a reference because of the scarcity of samples.

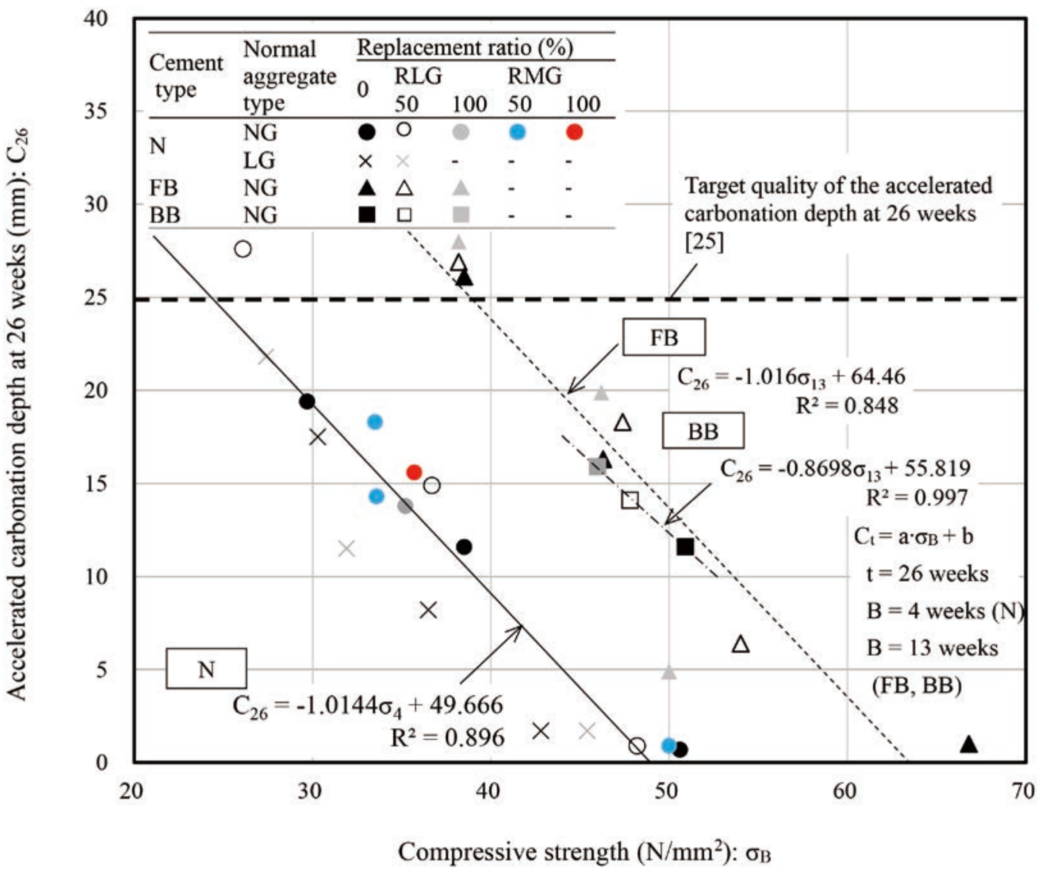

Fig. 6 Relationship between compressive strength and accelerated carbonation depth

4.2.5. Freezing and thawing resistance

Figure 7 shows the relationship between the air content of fresh concrete and its durability factor. The durability factor was >85 regardless of the RA replacement ratio and cement type as long as the air content was within 4.0%–6.0%, which complies with the requirements of JASS 5 [19] for concrete subjected to severe freezing and thawing action. However, the durability factor of RAC is influenced by multiple factors, including the type of original aggregate, air content, W/B manufacturing method of the original concrete, and the crushing method [27]. Further evaluation according to JIS A 5022 Annex D is required to confirm these effects.

4.2.6. Total evaluation

Table 10 presents the relationship between the performance requirements and materials employed according to the mix proportion. The results indicate that the performance of RAC can be elevated by optimizing the replacement ratio of RG and selecting appropriate materials as the cement and normal coarse aggregate while adjusting the mix proportion in terms of the W/B, air content, and water content per unit volume.

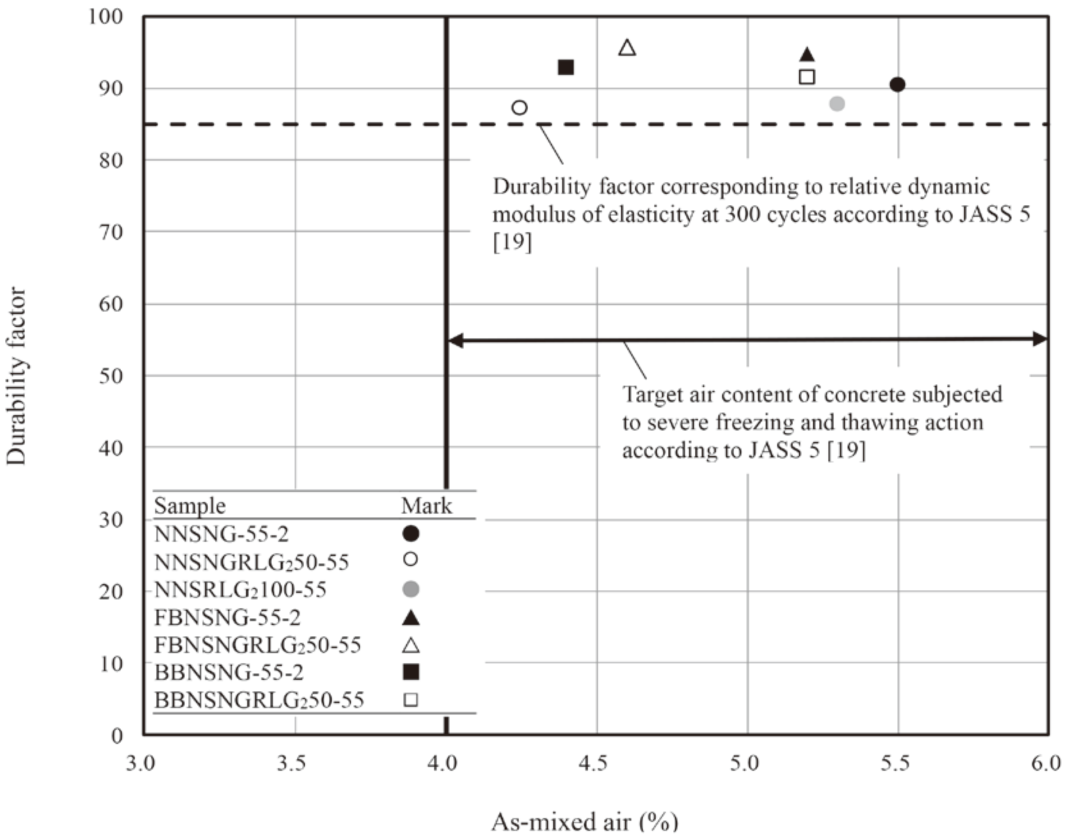

Fig. 7 Relationship between the as-mixed air content and durability factor

Table 10 Relationship between performance requirements and materials used*1

Performance requirement	Cement			Coarse aggregate		Mix Proportion			
	N, E	FB	BB	NG	LG	W/B	Air content	Water*2	Replacement ratio of RAC
Increase compressive strength	●			●					●
Increase long-term compressive strength		●	●						
Increase static modulus of elasticity					●				●
Suppress drying shrinkage					●			○	●
Suppress carbonation resistance					●	●			●
Improve freezing and thawing resistance							●		

*1 ● : factors contributing to performance improvement. ○ : factors contributing to performance degradation. *2 Water content per unit volume of concrete

4. Conclusions

The aim of this study was to develop a simplified manufacturing method that promotes the use of RG and environmentally friendly cements to produce concrete with excellent resource recyclability and economic efficiency. To simplify the improvement of RAC Class M, general-purpose cements and aggregates were used instead of SCMs. The following conclusions were obtained:

(1) The slump and air content of RAC samples using RLG and RMG mostly satisfied the target values, regardless of the cement type and replacement ratio. The density of RAC tended to decrease with increasing replacement ratio, which can be attributed to the lower density of RG due to the adhesion of original mortar or cement paste. The RG replacement ratio had

no significant effect on the concrete temperature, and the chloride ion contents of the RAC samples satisfied the limit of 0.30 kg/m^3.
(2) The replacement ratio influenced the compressive strength of RAC samples using RLG but had no effect on samples using RMG. The cement type influenced the development trend of compressive strength. The static modulus of elasticity decreased with increasing replacement ratio when more RLG was used. These results indicate that mixing crushed limestone with RG is effective for improving the static modulus of elasticity.
(3) The replacement ratio had a greater influence on the drying shrinkage when RLG was used. The drying shrinkage can be reduced by mixing RG with crushed limestone. It can also be reduced by lowering the water content per unit volume, which can be achieved by using blended cement.
(4) The replacement ratio influenced carbonation when RLG was used. Carbonation was also accelerated when FB was used as the cement type. The influence of the W/B was dominant, and the target quality could be achieved by reducing the W/B even at high replacement ratios.
(5) When the air content of the as-mixed fresh concrete was within a suitable range, the durability factor was >85, regardless of the RG replacement ratio and cement type. However, multiple factors influence the durability factor of RAC, including the type of original aggregate, air content, W/B, manufacturing method of the original concrete, and the crushing method. Further evaluation according to JIS A 5022 Annex D is necessary to confirm these effects.

These results indicate that replacement with RMG had almost no effect on the concrete performance, whereas replacement with RLG degraded the concrete performance. However, the performance of RAC using RLG can be enhanced by applying the same approach used to optimize the performance of normal concrete, such as selecting the appropriate cement type and normal coarse aggregate and adjusting the mix proportion to modify the W/B, air content, and water content per unit volume.

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Conflicts of interest

The authors declare no conflict of interest.

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Agricultural Water Management in Singapore and Japan: Toward Sustainable Design and Innovation

Kheng Lim Goh[1,2], Katsura Nishiyama[3]

1) Newcastle University in Singapore, 1 Punggol Coast Road, Block E1, Level 2, Singapore 828608
2) Faculty of Science, Agriculture & Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, U.K.
3) Department of Environmental Technology, Faculty of Science and Technology, Meijo University, Tempaku, Nagoya, 468–8502, Japan

Abstract

This paper describes a comparative analysis of agricultural water management in Singapore and Japan, two countries with distinct geographies but shared challenges. Singapore, highly urbanized and water-scarce, relies on advanced technologies such as hydroponics, vertical farming, and closed-loop aquaponics, supported by its "Four National Taps" strategy—local catchments, imported water, desalination, and NEWater. Japan has greater freshwater resources but faces seasonal shortages, aging irrigation systems, and climate-induced droughts. Analysis of vegetable production and consumption shows Japan's practices to be consistently more water-efficient, though on a far larger production scale, while Singapore's high consumption footprint reflects dependence on imports. Emerging technologies—including smart irrigation, biochar amendments, digital farming, and circular waste-to-resource pathways—are explored as opportunities for cross-national learning. The insights highlight how technology, policy, and innovation could shape sustainable water use in crop farming across urban and rural contexts.

Keywords：Crop farming, recycled water, freshwater, urban agriculture, rural agriculture

1 Introduction

Modern agriculture is greatly dependent on technologies such as irrigation, fertilizers, and pesticides to overcome the limits of natural soil productivity and sustain global food production [1]. This food production dependence underpins water consumption which unfortunately involves inefficient practices in many parts of the world [2]. This leads to a global challenge in which technological progress seeks to provide abundance and creates problematic long-term sustainability issues.

Agriculture is the largest user of freshwater [2]. From the data from the UN Food and Agriculture Organization (FAO) and other water-use studies: about 70% of all freshwater withdrawals worldwide are used for agriculture [3]. This implies 2,500–3,000 cubic kilometers (km^3) of water per year, which translates to 2.5–3 trillion cubic meters annually. In water-scarce regions (e.g., parts of Asia, the Middle East, and Africa), agriculture can account for up to 90% of freshwater use; the bulk of this water goes into irrigation, while smaller portions are used for livestock watering and aquaculture.

Table 1 Singapore and Japan: Area, Population, and Density.

Country	Area (km^2)*	Population (million)*	Density (people/km^2)#
Singapore	736	6	7,800
Japan	377,975	123	330

* https://data.un.org; # estimated from area and population data

Table 1 lists the size, population and density of Singapore and Japan. To meet population growth in highly urbanised areas that aligns with mitigating climate change and disruption arising from geopolitical tensions as well as the next epidemic effects, countries like Singapore and Japan approach agricultural sustainability in the following ways. In land-scarce and water-constrained regions like Singapore, the shift from traditional soil-based farming to high-tech urban agriculture requires a re-evaluation of how water—one of the most critical inputs—is sourced, utilized, and conserved; Singapore aspires to locally produce 30% of its nutritional requirement by 2030 [4]. Japan, while geographically and demographically different, also faces growing pressure to enhance water efficiency across its diverse agricultural systems, albeit some differences. In July 2025, the Tohoku rice-growing region faced record-low rainfall—Yamagata received just 8 mm (～4% of normal), and Niigata only 3.5 mm (～2%). Farmers faced water rationing as a dam turned dry and another dropped to 20% capacity [5]. Extreme heat and drought also caused a rice shortage in 2024, driving inventories to a 25-year low. In response, the government released reserves and began testing heat-resistant rice varieties [6]. Multiple sources point to drought as a recurrent threat to rice yields and food security, with climate change projected to cause ～20% declines in paddy yields by 2100 [6, 7]. Table 2 highlights the areas of interest in the comparative analysis of Japan and Singapore.

Table 2 Water challenges in Japan and Singapore

	Water Scarcity (Agriculture)	Pressures
Singapore	Clearly water-scarce, with limited natural supply and high withdrawals [8]	Full reliance on advanced technology for water supply and recycling; agriculture is minor and technology-intensive [9]
Japan	Not initially water scarce, but faces localized and seasonal water stress affecting agriculture [5]	Regional and temporal shortages; infrastructure inefficiencies; climate-induced droughts; aging farming systems [2]

This paper presents a preliminary comparative analysis of the landscape of agricultural water management for crop farming, as well as insights, in Singapore and Japan. The aim is to draw parallels on sustainable practices that could be of value to each country. Following from the Net Zero Urban Farming workshop, which brought together academics from Singapore Institute of Technology and Newcastle University, where discussion produced an insightful paper [10], this study adds perspectives of Singapore and Japan's water-focused innovation efforts for examining broader themes of sustainability, technology, and policy in agriculture.

2 Crop farming landscape in Singapore and Japan

Currently understanding of the mechanics of the global circulation of fresh water, i.e. the hydrological cycle, is outlined as follows, with further details described elsewhere [11]. Water evaporates from the oceans into the atmosphere, then condenses and falls back to Earth as dew, mist, rain, snow, or hail. This precipitation either returns directly to the oceans or falls on land, from where it eventually flows back to the oceans through rivers, runoff, or groundwater. The hydrological cycle is important for living things on earth that consumes or uses fresh water, as the cycle controls the amount of fresh water available at any one place at a given time.

Of the water input from all forms of precipitation, only a small fraction, about 25%, falls on land surfaces. Of this potential supply, the amount and form in which the water reaches us depends on the routes by which it is returned to the atmosphere. Almost all land plants depend on water stored in the soil, which they absorb through their roots. Only a very small number of plants get their water directly from the air or other sources. The availability of water for absorption by a plant's roots depends on the depth of the root zone, which can vary from a few cm to around 15 m, and the ability of the soil to hold or retain precipitation.

Of the total incoming precipitation, some is intercepted by the vegetation cover and held or 'stored' long enough to be lost by evaporation before it reaches the land surface. (Infiltration of water into the soil will depend on the amount of precipitation, less than which is intercepted or runs off the surface.) On reaching the land surface, a proportion of this water will leave the land by surface run-off into streams, rivers, lakes, etc, which discharge into the oceans.

Return of water from the soil may be by two routes: (1) evaporation and evapo-transpiration (a process where water taken up by the plants is returned to the atmosphere), (2) longer and slower route of percolation, as freely draining soil-water, down to ground-water levels from where it eventually seeps into streams, lakes, or directly into the sea.

The total volume of water circulating through a given terrestrial ecosystem, and its distribution among the possible routes it can follow, are determined by prevailing climatic conditions, landforms and the nature of the vegetation cover and the underlying soil. A shift in any of these variable will be reflected throughout the hydrological cycle.

Today the world contains almost eight billion people, with a population doubling time of about 25 years. Energy-driven water technology is needed to raise the productivity of land, a productivity which in some of today's most intensive systems produces fifty times as much protein per hectare as a natural system. In Singapore, by virtual of the limited land, (1) cutting fresh water loss interception and evapo-transpiration, and (2) increase the 'water yield' by capturing the proportion of surface run-off as a result of deforestation (which is replaced by buildings, roads and other infrastructure-related to urbanisation). In Japan, the concern is not increasing overall water yield, since rainfall is abundant, but ensuring reliable storage and distribution. The chief concern are the seasonal and regional imbalance of water, inefficiencies in aging irrigation systems, and climate-induced stresses such as droughts and heat waves, which could disrupt Japan's agricultural supply. Clearly, despite having better knowledge of the hydrological processes, manipulating the hydrological cycle at other than a relatively local scale is limited by our ability to control global climate.

Table 3 Water consumption for food (vegetables) production in Japan and Singapore (https://www.watertofood.org)

	Singapore				Japan			
	1990	2000	2010	2016	1990	2000	2010	2016
Unit water footprint of production (m^3/t)	251	268	228	239	139	142	158	165
Unit water footprint of consumption (m^3/t)	346	346	317	283	160	164	182	192
Water footprint of production (m^3)	2.2×10^6	3.1×10^6	4.3×10^6	5.2×10^6	5.0×10^8	4.1×10^8	4.6×10^8	4.4×10^8

The price we pay for this intensification may be gauged from Table 3 and Figure 1, which shows the water consumption for food production in Japan and Singapore from 1990 to 2016. Singapore's unit water footprint of vegetable consumption has decreased since 2000, reflecting efficiency gains from hydroponics, vertical farming, and recycled-water use. However, its total production water footprint has increased because overall domestic output has grown. In short, each ton of vegetables now requires less water, but rising production volumes mean that Singapore's aggregate water demand for vegetables is higher. Japan's unit water footprint of vegetable production has risen slightly over time, from 139 m^3/t in 1990 to 165 m^3/t in 2016, indicating reduced efficiency per ton. At the same time, its total production water footprint shows an overall downward trend, declining from about 496 million m^3 in 1990 to 440 million m^3 in 2016, with fluctuations in between. This pattern reflects shrinking domestic output and structural changes in agriculture.

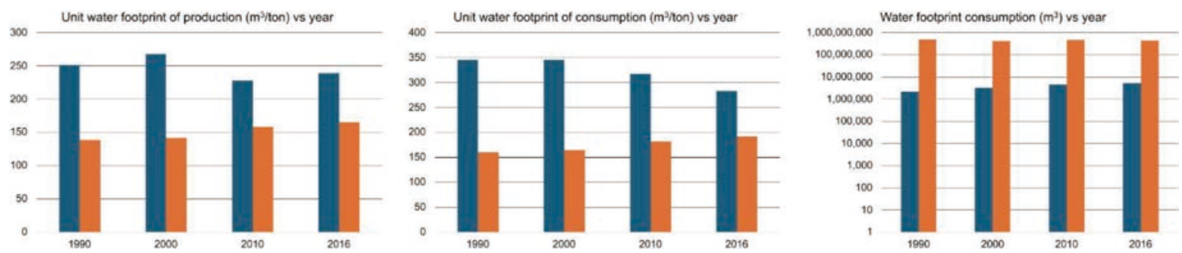

Figure 1 Water footprint of vegetable production and consumption in Singapore (dark blue bars) and Japan (orange bars)

3 How water is delivered to crop farmers in Singapore and Japan

In Singapore, urban crop farming is influenced by spatial and resource limitations. As the 2021 workshop report highlighted, as agriculture occupies less than 1% of Singapore's land; to overcome the land limitation for crop farming and meet scalability, intensive methods such as vertical farms, hydroponics, and controlled-environment systems are used. This requires how water is managed, using recycled or desalinated water. "Closed-loop" systems also combine fish rearing (aquaculture) with vegetable farming, making water use more circular [10].

Water for agriculture in Singapore is regulated by the "Four National Taps", namely local catchment water, imported water, NEWater (i.e. recycled water), and desalinated water. NEWater and desalination are increasingly used in agriculture. Farming technology that requires low water consumption are best able to meet the farmer's bottom line. These technologies are vertical farming, hydroponics, and aquaponics; these technologies use less water than traditional soil-based farming. Hydroponics can reduce water use by up to 90%, as water is recycled within the system [12]. The following paragraph outlined how water is delivered to crop farmers in Singapore.

From the four centralized water sources ("Four National Taps") [9], namely local catchments, where rainwater is collected in reservoirs, imported water, i.e. from Johor, Malaysia, NEWater process creates recycled wastewater for use by farms. Desalination, i.e. where seawater is converted to freshwater, water from these sources is fed into a single national distribution network, managed by the Public Utilities Board. Treated water (potable or NEWater) passes through municipal pressurized pipes which are connected to farms (unlike Japan's canal/ditch systems). At farm-level, water to hydroponics & vertical farms is delivered into nutrient solution tanks; pumps circulate it through growing trays and recycle it in closed loops. Water to aquaponics is circulated between fish tanks and plant beds, with pumps regulating flow. Water to soil-based farms comes through drip irrigation connected directly to the piped supply to reduce loss through evaporation.

In contrast, Japan possesses a relatively abundant of freshwater supply and a wider variety of agricultural landscapes. Japan's efforts include precision irrigation technologies, decentralized water management, and soil moisture sensing in rural farms. The following paragraph outlined how water is delivered to crop farmers in Japan [2].

Water, for example from rain, flows into streams and rivers and is dammed or diverted for storage in reservoirs, ponds,

Table 4 Comparison of water delivery methods for crop farming

	Singapore [9]	**Japan [2]**
Water Source	PUB's Four National Taps: local catchments, imported water, desalination, NEWater (recycled water). NEWater widely used for farms.	Rainfall-fed rivers, reservoirs, dams, and ponds. Groundwater plays a limited role.
Delivery System	Pressurized piped supply from national water grid directly to farms.	Diversion structures feed water into main, secondary, and tertiary irrigation canals.
Farm-Level Application	Hydroponics (nutrient solutions in closed loops), aquaponics (fish-plant cycles), drip irrigation for limited soil-based farms.	Flood irrigation in paddy fields, distributed through field ditches and gates.
Management	Managed by Public Utility Board (PUB). Farmers pay non-domestic water tariffs; some receive subsidized NEWater for irrigation.	Managed by Land Improvement Districts (LIDs), farmer cooperatives that allocate water and maintain canals.
Efficiency	High efficiency: closed-loop hydroponics recycles up to 90% of water; minimal open evaporation losses.	Lower efficiency: paddy flooding uses large volumes but water is partly returned to rivers/groundwater.
Technology Emphasis	Urban farming, vertical farms, automation, precision dosing, recycling.	Canal infrastructure modernization, rotational irrigation scheduling, multipurpose dam systems.

and multipurpose dams during wet periods. The stored water is then released during the growing season. The water is distributed via canals. The main irrigation canals receive water via large headworks (diversion structures). Secondary & tertiary canals carry water flows from main canals to the farming region. At each farming region, the Land Improvement Districts allocate water to individual farmers in scheduled turns, a practice called warabuchi (rotational irrigation). At the farm level, water enters paddy fields via small ditches or gates; the water spreads across fields and infiltrates the soil. Some water percolates to groundwater or drains back to canals/rivers and this enables the water to be reuse.

This comparison highlights a critical insight: while water is a universal agricultural concern, the socio-environmental framing and technological response differ significantly between urbanized (Singapore) and rural (Japan) geographies.

4 New efficient water and related technologies for crop farming

Over the years, Singapore and Japan have gained valuable experience in sustaining water for farming, but national food supply remains vulnerable to the impacts of global climate variability. This limitation underscores the need for continuous innovation in crop water management. Given these ongoing challenges, the following sections highlight key technological directions emerging from the 2021 SIT-NU workshop [10] that may hold potential for future adoption in Singapore and Japan. For a summary of these technologies, see Table 5.

(1) Crop health and disease management

For Singapore, early detection of root diseases in hydroponic or vertical farms can reduce the need to flush entire water systems, saving both water and nutrients. For example, photonic laser spectroscopy developed in Singapore allows real-time monitoring of crop nutrient levels and stress [13]. For Japan, better control of fungal pathogens in paddy fields helps align irrigation more closely with plant health. Recent work on short-wave infrared hyperspectral imaging enables non-invasive root health monitoring [14].

(2) Low-energy farms

For Singapore, having controlled-environment farms using heat gradients, solar-powered IoT irrigation, such as solar green roofs, and ground-source heat pumps can reduce cooling loads in vertical farms, lowering evapotranspiration and irrigation demand. Such systems reduce evapotranspiration and optimise water use [15]. For Japan, smart greenhouses in regions such as Miyazaki integrate data-driven control of water, heat, and CO_2, reduce water stress linked to heating/cooling needs across seasonal climates [16].

(3) Alternative fertilizers and biostimulants

For Singapore, driving the adoption of clean nutrient sources such as green ammonia and bio-stimulants in hydroponics reduces residues in recycled water loops [17]. For Japan, research into controlled-release fertilizers is underway and shows promise for lowering nutrient runoff into irrigation canals; this could be a step forward to keep the water clean and reduce downstream treatment needs [18].

(4) Sensor networks, IoT and digital farming

For Singapore, IoT and machine learning systems in farms (e.g., AbyFarm) are applied to automate irrigation and optimise nutrient and water dosing in hydroponics, ensuring minimal water waste [19]. For Japan, large-scale canal and paddy irrigation can benefit from digital flow monitoring; this approach can lead to more efficient water allocation to farmers. Paddy field irrigation is being modernised with water-level sensor networks using e-Tape, Arduino, and XBee, allowing precise irrigation scheduling [20].

(5) Composting and growth media innovation

For Singapore using compost, coir, and biochar as alternatives to perlite/rockwool improves water retention in hydroponic substrates, reducing freshwater demand [12]. For Japan, organic soil amendments (compost, biochar) are expected to increase soil water-holding capacity in upland fields, so as to be able to mitigate drought stress. Biochar soil amendments are tested in rice fields to increase water-holding capacity and improve yields under evaporation stress [21].

(6) Circular Use of Biomass & Waste

For Singapore, biowaste conversion (e.g., hydrothermal carbonisation (HTC)) is expected to support water-energy synergies in urban farms by recycling organic matter. HTC of organic waste into hydrochar is being developed, providing water-energy synergies and new absorbent media for urban farms [22]. For Japan, biomass-based carbon sequestration is expected to improve soil structure and enhances natural water infiltration and retention in farmland so as to be able to support sustainable circular practices in farmland [21].

Table 5 Comparison of new methods for adoption in Singapore and Japan

New methods for adoption	Singapore	Japan
Crop health and disease management	Photonic spectroscopy for hydroponic monitoring [13]	SWIR hyperspectral root health monitoring [14]
Low-energy farms	Solar-powered IoT irrigation systems [15]	Smart greenhouses with data-driven controls [16]
Alternative fertilizers and biostimulants	Green ammonia/hydrogen pathways [17]	Carbon-free fertilizers to reduce runoff [18]
Sensor networks, IoT and digital farming	IoT and ML-enabled smart hydroponic farms [19]	Paddy water-level sensor network [20]
Composting and growth media innovation	Biochar plus perlite mixes improve water retention [12]	Biochar amendments improve paddy water-holding [21]
Circular use of biomass and waste	Hydrothermal carbonisation (HTC) of organic waste into hydrochar [22]	Biochar recycling improves water infiltration [21]

5 Concluding remarks

Singapore and Japan face contrasting water challenges in agriculture: scarcity in Singapore and distribution in Japan. Singapore responds with ‘closed-loop’ systems like hydroponics and NEWater, while Japan relies on extensive irrigation networks that now require modernization under climate stress. Both countries show that efficiency is not only about water supply but also technology (and governance).

The new efficient water and water-related technologies from Singapore and Japan illustrate how emerging technology can shape sustainable water use in very different contexts. In Singapore’s urban farms, advances such as hydroponics, smart IoT irrigation, clean fertilizers, and biowaste recycling are intended to reduce freshwater demand and close resource loops within controlled environments. In contrast, Japan’s rural agriculture emphasizes modernizing paddy irrigation, adopting controlled-release fertilizers, and improving soil water retention; we highlighted these to show how traditional large-scale systems can be adapted to address climate pressures and resource efficiency.

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ポスト・ゴンサレス期カジェホン・デ・アメルの持続可能性と文化的意義

森口 舞

名城大学理工学部教養教育　准教授　博士（政治学）

要　旨

カジェホン・デ・アメルは，芸術家サルバドール・ゴンサレスによってハバナ市内の住宅街の一角に1990年頃から作られた，全長約100メートルの空間である。文化に対する国家の管理が強いキューバにおいても，一貫して国家から独立した形で芸術（美術，音楽，ダンス），アフリカ系宗教，社会活動を融合させた実践の場として注目に値する。ゴンサレス自身は2021年に死去しているが，その後もこのプロジェクトは継続している。このプロジェクトは，革命体制下で軽視されてきたアフリカ系の文化や宗教に，キューバの積極的アイデンティティを見出す文化的オルタナティブとして機能しており，その持続可能性は一部で観光を取り入れることによっても支えられている。本稿は，ゴンサレス亡き後のカジェホン・デ・アメルの実態やプロジェクトの目的，意義を，メンバーへのインタビューや現在の活動を踏まえて概観した上で，キューバ社会における宗教や文化の中に位置づけるものである。

The Sustainability and Cultural Significance of Callejón de Hamel in the Post-González Period

Moriguchi Mai

Division of General Education, Faculty of Science and Technology, Meijo University.

Abstract

Callejón de Hamel is an alley of approximately one hundred meters in a residential district of Havana, created by the artist Salvador González Escalona around 1990. Despite Cuba's strong tradition of state control over culture, it has consistently developed as an autonomous space where the practices of visual arts, music, dance, Afro-Cuban religions, and community-oriented social activities intersect. González passed away in 2021 by disease, yet the project has continued under new leadership, his daughter Jaqueline, maintaining its relevance both locally and internationally.

This paper examines the current state of Callejón de Hamel after González's death, focusing on its objectives and significance through interviews with members and an analysis of ongoing activities. It situates the project within the broader context of religion and culture in Cuban society, highlighting how it functions as a unique cultural alternative. In particular, this space has served as a site where Afro-Cuban cultural and religious traditions—long marginalized or dismissed under the revolutionary regime—are reclaimed as a positive source of Cuban identity.

Furthermore, Callejón de Hamel illustrates a distinctive model of sustainability. Rather than being reduced to a mere tourist attraction, it reinvests income from art sales and limited tourist-oriented services into community programs such as workshops for children, events for the elderly, and initiatives for social inclusion. Through this structure, the project demonstrates how cultural spaces can incorporate tourism without displacing local communities, ensuring both economic viability and social accessibility.

By analyzing the post-González trajectory of Callejón de Hamel, this study argues that the alley represents more than a cultural heritage site: it is an ongoing experiment in autonomy, hybridity, and cultural empowerment. It exemplifies how grassroots initiatives can create sustainable alternatives in the face of state-centered cultural policies, providing insight into the dynamic intersections of art, religion, identity, and politics in contemporary Cuba.

1. はじめに

カジェホン･デ･アメル（Callejón de Hamel）は，キューバ共和国の首都ハバナ，セントロ・ハバナ地区にある全長100メートルほどの小さな横丁である。閑静な住宅街の一角だが，その独特な空間構成と文化的活動によって，今日では国内外の観光客を引きつける象徴的な文化拠点になっている。大型観光バスが横付けされる光景は，この場所が地元住民のみならず，国際的な観光シーンでも一定の認知度を獲得していることを示している。

画像1に示したカジェホン・デ・アメルの入り口は，一般的な住宅とは明らかに異なるものであり，初見であればこれは一体何であろうと首をかしげるだろう。この横丁を芸術的，宗教的空間へと変貌させたのは，画家，壁画家・彫刻家，詩人として多彩な活動を行ったサルバ

画像 1

ドール・ゴンサレス・エスカローナ（Salvador Gonzáles Escalona）である。彼は1990年頃からこの横丁全体を自身のキャンバスとして用い，大胆な壁画やリサイクル素材を活用した立体作品を制作した。さらに，ダンスや音楽イベントを定期的に開催し，独自の空間を築き上げた。ここで重要なのは，カジェホン・デ・アメルが単なる一芸術家の実験的表現にとどまらず，アフリカ系キューバ宗教をモチーフとする芸術を通じて文化的・社会的意識を高める場となってきた点である。すなわち，これはキューバにおけるアフリカ系キューバ宗教復興運動の先駆的実践の一つとして位置づけられる。

ゴンサレスは2021年4月に病死しているが，彼の亡き後も娘のジャケリン・ゴンサレス（Jaqueline González）がリーダーとなり，活動は途絶することなく継続されている。創設者のカリスマ性に強く依存した活動が，指導者を失った後もいかに持続可能性を確保できるのかという点は，社会運動研究や文化研究において重要な問題であり，カジェホン・デ・アメルはその例を提供してもいる。

この横丁は常時公開され，誰もが自由に出入りできる。筆者が外国人観光客として訪れた際にも，常勤のメンバーが自発的に声をかけ，内部を丁寧に案内してくれた。細長い通路に足を踏み入れると，壁一面に描かれた鮮烈な色彩の壁画，宗教的シンボルを組み込んだオブジェなどが目に飛び込んでくる。さらに，ドリンクスタンドや土産物販売のスペースが設けられており，屋内の一室にはゴンサレスが国内外の著名人と撮影した記念写真が数多く貼り出されている。奥へ進むと，浴槽や椅子といった日常的な物品の廃材を再利用して制作された大型のオブジェが置かれ，公園のような広場が広がっている（画像2）。そこは同時に地域の子どもたちの遊び場でもあり，芸術と日常生活が交錯する場となっている。

画像 2

販売されるアート作品は幅広い価格帯を持つ。故ゴンサレスの大型作品は1万米ドルを超える値が付けられているが，他のメンバーの作品は比較的安価であり，小規模な作品であれば10米ドル程度で購入できる。作品に加えて書籍，DVD，人形などの土産物や外国人観光客向けの高価格帯カクテルも販売され，これらの収益がプロジェクトの財源を形成している。2023年12月時点では13名の常勤スタッフが働いており，単なる芸術空間ではなく経済的に自立したコミュニティ拠点としての性格も有している。

学術的な関心の対象として，カジェホン・デ・アメルに関する研究は未だ限られている。歴史学者ド・ラフォルカード（2017）は，美術史および宗教史の文脈にゴンサレスの活動を位置づけ，黒人研究の観点から文化的エンパワーメントの事例として分析した。一方でデイグル（2015）は，冷戦後の経済危機下におけるセックスツーリズム現象に関連づけ，この場所を「ヒネテリスモ（jineterismo）」の一事例として取り上げている。ヒネテリスモとは，スペイン語の中でもキューバ独自の語彙であり，現地住民が外国人観光客と恋愛関係または性的関係を築くことで報酬や経済的支援を得る行為を意味する。売春から街中で酒などのちょっとしたものを奢らせる程度のものまで，観光客の多いエリアで幅広く存在した。デイグルはかつてカジェホン・デ・アメルがキューバ人ヒネテロ（男性）やヒネテラ（女性）と外国人の出会いの場となっていたと述べる。だが，これは長期的な現象とは言えなかったのではないか。ヒネテリスモ

は，冷戦が終結しソ連が解体し未曽有の経済危機に陥った1990年代のキューバの特別期間において出現し，広く社会問題となった現象である。外国人観光客から得られる外貨は，例えば先進国ではベッドメイキングやポーターへのチップ程度の額が，キューバ人にとっては一日分の給料よりも高い場合もあるほどに価値が高いため，多くの女性（中には男性もいた）が安易な外貨獲得手段としてヒネテロ，ヒネテラになった（Garcia 2010）。

しかし，1990年代後半にこの事態を憂慮した政府による大規模な取り締まりが行われた結果，少なくとも表面的には大きく減少している。筆者が2023年に複数回現地を訪問した際には，カジェホン・デ・アメル内部や周辺にその様子は見られず，デイグルが目撃したという警察による監視の姿も確認できなかった。加えて，次節で述べる市民社会における役割からも，現在のカジェホン・デ・アメルを単なるヒネテリスモの場として理解することは適切ではない。ロランド（2013）もまた，黒人文化の観光資源化を論じる中で，カジェホン・デ・アメルには観光客以上に常に多くの地元住民が集っていると指摘している。

以上の先行研究を踏まえると，本稿の課題はより明確になる。すなわち，カジェホン・デ・アメルは観光や性的経済活動の文脈で語られるだけの場なのか，それとも芸術・宗教・社会活動を通じて地域社会と共鳴し，新たなアイデンティティを創出する文化的拠点なのか，という問いである。本稿では，創設者ゴンサレスの死後における同プロジェクトの実態を検討し，現代キューバ社会において担う役割と今後の方向性を明らかにする。その際，特に社会活動，宗教，芸術の三側面，さらに「キューバ性」の強調に焦点を当てることで，カジェホン・デ・アメルが持つ多層的な意義を浮き彫りにする。

2. 地域社会への貢献とソーシャルワーク活動

カジェホン・デ・アメルを支える最も重要な柱の一つが，地域に密着した社会活動である。このプロジェクトは，単なる芸術表現にとどまらず，地域住民とともに芸術を創造し，その成果を共有するコミュニティ主導の取り組みとして位置づけられている。つまり，ここでは「芸術の鑑賞」ではなく「芸術を通じた社会実践」が重視されている。こうした活動は体系的に展開され，メンバーは「社会的疎外を受けた人々や所得の低い人々に文化的機会を提供すること」を中心目的の一つとして明言している。

この社会的使命は，キューバという国家の歴史的背景を考慮すると一層明確になる。キューバは1959年の革命以来，教育・医療の無償化や社会福祉の充実を国是としてきており，比較的平等性の高い社会が維持されている。だが，その平等性は実質的には貧しさを分かち合うようなものである。つまり一方では，慢性的な物資不足や賃金の低さが人々の生活を困難にしている。とりわけ，国営部門[1)]に従事する労働者は，たとえ高度専門職者（医師や法律家など）であっても，給与が観光地の土産物屋や飲食宿泊といった観光関連産業の労働者よりも低くなることが珍しくない。その結果，多くの市民，特に外貨に直接的なアクセスを持たない国営部門の労働者は，劇場や映画館，バーに行って音楽の演奏を聴いたり，演劇を観たりといった日常的な娯楽や文化的活動に容易にはアクセスできない。国によって提供される芸術やスポーツなどの文化プログラムは存在するが，その選択肢は限定的であり，国家の方針に依存しているという制約がある。

こうした現状を背景に，カジェホン・デ・アメルは文化的活動へのアクセスを地域住民に保障する「オルタナティブな空間」として重要な役割を担っている。提供されるプログラムは多岐にわたり，曜日や週ごとに異なる活動が実施されている。具体的には以下のような活動が行われている。

毎週日曜日：ルンバ
毎月第1土曜日・第1日曜日：午前には子ども向けのワークショップ，午後にはアフリカ系LGBTコミュニティのためのプログラム
第2土曜日：ラップのアクティビティ
第4土曜日：地域企業によるフェアや，講師によるサルサ，ルンバ，アフリカンダンス
毎週木曜日：病院とも連携した高齢者を対象としたアクティビティ
毎月最終金曜日：伝統音楽の演奏

さらに，上記の定例活動に加えて，青少年を対象としたプロジェクトや，市外の地域コミュニティとの交流事業，刑務所出所者や法的問題を抱えた人々の社会復帰を支援する活動など，多面的な社会的プログラムが展開されている。英語やフランス語といった外国語，歴史を学

ぶワークショップも実施されており，教育的価値も兼ね備えている。

住宅街の中のわずか100メートルほどの横丁で，このように多彩な文化イベントが常に開催されており，これらは基本的には地元の人々が対象である。これに加えて，今後更に子供向けのダンスやレコード音楽のワークショップも行いたいとメンバーは語っていた。著者は子供ルンバのイベントの日に訪問したが，ぎっしりと細長い横町を埋めつくほどの多くの人びとが集まり，ダンスの発表用に，グループごとに揃いの衣装を着た多くの子供たちが見事なダンスを披露していた（画像3）。多くの参加者のダンスのレベルは非常に高く，熱心に練習を重ねたことは疑いない。また，イベントの有無にかかわらず，日常的に近所の子どもたちがオブジェで遊んでおり，この空間が地域住民に開かれた生活空間であることを物語っている。

画像 3

こうした活動は，観光収益を地元住民に還元する仕組みを備えている点でも注目される。観光地化が進む多くの地域では，観光客向けの高価格設定が地元住民を排除する傾向を生むが，カジェホン・デ・アメルはむしろ逆であり，観光収益をもって地域社会に還元し，文化活動を支える構造を持っている。

インタビュー調査[2)]において，常勤スタッフのエリアス・アセフ氏は次のように述べている。

> 「カジェホン・デ・アメルはコミュニティ・プロジェクトです。今日，基本的な目的のひとつは，特に社会から疎外された人々，所得の低い人々，劇場や映画館やバーに行ってルンバ・グループを聴いたり，演劇を観たり，子供向けのアクティビティを提供したりすることができない人々のためにソーシャルワークを発展させることです」。

この発言は，国家による福祉制度の限界を補完し，地域住民に自律的な文化的機会を提供するというカジェホン・デ・アメルの存在意義を端的に示している。すなわち，ここでは芸術が娯楽として消費されるのではなく，社会的包摂を実現するための実践として機能しているのである。

3. アフリカ系宗教の可視化と公共性

カジェホン・デ・アメルの活動を理解するうえで欠かせないもう一つの柱が，アフリカ系キューバ宗教の要素である。キューバにおける宗教的景観は複雑であり，カトリックを最大宗派としながらも，植民地期に奴隷として連行されたアフリカ出身者の文化的・宗教的伝統が深く刻まれている。こうしたアフリカ起源の宗教は，単なる「残存文化」ではなく，数世紀にわたり変容と融合を繰り返し，キューバ社会に固有の形態として定着してきた。

アフリカ系キューバ宗教の多くは，キリスト教との「シンクレティズム（宗教習合）」によって存続してきた。例えば，カトリックにおけるキューバの守護聖人エル・コブレの聖母はアフリカ系宗教におけるオチュンと習合されている。奴隷制時代，アフリカ系住民は支配者である白人の監視を逃れるため，キリスト教の聖人に自らの神々を重ね合わせるなどして，表面的にはキリスト教を装いながら，実際にはアフリカ的世界観を保持したのである。また，ルーツとなる言語やアフリカにおける地域も様々で極めて多様だが，これらは必ずしもそれぞれに独立した別個の宗教ではなく，しばしば重複し混淆している。つまりは，アフリカにおいて体系化されていた宗教がそのままカリブに持ち込まれたものではなく，カリブで発展し現在の形に至っているといえる。キリスト教にしても，アメリカ大陸に渡る前の時点で，アフリカで既にキリスト教が取り込まれていたからではない。

キューバで代表的なアフリカ系宗教は，サンテリア，パロ・モンテ，アバクア，そしてアララである。カジェホン・デ・アメルは，プロジェクト初期には明確に宗教性はないもの，アフリカ文化にインスパイアされたものが作られていた。現在はアフリカにルーツのあるこれら4つの宗教に基づいて空間が作られ，これらの世界観に根差すアートやメッセージ，オブジェが通りのあらゆるスペースを埋め尽くしている。

歴史的にキューバを含むカリブ諸国におけるアフリカ

系宗教は，尊重されず，弾圧や迫害の対象となってきた。カリブにはアフリカ人の子孫である黒人や黒人を含む混血の人口が多い。キューバでは人口の約25％が黒人，また黒人の血を引く混血を含めれば，人口の半数を大きく超える。その他のカリブ諸国では，黒人が約92％と圧倒的多数を占めるジャマイカのような国や，奴隷制廃止後に労働力としてカリブに来たインド系の人々とアフリカ系黒人が人口を二分するトリニダード・トバゴのような国といった人口構成が多い。このような黒人系人口の比率の高さにもかかわらず，アフリカ系宗教は，植民地時代には魔術や呪術などとしてカリブ全域で弾圧あるいは差別されていた。その主たる目的は，奴隷反乱の精神的支柱となり得るものを奪うことであった。奴隷制廃止後もアフリカ系宗教への法規制や差別は現在に至るまでなくなってはおらず，そうした否定的見方の根拠とされがちなのが，キリスト教のあり方を宗教の定型としたかのような宗教観である。例えば聖典を有すること，超自然的な力を利用する実践がないことなどを宗教の定義として，アフリカ系宗教を「宗教ではない」として信教の自由の枠外に置き，法的に禁じた。むろん，こうした定義はアジアなど非キリスト教圏における宗教観とも相いれないだけではなく，現在の学術的な宗教の定義とも合致しない非合理的なものといえる。

カリブのアフリカ系宗教で最も知られているのはハイチのブードゥであろう。映画などのモチーフとなって世界中に知られるようになったが，それは決して好ましいイメージを伴うものではなかった。魔術や悪魔崇拝，ゾンビなどと結びつけられ，娯楽メディアを通じてネガティブなイメージが拡散した。1980年代以降，いくつかの国でこうしたアフリカ系宗教，特にキリスト教との融合のない「呪術」とのレッテルを貼られた宗教でも非犯罪化が進んだが，ジャマイカなど未だ多くの国では，現在もこの禁止法は，形骸化しつつも維持されている（森口 2023）。

キューバにおいては，1959年の革命後には国家が「無神論国家」を標榜し，カトリックさえも含めた宗教活動は抑制された。宗教への態度が大きく変わったのは1992年の憲法改正であり，ここで初めて宗教差別の禁止が明記された。しかし，それ以前の数十年間，カトリックさえも制約を受ける状況の中で，アフリカ系宗教はさらに強い周縁化を強いられていた。グティエレス（2024）は，キューバの文化遺産政策が「植民者の視点」に基づき，黒人奴隷制の歴史を抹消し，アフリカ系キューバ文化を観光演出の中で従属的に扱ってきたと批判している。つまり，革命政権は人種平等を掲げながらも，実際にはアフリカ的要素を「不都合な歴史」として後景化していたのである。

しかしながら，アフリカ系宗教は他のカリブ諸国ももちろん，キューバにおいても人々の日常に根付き，親しまれている。人々は何か困ったことや悩みがあれば占いや超自然的な力を求めてこうしたアフリカ系宗教の司祭などを頼り，それは何も，アフリカ系宗教といえばイメージされがちな，相対的に貧しい黒人市民に限られなかった。白人や富裕層も当然のようにそこに含まれ，地区を問わず，年寄りたちは，昔は金持ちや上流の人々もよくブルヘリーア（呪術）を行っていたという（Menendez 2002）。司祭になることさえ黒人であることは条件ではなく，日本人の文学研究者がサンテリアの司祭になった例すらある（越川 2022）。「［ハバナ：筆者註］市内で，その根元に『怪しげな』包みが置かれていないセイバの木は珍しい」（Menéndez 2002）と報告されているように，サンテリアをはじめとするアフリカ系宗教において神聖な存在とされるセイバの木には必ずといっていいほど供え物などが置かれているというほど，アフリカ系宗教の実践は日常の風景であった。また，「学者たちは［筆者註：キューバ人の］75％の人々が『拡散的宗教』を実践していると結論付けた」というアセフ氏の証言もある。拡散的宗教とはつまり，複数の宗教を同時に信仰する，あるいは宗教の境界が曖昧な信仰の形であり，この場合は，アフリカ系宗教とキューバ最大の宗教であるカトリックや，あるいはプロテスタントの信仰が，キューバにおいては必ずしも排他的ではないことを意味する。カトリックの信者を自認する人が，時にサンテリアなどのアフリカ系宗教を実践することは，カトリックの教義上はともかく，キューバを含むカリブ諸国の実態としては日常の光景なのである。

ただし，こうした広範な実践にもかかわらず，アフリカ系宗教に対する否定的なイメージは依然として存在した。アフリカ系子孫の市民の間にさえ，占いや魔術のようなものに対する強い拒否感が存在し，それらとキリスト教，キリスト教徒であることとを対比させ，キリスト教徒であることを文明人であることを同一視する言説は，しばしばカリブ社会においてみられるものである。この点において，アフリカ系宗教はしばしば「未開」「迷信」といったスティグマと結びつけられてきた。

このような社会的状況の中で，ゴンサレスはアフリカ

系キューバ宗教を芸術の枠組みで可視化し，正当化する空間を創出した。彼の作品群は，芸術と宗教の境界を越境し，両者を不可分のものとして提示した点に意義がある。アセフ氏はこれがカジェホン・デ・アメルの基本的目的であると語っている。つまりは，「このプロジェクトは，アフリカの精神性における一貫した特徴を再確認した。それは，それまで革命文化によって事実上無視されてきたものであり――すなわち，芸術･社会的なもの･神聖なもののあいだに境界が存在しないということである（Laforcade 2017: 224）」。

さらに，カジェホン・デ・アメルにおける宗教性は，伝統を単に保存するのではなく，現代的価値観に即して再構築されている。サンテリアの秘儀を公開形式で行うこと，女性の役割を拡張すること，人種やジェンダーに関わる平等性を強調することなどは，従来の宗教実践に挑戦する革新的要素である（Laforcade 2017）。これは単なる「伝統の保存」ではなく，アフリカ系キューバ宗教を現代社会に適合させ，新たな意義を与える営みといえる。

総じて，カジェホン・デ・アメルはアフリカ系キューバ宗教を抑圧から解放し，芸術を媒介にして社会的・文化的に正当化する場である。その空間は，宗教的周縁化に対する抵抗であると同時に，地域社会における文化的包摂と教育的啓蒙を担う，きわめて独自性の高い実践である。

芸術表現と国家・社会との関係

カジェホン・デ・アメルにおける第三の柱は，芸術活動である。創設者サルバドール・ゴンサレスは，絵画や壁画にとどまらず，彫刻，詩，さらには空間全体を統合する総合芸術的実践を展開した。彼の作品はアフリカ的伝統を基盤としながらも，同時にキューバ固有の文化的現実を反映しており，国家によって制度化されたアカデミック・アートとも呼ばれる「公的芸術」に対するオルタナティブな表現として位置づけられる。

革命後のキューバにおいて芸術は国家の管理下に置かれ，体制を支持する表現が奨励された一方で，体制に批判的あるいは単に逸脱的と見なされる表現も制約を受けてきた。とりわけアフリカ系文化に根ざした芸術は，欧米由来の芸術に比べ軽視される傾向が強く，黒人系市民が芸術分野で活躍するには多くの障壁が存在した。音楽においても同様で，アフリカ系音楽は社会的評価が低く，音楽家として成功するためには資金や人脈といった資本に恵まれなければならなかった（Weener 2022）。

ゴンサレスの芸術はまた，宗教的要素を強く帯びていた。壁画やオブジェに描かれるのは，サンテリアの神々やアフリカ起源の精霊，あるいは宗教的世界観に根ざしたシンボルである。しかし，ド･ラフォルカード（2017）が指摘するように，それは「宗教を芸術の主題とする」というよりも，「宗教的概念を芸術的媒体として利用する」ものであった。つまり，彼にとって宗教は信仰実践そのものではなく，文化的アイデンティティを表現するための象徴的手段であったといえよう。

この点でカジェホン・デ・アメルの芸術は，国家が管理する公式的な文化政策に対する抵抗の意味を持っていた。キューバにおける芸術は，支援や検閲を通じてあるべき形が示されつつも，1990年代後半から2000年代初頭にかけては，国家と芸術家の「理解」と「交渉」を通じて公的芸術が再興したとされる。特にソ連崩壊後のキューバの深刻な経済危機下で，芸術活動を続けるための材料などへのアクセスの困難さは，その状況を後押しした。（Fernandes 2006: ch.4.）しかし，ゴンサレスはこうした動きに組み込まれることを拒み，あくまで自律的な立場を堅持したのである。彼の芸術は「文化的シマロニエ」（LaForcade 2017），すなわち支配的社会構造から逃れ，新たなアイデンティティを構築する逃亡奴隷の姿勢になぞらえられている。

ただし，ゴンサレスと国家の関係は単純な敵対関係ではなかった。カジェホン・デ・アメル内部には彼が国内外の著名人と撮影した写真が掲示されており，その中にはキューバの文化大臣との写真も含まれている。つまり，彼は国家と一定の接触を保ちながらも，国家の影響下に従属することを避ける独立的な立場を選択していた。これは，国家と芸術家の関係が「対立」か「従属」の二項対立に収まらないことを示す好例である。

さらに注目すべきは，芸術活動が経済的持続可能性とも結びついている点である。アート作品の販売や観光客向け商品の提供は，プロジェクトを支える収益源であると同時に，芸術そのものを地域経済に接続する回路を形成している。これは芸術を「国家の補助金」に依存させるのではなく，「地域の創造性と観光経済」の間で循環させる仕組みであり，キューバにおける独立系芸術活動の可能性を示す実践といえる。

つまりまとめると，カジェホン・デ・アメルは，上述

の通り観光客へのアート作品等の販売収益で活動を成り立たせており，経済的に国家から自立している。これはもちろん，補助金を得られないからではなく，意図的なものである。芸術分野においても経済的に保障される代わりに国家が介入する社会主義国家キューバでは，こうした形は芸術プロジェクトのあり方として一般的ではない。

総じて，カジェホン・デ・アメルにおける芸術は，国家の文化政策への従属を拒否しつつ，宗教的象徴と結びついた独自の美学を展開したものである。それは単なる美術表現を超え，政治的・経済的文脈における抵抗と自律の実践であり，同時に地域社会に文化的誇りと経済的利益をもたらす持続可能な仕組みとして機能しているのである。

4. キューバ性と混血性

そして，二点目と三点目に関して誤解が生じやすいものの，プロジェクトにとって重要なのが「キューバ性」の重視と強調である。筆者は本稿を通して一貫して，カジェホン・デ・アメルにおける宗教を「アフリカ宗教」ではなく「アフリカ系宗教」と表現してきた。これは，彼らにとってそれがアフリカの宗教ではなく，あくまでキューバの宗教であることを示すためである。実際，アセフ氏（2023）も筆者のインタビューにおいて「アフリカの宗教ではない。アフリカに起源を持つキューバ宗教である」と強調していた。彼らの基本姿勢は，アフリカ起源の要素を尊重しながらも，アイデンティティをアフリカそのものに求めるのではなく，混血性や文化的習合に基づくキューバ独自のものとして位置づける点にある。

加えて，彼らは「一見黒人に見えても，白人に見えても，キューバ人のほとんどは混血だ」と語る。混血性にアイデンティティを見出すことはラテンアメリカでは比較的一般的である。数百年にわたる混血の歴史を経てきたキューバをはじめとするラテンアメリカ諸国では，人種的な区分は容易ではない。ここで重要なのは，全ての人々が実際に混血であるかどうかではなく，混血であることに象徴的な意味を見出している点である。たとえ見た目が「純血」に見えたとしても，“私たちは混血なのだ”と信じることに価値が置かれる。例えばアセフ氏は筆者から見ると白人に見えたが，曽祖父が黒人だったと語っていた。彼の髪は細かく縮らせて丸く膨らませた，いわゆるアフロヘアーであったが，人工的に髪を縮らせたのかもしれない。つまり，一見するときわめてアフリカ的な文化表象に見えるカジェホン・デ・アメルも，黒人だけのものではないのである[3)]。

「この場所の基本的な目的は，キューバ人のアフリカ起源の伝統を視覚化し，正当化し，教えることです。このカジェホン・デ・アメルという場所は，キューバで実践されているアフリカ起源のさまざまな宗教に触発された道徳と彫刻の最初の複合施設です」。アセフ氏がこう述べるように，三つの柱を基盤とするカジェホン・デ・アメルは，音楽やダンスといった人々が楽しむ活動を通じて，自然にアフリカルーツの宗教を知り，親しむ場となっている。約100メートルにわたる通りを埋め尽くす壁画やオブジェには宗教的な意味が込められており，地元の子どもたちはその中で遊ぶ。宗教を教科書で学ぶのではなく，日常的に，あるいは娯楽の場で触れ，体験するのである。「この音楽やダンスは，この精霊に捧げる」など，宗教的意味を持つ形で行われることもある。こうした営みこそがカジェホン・デ・アメルの目的であり，文化の観光化ではなく，観光と共存し外貨を得ることで持続可能性を担保しているのである。

既に述べたように，大型バスで外国人観光客が訪れることもあるが，それはカジェホン・デ・アメルの日常ではない。先行研究でも指摘されるように（Roland 2013: 413），大部分の時間は地元住民のために存在している。観光客は時折訪れ，アクティビティを見学し，アートや土産物，ドリンクを購入して短時間で去っていく。その現実的な位置づけは，次のアセフ氏の言葉に端的に表れている。「観光は私たちの持続性のために必要です。もし観光がなかったら，自分たちの生活を維持することはできないでしょう。芸術は一日中売れるものではありませんから」。

これまで述べてきた通り，創設者でありリーダーであったゴンサレスの死後も，プロジェクトは活発に継続されている。先行研究の多くはゴンサレスの役割やカリスマ性に注目してきたが，カジェホン・デ・アメルは観光との共存や地元住民からの受容を通じて，このように持続可能な形を獲得しているといえる。実際，筆者がハバナ市内でさまざまな職業・立場・年齢の人々にカジェホン・デ・アメルについて尋ねたところ，認知度は高く，全員が訪れた経験を持つか，少なくともその存在を知っていた。また否定的な感情を持つと答えた人は一人もいなかった。

5. むすびにかえて

以上の分析から，カジェホン･デ･アメルは単なる「文化を観光資源として消費する場」ではなく，キューバにおける独自の文化的オルタナティブを体現する，多層的なプロジェクトであることが明らかとなった。このプロジェクトは，国家の公式的・伝統的な宗教や人種，芸術体系から一定の独立性を保ちながら，アフリカに深く根ざすルーツを基盤にしたキューバのオルタナティブ・アイデンティティを表現し，持続可能な形で地域社会及び国際社会に向けて発信している。さらに，地域への文化的・社会的貢献を積極的に行うことで，参加者や訪問者に対して単なる娯楽ではなく，学びや気づきを伴う体験を提供している点も重要である。

一方で，現行の社会主義体制下において，芸術や表現活動が完全に自由であるとは言えない現実も存在する。キューバでは芸術などの文化は「社会関係の表現として，芸術的表現から，古い結びつきの解体と新しい社会的･権力的関係の構築を反映することを求められている。それは革命的ヘゲモニーを支え，新たな国民文化を創造するものである（Álvarez, 2010）」とされる。これは，「革命の内部であればすべてを許す。しかし革命に反するものは何も許さない（Castro, 1961）」を示唆しているようにも受け取れる。キューバでは原則として芸術は国営の管理下に置かれており，特に近年では，2019年に施行された法令349が，芸術活動やその契約などについて定めている。国家から独立した芸術活動や契約が事実上違反とされたこと，望ましくないとされる内容を違反としたことから，国家による芸術への介入が懸念され芸術家の間に反発と警戒を呼んだ（Weener 2022; Gonzales 2023）。後者に関しては恣意的な解釈が可能となることも批判の対象となっている（Martinez 2020）。たとえば，2021年に発表され社会的注目を集めた楽曲“Patria y Vida（祖国と生と）”は，革命のスローガン“Patria o Muerte（祖国か死か）”に対する批判的な皮肉を込めたものであり，この楽曲に関わったキューバ在住のミュージシャン，マイケル・オソルボ（Maykel Osorbo）氏は公共秩序紊乱の罪で起訴され，実刑判決を受けた。この事例は，国家による芸術活動への介入の象徴的事例として広く注目されており，キューバにおける芸術活動の制限に関する象徴的な事例である。

しかしながら，こうした制約の存在にもかかわらず，カジェホン・デ・アメルのような独立系の芸術活動が確実に存在していることは注目に値する。本稿で示した事例は，キューバの芸術状況が単純に「国家による統制」か「完全自由」かという二元論では捉えきれない複雑さを有していることを示しており，芸術の現場における主体性や創造性の可能性を明確に浮かび上がらせている。さらに，このプロジェクトは地域社会や訪問者に対して具体的な影響を与え続けており，文化的アイデンティティの再構築や教育的価値，さらには観光との適度な接点を通じた経済的循環にまで寄与している点でも，単なる「観光目的の文化提供」とは一線を画す存在である。

総じて，カジェホン・デ・アメルは，国家の制約下でも独自性を保持しながら文化的・社会的価値を創出しうる，キューバ芸術の多面的な可能性を示す重要な事例である。制約の中にあっても表現の幅を追求し，地域と世界に影響を及ぼすこのプロジェクトは，今後のキューバ文化研究のみならず，グローバルな文化政策や芸術実践の議論においても示唆に富む存在であると言えるだろう。

注

1）国営部門とは，日本などの自由主義経済の国々で想定される公務員の位置づけとは全く異なる。近年では拡大されているとはいえ，キューバでは依然として部門や規模，経営に様々な制限が課せられた，限られた民営部門を除いて多くの企業が国営となっている。

2）2023年12月にカジェホン・デ・アメル内にて，常勤メンバーであるエリアス・アセフ（Elias Aseff）氏に対し筆者が実施した。

3）付記しておくと，キューバには米国のいわゆるワンドロップルールという考え方はない。周知のとおりこれは，一滴でも黒人の血が入っていれば黒人とみなすという考え方である。

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ガックフルーツ粉末の給与がコオロギの成長，成分および カロテノイド蓄積に及ぼす影響

林義明[1)]，本田真己[2)]，Pawat Seritrakul[3)]，Krissana Ruang-Rit[3)]，Pattaraporn Poommarin[3)]

1）名城大学農学部
2）名城大学理工学部
3）Silpakorn University, Faculty of Animal Sciences and Agricultural Technology

要旨

近年，新たなタンパク質源として昆虫が注目され，高付加価値化が求められる。そこで，飼料にカロテノイドを含むガックフルーツ粉末（GF）を添加し，コオロギ（HC）の成長と成分，リコピン（Lyc）とβ-カロテン（BC）の蓄積に及ぼす影響を調べた。基礎飼料のT1区，基礎飼料にGFを2.5％または5.0％含むT2区またはT3区を設定した。孵化2日後のHCを飼料上に静置し，孵化7日後から体重測定した。孵化52日後にHCを絶食，絶命後，凍結乾燥して未脱脂で粉砕した。飼料とHCでの成分，LycとBCの含量およびシス異性体比率を測定した。区間の体重と成分に有意差はなかった。LycとBCの含量はT3が最高，T1が最低であった。シス異性体比率はT2とT3間で差はないが，飼料に比べてHCのLycは高く，BCは低かった。GF給与はHCの成長と成分に悪影響なく，LycとBCを蓄積させ，そのシス異性体比率の変化により高付加価値化の可能性が示された。

キーワード：カロテノイド，コオロギ，ガックフルーツ，成長，シス異性体

Effects of gac fruit powder feeding on growth, chemical composition and carotenoid accumulation of crickets

Yoshiaki Hayashi[1)]，Masaki Honda[2)]，Seritrakul Pawat[3)]，Ruang-Rit Krissana[3)]，
Poommarin Pattaraporn[3)]

1）Faculty of Agriculture, Meijo University
2）Faculty of Science and Technology, Meijo University
3）Faculty of Animal Sciences and Agricultural Technology, Silpakorn University

Abstract

Insects have recently gained attention as a new protein resource, with a demand for higher value-added products. Therefore, the effects of supplemental gac fruit powder (GF), which contains carotenoids, feeding on the growth and composition of crickets were investigated, as well as the accumulation of lycopene (Lyc) and β-carotene (BC). Basic feed was used in T1, while T2 or T3 contained basic feed supplemented with 2.5% or 5.0% GF. Crickets were placed on the feed two days after hatching, and bodyweight was periodically measured after seven days post-hatching. After 52 days of incubation, the crickets were starved, euthanized, freeze-dried, and pulverized without defatting. The composition, the Lyc and BC content, and the *Z*-isomer ratio in feed and crickets were measured. No significant differences in bodyweight and composition among the groups were found. Cricket's Lyc and BC content was highest in T3 and lowest in T1. The *Z*-isomer ratio showed no difference between T2 and T3, though crickets had higher Lyc and lower BC than the feed. GF feeding did not adversely affect growth and composition in crickets. However, crickets accumulated Lyc and BC, and had potential for higher value-added production through changes in *Z*-isomer ratios.

Keywords：carotenoid, cricket, gac fruit, growth, *Z*-isomer

はじめに

世界における今後の人口増加と経済発展による需要増加に対応して，2051年から2060年の平均の世界での主要作物（小麦，米，トウモロコシ，大豆）の生産量は2011年から2020年の平均（基準年）に比べて1.4倍，主要肉類（牛肉，豚肉，鳥肉）では基準年の1.5倍と予測されている[1)]。その中で近年，食料増産に向けた食用や飼料用のタンパク質源として昆虫が注目されている[2)]。昆虫は従来のタンパク質源と代替可能とされ，動物の腸内環境改善や免疫賦活化の可能性が示されている[3)]。様々な昆虫の中でもヨーロッパイエコオロギ（House cricket, *Acheta domesticus*, HC）は既に食用等として世

界的に利用されており，植物性の飼料で飼育可能であり，産卵数が多い等の優れた能力を持ち，発育が良いことが報告されている[4,5]。一方，昆虫がタンパク質源として社会に受容されるためには，その利用が持続的かつ高付加価値であることが求められる。その中，一部の昆虫は飼料に含むカロテノイドを体内蓄積することが報告されている[6,7]。カロテノイドは人間や動物の健康増進や疾病予防への有効性が指摘されており，熱帯果物等の農産物に多く含まれる。しかし，これらの農産物の加工時にはカロテノイドを含む果皮等が大量廃棄され，カロテノイド源の有効活用や環境負荷の低減が求められている。そこで，廃棄される天然物由来のカロテノイドをアップサイクルにより昆虫に蓄積し，その昆虫をタンパク質源のみならず，カロテノイド源とすることで安価かつ有益な食料や飼料の開発が可能と考えられる。カロテノイド分子内には共役二重結合が存在し，通常，植物体内では全ての二重結合がトランス型のトランス異性体が優勢であるが，動物体内では一部の二重結合がシス型に異性化したシス異性体が豊富に存在し，体内吸収性が高いとされる。ヒトでは一部のカロテノイドでトランス異性体よりシス異性体での高い抗酸化活性が示され，異性体比率の評価が求められている。

そこで本研究では，農産物加工において廃棄される果皮等をHCの飼料として利用することを想定して，トマトの約8倍のLycやニンジンの約5倍のβ-カロテン（BC）を有する[8] 熱帯果物ガックフルーツ（GF）の粉末をHC用飼料に添加し，その給与がHCの成長，成分，体内蓄積するカロテノイドの含量と異性体比率に及ぼす影響を食用昆虫の生産が盛んなタイにおいて実施した。

材料および方法

持続的に利用可能な昆虫としてタイ国内で流通するHCを選定し，その飼料添加物としてGF粉末を用いた。タイ国内で市販されるブロイラー用飼料（粗タンパク質：18%，代謝エネルギー：2800 kcal/kg）を基礎飼料として，無添加給与のT1区，基礎飼料にGF粉末を2.5%または5.0%含む飼料給与のT2区またはT3区を5反復で設定した。タイ西部Phetchaburi, Cha-amに所在するFaculty of Animal Sciences and Agricultural Technology, Silpakorn Universityにおいて，各区の飼料を含む箱（47.5 cm×98.5 cm×46.5 cm）内に紙製卵トレイを設置したうえで，孵化2日後のHC約1万頭を各区の飼料35 gと共に収容し，試験開始8日後，13日後，17日後に各区の飼料を50 gずつ追加した。その後，試験開始45日まで7日毎に各区の飼料を1 kgずつ追加した。孵化7日後から定期的に無作為に選んだHC30頭の体重を測定した。孵化52日後にHCを24時間絶食した後，絶命させた。HC試料は凍結乾燥後に未脱脂で粉砕した。HC中の一般成分（乾物，粗タンパク質，粗脂肪，粗灰分）を定法[9] にて，LycとBCの含量およびシス異性体比率を順相高速液体クロマトグラフィーにて測定した[10,11]。試験結果の統計処理は一元配置の分散分析を行った。有意性が認められた結果は，Tukeyの多重比較検定により試験区間または測定日間の有意差を検討した。検定の有意水準は5%とした。

結果および考察

孵化52日後までの各区のHC1頭当たりの体重を図1に示す。各測定日におけるHCの体重で試験区間に有意差はなかった。測定日間のHCの体重においては，孵化28日後から有意に増加し，孵化35日後には1頭当たり100 mgを超え，孵化52日後には1頭当たりの体重が400 mg前後となった。HC1頭当たりの体重は成熟時の大きさによって多様であり，乾物で約200 mgともされる[12]。HCの成分を表1に示した。乾物，粗タンパク質，

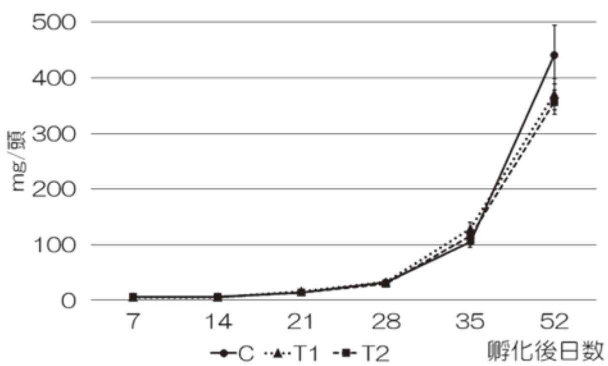

図 1.　コオロギの体重

表 1.　コオロギの成分（%）

	T1	T2	T3	SEM	P値
乾物	29.2	28.4	29.8	1.9	0.536
粗タンパク質†	70.1	68.9	70.9	1.9	0.329
粗脂肪†	21.2	19.9	21.1	2.6	0.753
粗灰分†	6.1	6.5	6.7	0.7	0.555

†乾物当たり. SEM: Standard error of the mean.

粗脂肪，粗灰分ともに試験区間に有意差はなかった。得られた乾物含有率から算出すると本試験におけるHC1頭当たりの体重は乾物当たり117 mg程度となった。粗タンパク質や粗灰分の含有率は既報[13,14]と同等であったが，粗脂肪含有率は約10％高値であり，試験に用いたHCの種類や飼料の違いによる可能性が考えられた。HCと飼料のLycとBCの含量を図2に示した。T1区のHCからLycは検出されないものの，BCは微量に検出された。いずれのカロテノイド共にHCでの含量はT3区が最高，T1区が最低であった（P<0.05）。飼料と比較した場合，HCではLyc含量が低いが，BC含量は高く，異なるカロテノイドにおけるHCでの蓄積量の違いが示された。HCと飼料でのカロテノイドのシス異性体比率を図3に示した。HCのシス異性体比率は飼料に比べてLycが高い一方，BCは低かった。HCにおける異なるカロテノイドの利用性または代謝の相違が示唆された。

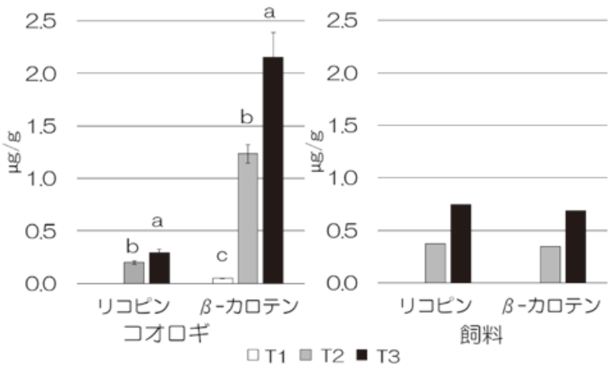

図 2. コオロギと飼料でのカロテノイド含量
[abc] 各項目における異符号間に有意差あり（P<0.05）

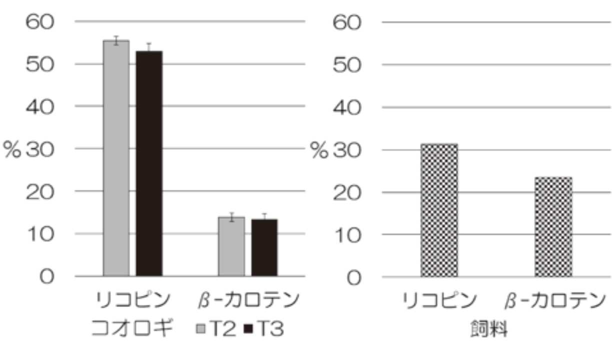

図 3. コオロギと飼料でのカロテノイドのシス異性体比率

今後はHCへのカロテノイド蓄積量の増加に向けた方策や，食料や飼料としての適切な生産方法の検討が必要である。

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「名城インターナショナル研究」投稿規則

１．投稿資格

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〒468-8502　愛知県天白区塩釜口1-501
TEL:052-838-2529 FAX:052-832-1410
ホームページアドレス：https://marc.meijo-u.ac.jp/

Meijo International Education and Research Center
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1-501 Shiogamaguchi, Tempaku-ku, Nagoya 468-8502 JAPAN
TEL:+81-52-838-2529 FAX:+81-52-832-1410
https://marc.meijo-u.ac.jp/

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