KINGS 한국전력국제원자력대학원대학교
KEPCO INTERNATIONAL NUCLEAR GRADUATE SCHOOL

Climate Resilience of a Large PWR versus an Integral SMR at a Tropical Marine Site : The Role of Regulatory Discharge-Limit Form

Rachman Bagus Sujiatmoko & Hak-kyu Lim

Department of NPP Engineering, KEPCO International Nuclear Graduate School (KINGS)

rachman.bagus@kings.ac.kr · hklim@kings.ac.kr

2026 KNS Autumn Meeting | 26A-555

INTRODUCTION

Site Context: A Thin Thermal Margin Under the Constructed Limit

Under the limit constructed here (T_base + 5 °C), this site starts with a narrow thermal margin — a constraint from *day one*, not only under future warming.

1 Established literature: margin as buffer

Temperate, river-cooled plants: the intake water is usually well below the discharge limit. **In the studies we found, the limit restricts power mainly during heatwaves, not all year.**

2 This site: no buffer, even at baseline

At today's intake (29.17 °C), the limit (+5 °C) lets the cooling water warm by only 5 °C. At full power the APR1400 warms it by 10 °C, so it can run at about half power (5/10); the ACP100 (8 °C) at 62.5 % (5/8).

This shrunken margin — not a categorical or ecological difference — is why temperate-fleet findings cannot be extrapolated directly to this site.

In the Indonesian rules we reviewed there is no thermal-discharge standard written for nuclear plants: Permen LH 08/2009 caps discharge at 40 °C but does not list nuclear plants.

Motivation & Research Gap

A warmer intake lowers turbine output through condenser pressure and, where a discharge-temperature limit applies, can force a larger derating before that thermodynamic loss matters.

1 Gap in the literature

Temperate, river-cooled fleets: in the studies we found, outages occur mainly during extreme events such as heatwaves — but these studies cover river-cooled plants only and do not examine tropical equatorial sites, where the intake baseline may already sit close to the discharge ceiling.

2 Gap in Indonesian regulation

In the Indonesian regulations we reviewed there is no thermal-discharge standard specific to NPPs — only general marine water-quality rules, a power-plant effluent cap not calibrated to receiving-water conditions, and an overarching environmental framework.

With no standard, there is nothing to test the plant against. So this study first builds a limit from existing rules: a model input, not a proposed standard.

This study addresses both gaps at one coastal site: the Karimata Strait coast of West Kalimantan, Borneo, about 1° south of the equator.

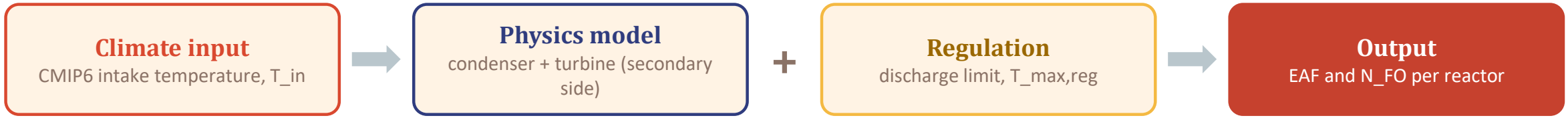
Purpose & Approach, at a Glance

PURPOSE

Compare how warming seawater limits operability, here the share of rated power a unit can deliver ("climate resilience"), of two condenser-cooling archetypes: a large PWR **(APR1400, 1,400 MWe)** and an integral SMR **(ACP100, 125 MWe)**, at a tropical marine site in West Kalimantan, under a discharge-temperature limit that must first be **constructed**, since no NPP-specific standard was found.
Not assessed: grid stability, demand growth, economics, or which reactor Indonesia should build.

APPROACH

Use projected seawater intake temperature **(CMIP6, 2025–2060)** to compute two power limits for each reactor, one **thermodynamic** and one **regulatory**; the lower one applies. Report the average share of rated power (EAF) and the months per year below a minimum-power floor (N_FO). Then test whether the type of limit (fixed ceiling or allowed rise), not only its value, changes the result.



Three limitations *are flagged where they matter and summarised on slide 21: an estimated ACP100 design value, fixed cooling-water flow, and one climate model.*

Case Selection and Analysis Window

Two design choices frame the comparison, and neither depends on the government's nuclear plan.

1 Why APR1400 and ACP100

- **Two condenser-cooling archetypes, not candidates in a build plan:** a large loop PWR (APR1400, 1,400 MWe) and an integral SMR (ACP100, 125 MWe). The choice does not depend on Indonesia's nuclear plan.
- **Size does not enter the comparison:** results are fractions of each unit's own rated power; what differs is the condenser design (ΔT_cool 10 vs an estimated 8 °C).
- **A published reference for the large unit:** APR1400 shares its design family with Barakah (UAE, 4 × APR1400); the +5 °C allowance is the value Kim & Jeong (2013) report for a Gulf NPP (UAE), and the model check (slide 10) uses their published APR1400 model result, not plant data.

2 Why 2025–2060

- **An analysis window, not a plant lifetime:** 2025–2060 follows the national planning horizon (RUKN 2025), not a build schedule.
- **After 2060:** further warming lowers both units and narrows the gap; the ACP100 stays ahead as long as its ΔT_cool stays below the APR1400's. Not computed here (backup slide 28).

Preview of the result: at the constructed limit, the discharge rule, not thermodynamics, sets how much power each unit can deliver. Thermodynamics matters only under a much looser limit, such as 40 °C (see Results).

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

Key Definitions

Every symbol used in this talk is defined here first.

$T_{in}(t)$	Seawater intake temperature at the condenser (time-varying, °C); baseline T_base = 29.17 °C (OISST climatology)
ΔT_{cool}	Design cooling-water temperature rise across the condenser
TTD	Terminal temperature difference (condensing steam vs. cooling-water outlet)
T_{sat}	Condenser saturation temperature = T_in + ΔT_cool + TTD — sets back-pressure
f_{thermo}	Thermodynamic power fraction — limited by condenser back-pressure
f_{reg}	Regulatory power fraction — limited by the discharge-temperature standard
$H(t)$	Headroom (author's term) = T_max,reg − T_in(t): how many degrees the cooling water is allowed to warm before the discharge reaches the limit
f_{allow}	Allowable power fraction = min[f_reg, f_thermo, 1.0] — the binding limit
$f_{min,tech}$	Technical floor (assumed 0.40 of rated power): below it the unit is treated as not operable
EAF	Energy Availability Factor, as used here — the window-mean f_allow over 2025–2060; climate- and limit-constrained only, not the IAEA-PRIS plant definition
N_{FO}	Months per year with f_allow below the technical floor (treated as not operable)

Research Objectives

i **Quantify:** the Energy Availability Factor (EAF) and months per year below the technical floor (N_FO) of both reactors under a constructed discharge limit, 2025–2060.

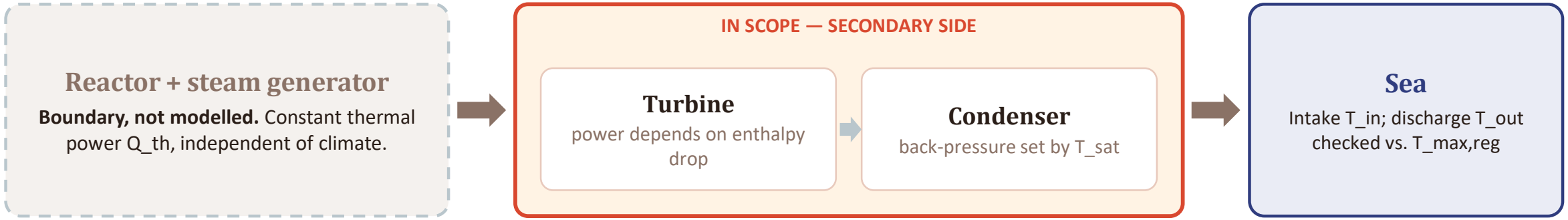
ii **Determine:** which constraint governs projected availability at this site — the regulatory fraction f_reg or the thermodynamic fraction f_thermo — at the baseline limit, and as the limit level changes.

iii **Test:** whether the discharge limit's functional form — not just its numerical level — changes the projected outcome.

METHODOLOGY

Model Scope: Secondary Side Only (Turbine and Condenser)

Only the part of the plant that **responds to sea temperature** is modelled; the rest is a fixed boundary.



What the model includes

- Condenser energy balance and saturation temperature
- Steam properties (IAPWS-IF97) and isentropic turbine enthalpy drop
- Discharge-temperature limit at the condenser outlet
- Monthly sea-temperature projection, 2025–2060

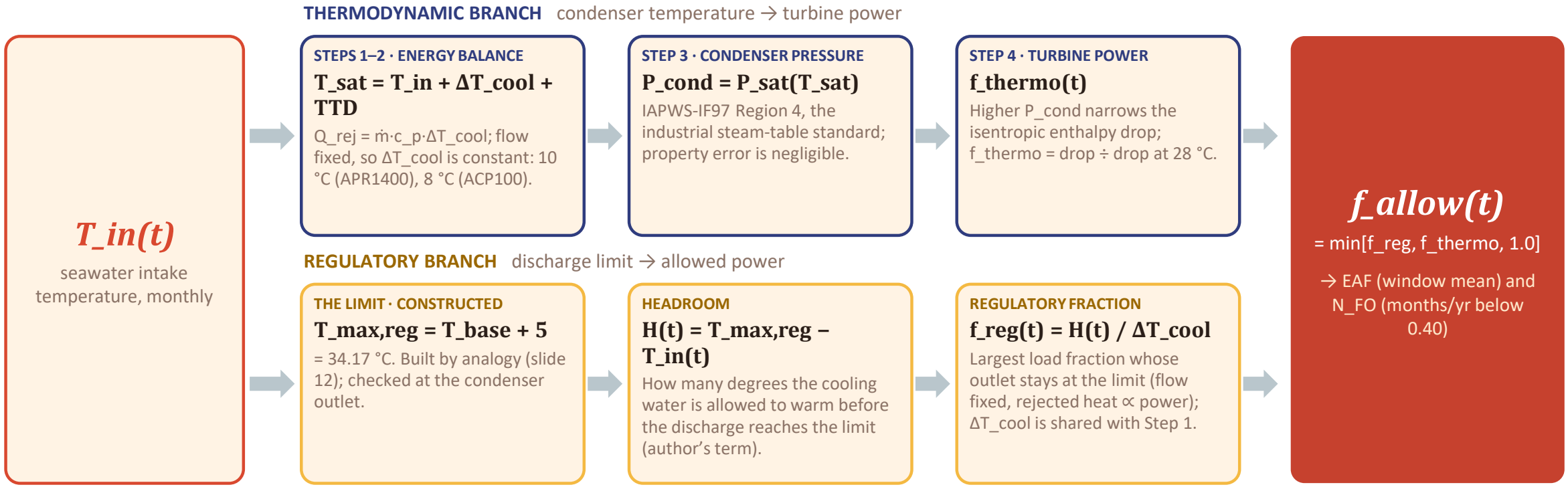
What it deliberately excludes

- Reactor core, primary loop, steam-generator performance
- Feedwater-heater train and individual turbine-stage losses
- Pump and intake hydraulics; flow adaptation (bounded, not modelled: slide 21)
- Bypass mixing of the discharge
- Plume dispersion and ecological effects of the discharge
- Sea-level rise; heat extremes shorter than one month (monthly data)
- Fouling and aging: only as TTD 4–6 °C (no effect on EAF)

The model is simple on purpose: **it shows which limit controls power, and why.** It is not a design tool for a specific plant.

The Model Chain: One Input, Two Branches

Steps 1–2 are identities under the model assumptions (bottom); Steps 3–4 use the IAPWS-IF97 steam tables. **The dominant uncertainty is parametric (ACP100 ΔT_cool and TTD), not computational.**



The plant runs at the lower of the two fractions, f_thermo or f_reg. This talk asks which one is lower, and why.

Model assumptions: *constant reactor thermal power and cooling-water flow; constant condenser heat-transfer coefficient and area; steam enters the condenser wet, so it condenses at one temperature.*

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

Model Checks: What Is Cross-checked, and What Cannot Be Tested

1 Physics chain vs. a published model

Against Kim & Jeong's published APR1400 model (not plant data): at 35 °C our model keeps **92.0 %** of its 20 °C output, theirs **93.8 %**. Our derating slope is steeper (0.53 vs 0.41 %/°C); the cause is not yet known.

2 Does the steeper slope matter?

Not for the results shown here: the discharge limit, not thermodynamics, sets power in every month (slide 17), so using 0.41 %/°C changes EAF by less than 0.00002.

3 Climate input

Baseline 29.17 °C from observed sea-surface data (NOAA OISST, 1982–2010); **the climate model adds only the warming, so its own 0.57 °C cold bias does not enter.**

4 What cannot be checked against data

The discharge limit is constructed; no plant operates under it. It is therefore tested by changing its type, its level and the ACP100 cooling-water rise (slides 18, 19), not against data.

Checked: the physics chain (its slope still differs). Not checkable: the constructed limit, so results come with sensitivity tests.

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

Key Assumptions and Why They Are Made

1 Thermal power and steam conditions fixed

Why: both units are treated the same way, so part-load effects should shift both in the same direction. **Excluded:** turbine stage losses and part-load efficiency curves.

2 Cooling-water flow fixed at design

ΔT_cool is then constant: 10 °C (APR1400, derived from Kim & Jeong), 8 °C (ACP100, estimate). **Excluded:** raising the flow. If only the APR1400 could raise it by more than 25 %, it would overtake the ACP100 (slide 21).

3 ACP100 as one module

One reactor, one turbine, one condenser. **Why:** the simplest SMR configuration. **Excluded:** multi-module layouts, where ΔT_cool per module may differ.

4 Technical floor = 0.40

Below 40 % of rated power a unit is treated as not operable; N_FO counts those months per year. Counting them as zero in EAF widens the gap to ≈ 19–20 pp; **a 0.30–0.50 floor sweep leaves the ordering unchanged.**

Each assumption keeps the comparison traceable to one design parameter, ΔT_cool.

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

Constructing the Regulatory Limit

Indonesia has no discharge standard for nuclear plants, so the limit is built from three references:

Marine water standard (receiving water)

+2°C (≈ 31.2°C)

PP 22/2021 App. VIII: limit in receiving water · strict end of the range tested

Thermal-power-plant effluent cap (seawater, once-through; nuclear not named)

40°C

Indonesia thermal-effluent rule (Permen LH 08/2009) · loose end of the range tested

Allowance borrowed from a Gulf NPP: **+5 °C from intake to discharge (Kim & Jeong, 2013), met there by seawater bypass, not modelled here** → allowance Δ_reg = +5 °C, **T_max,reg = 29.17 + 5 = 34.17 °C**

Two types of limit, equal today (34.17 = 29.17 + 5 °C), different only as the sea warms:

Fixed ceiling (absolute cap)

Example: Permen LH 08/2009 (40 °C). As the sea warms, the allowed rise shrinks, so f_reg falls.

Allowed rise above sea temperature (incremental limit)

Examples: marine standard +2 °C; Gulf NPP +5 °C. f_reg stays constant under warming.

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

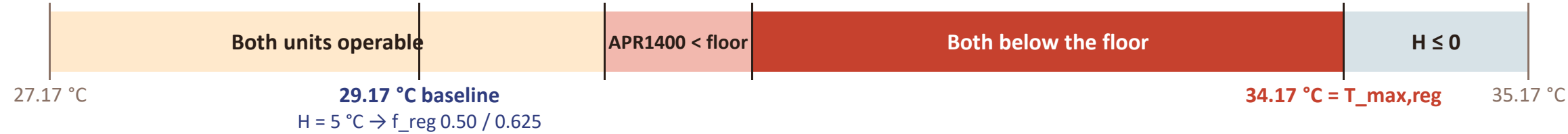
Headroom: How the Limit Becomes a Power Fraction

$$H(t) = T_{max,reg} - T_{in}(t) \rightarrow f_{reg} = H / \Delta T_{cool} \rightarrow \text{below the floor if } f_{reg} < 0.40$$

30.17 °C: APR1400 f_reg = 0.40
(H = 4.0 °C = 0.4 × 10 °C)

30.97 °C: ACP100 f_reg = 0.40
(H = 3.2 °C = 0.4 × 8 °C)

Intake temperature T_in at a 34.17 °C limit



Headroom (author's term, not a regulatory one): how many degrees the cooling water is allowed to warm before the discharge reaches the limit.

Same headroom, different power

At the baseline intake (29.17 °C), H = 5 °C: APR1400 f_reg = 5/10 = 0.50, ACP100 5/8 = 0.625. The 12.5-pp difference comes from ΔT_cool alone.

Why the 0.40 floor matters

A unit drops below the floor once H < 0.4·ΔT_cool: 4.0 °C (APR1400) or 3.2 °C (ACP100), i.e. at intake above 30.17 °C or 30.97 °C. So the APR1400 falls below it in more months (slide 16).

Reading the gap

Gap = H × (1/8 − 1/10) = 0.025·H. Warming shrinks H and the gap (2.5 pp per °C); a looser limit enlarges both, until the ACP100 reaches full power (slide 19).

Assumed: cooling-water flow fixed at design; bypass mixing not modelled; the +5 °C allowance applied at the condenser outlet (stricter reading).

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

Reactor Input Parameters: APR1400 vs. ACP100

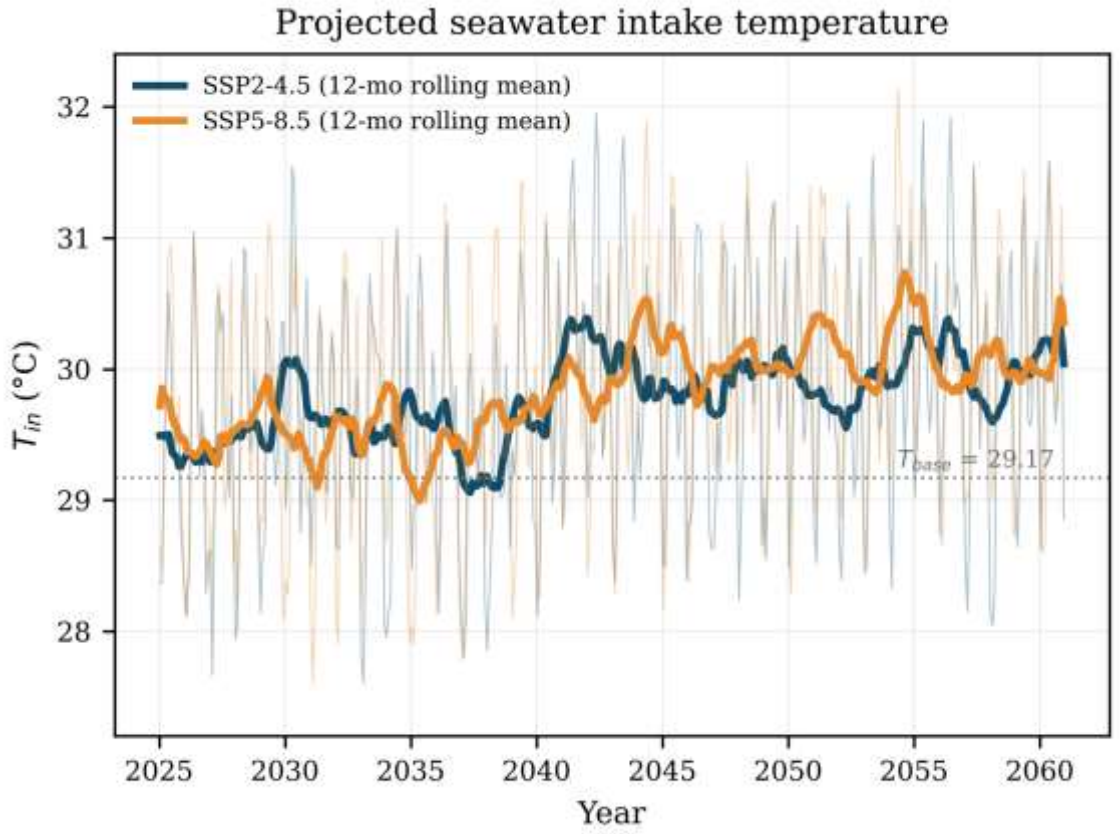
Parameter	APR1400	ACP100
Rated power	1,400 MWe	125 MWe
ΔT_cool (APR1400 derived, ACP100 estimated)	10°C †	8°C *
TTD	4°C	5°C *
f_thermo at T_base = 29.17 °C (normalised to 1 at 28 °C)	*0.993*	*0.993*
f_thermo – sensitivity to T_in (%/°C)	−0.553 %/°C	−0.601 %/°C
f_reg at T_base (T_max,reg = 34.17 °C)	**0.500**	**0.625**

* ACP100 ΔT_cool estimated from rejected heat (≈ 260 MWt) and a published circulating flow (Wang et al., 2026): 7.5–7.9 °C; no vendor design document. TTD: no published value; 4–6 °C tested, no effect on EAF. † APR1400 10 °C derived from Kim & Jeong (2013), Tables 1–2; the DCD gives 8.4 °C for a cooling-tower plant.

Same cycle model, so near-identical f_thermo; but the smaller, estimated ACP100 ΔT_cool gives a 12.5-pp higher f_reg.

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

Projected Seawater Intake Temperature



SSP2-4.5

+0.018 °C/yr

≈ +0.6 °C by 2060. CMIP6 warming at 10 m depth, added to the observed baseline (29.17 °C)

SSP5-8.5

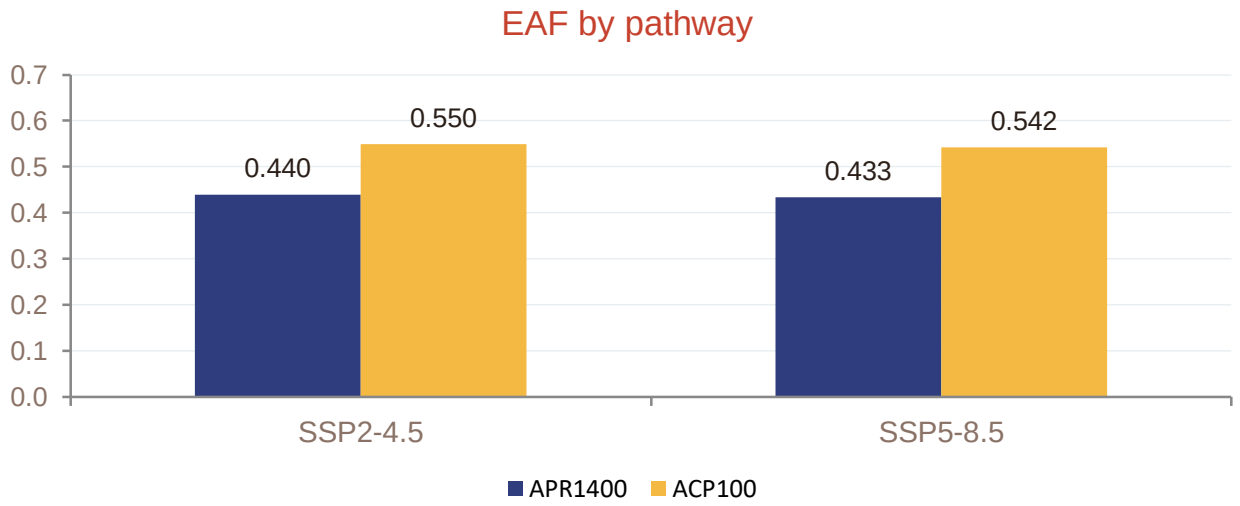
+0.025 °C/yr

≈ +0.9 °C by 2060. One climate model, one grid cell; trend uncertainty ±0.008 °C/yr (95 %)

The seasonal swing (≈ 2.5 °C, coolest in January, warmest in May) is three to four times the warming to 2060; May peaks push the intake above 30.17 °C, where the APR1400 drops below the floor. Model input: 432 monthly values per pathway; bold line = 12-month rolling mean (display only).

Model Result: Availability Factor & Months Below the Floor

Metric	Pathway	APR1400	ACP100
Average output (MWe)	SSP2-4.5	615.7	68.7
Average output (MWe)	SSP5-8.5	606.9	67.7
Months/yr below 40 % power (N_FO)	SSP2-4.5	4.0	1.2
Months/yr below 40 % power (N_FO)	SSP5-8.5	4.4	1.3



f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

WHAT 11 PP MEANS FOR ONE APR1400

~11

pp EAF gap (SSP2-4.5)

≈ 154 MWe

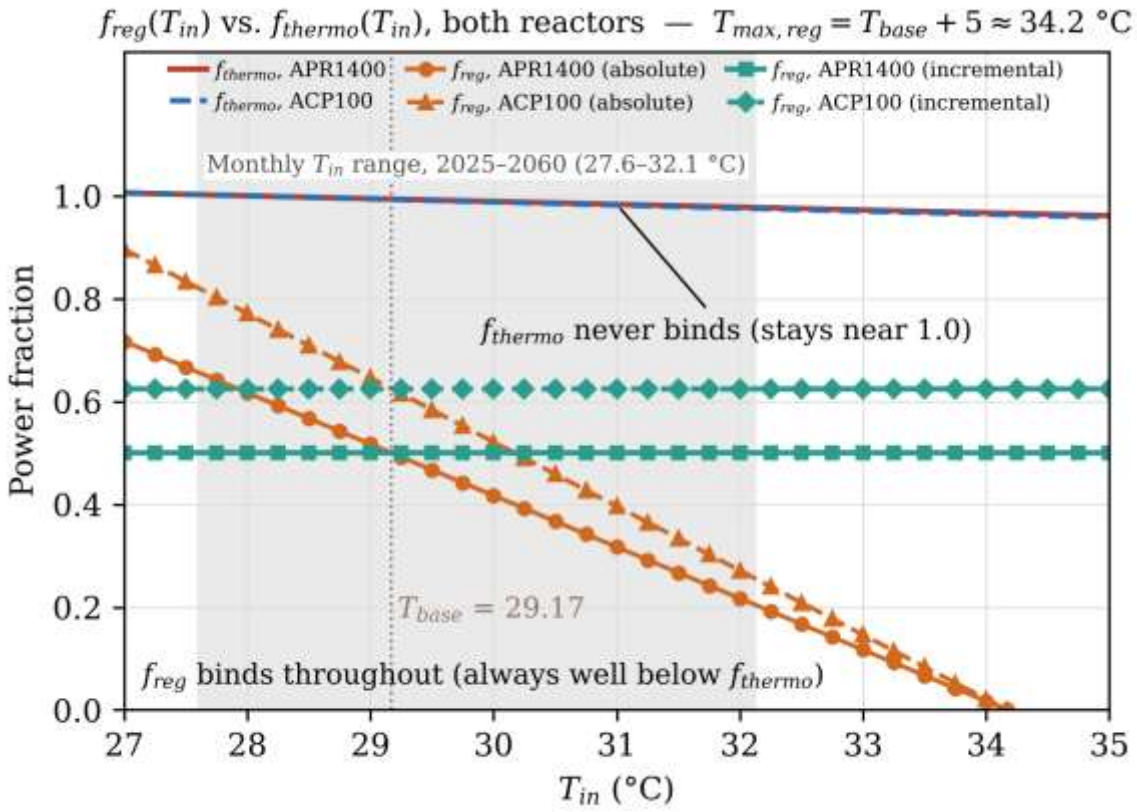
of average output (11 % of 1,400 MWe)

≈ 1.35 TWh

per year (11-pp gap × 1,400 MWe × 8,760 h, before planned outages)

The emission pathway changes EAF by only 0.6 pp (APR1400) and 0.8 pp (ACP100), against the 11-pp gap. MWe from unrounded EAF.

Why the Discharge Limit, Not Thermodynamics, Sets Power



In all 432 months, for both reactors and both pathways, ***f_reg*** is lower than ***f_thermo***, so the discharge limit sets the power. f_reg also falls 18–21 times faster with intake temperature (10 and 12.5 %/°C, against 0.55 and 0.60 %/°C).

Averaged over 2025–2060

EAF = mean headroom ÷ ΔT_cool

Gap = 0.025 × mean headroom = 0.025 × 4.4 °C ≈ 11 pp

No term for reactor power, layout or safety class: the design enters only through ΔT_cool. The gap shrinks with warming (−2.5 pp per °C) and changes with the limit level.

In this model, at the 34.17 °C limit, the discharge rule sets the power of both units. ΔT_cool decides which unit loses more.

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

The Type of Limit Matters

Same allowance, +5 °C (2025–2060)	EAF APR1400	EAF ACP100
Fixed ceiling at 34.17 °C (baseline)	0.440	0.550
Allowed rise: sea temperature + 5 °C	0.500	0.625
Difference (SSP2-4.5 / SSP5-8.5)	**+6.0 / +6.7 pp**	**+7.5 / +8.3 pp**

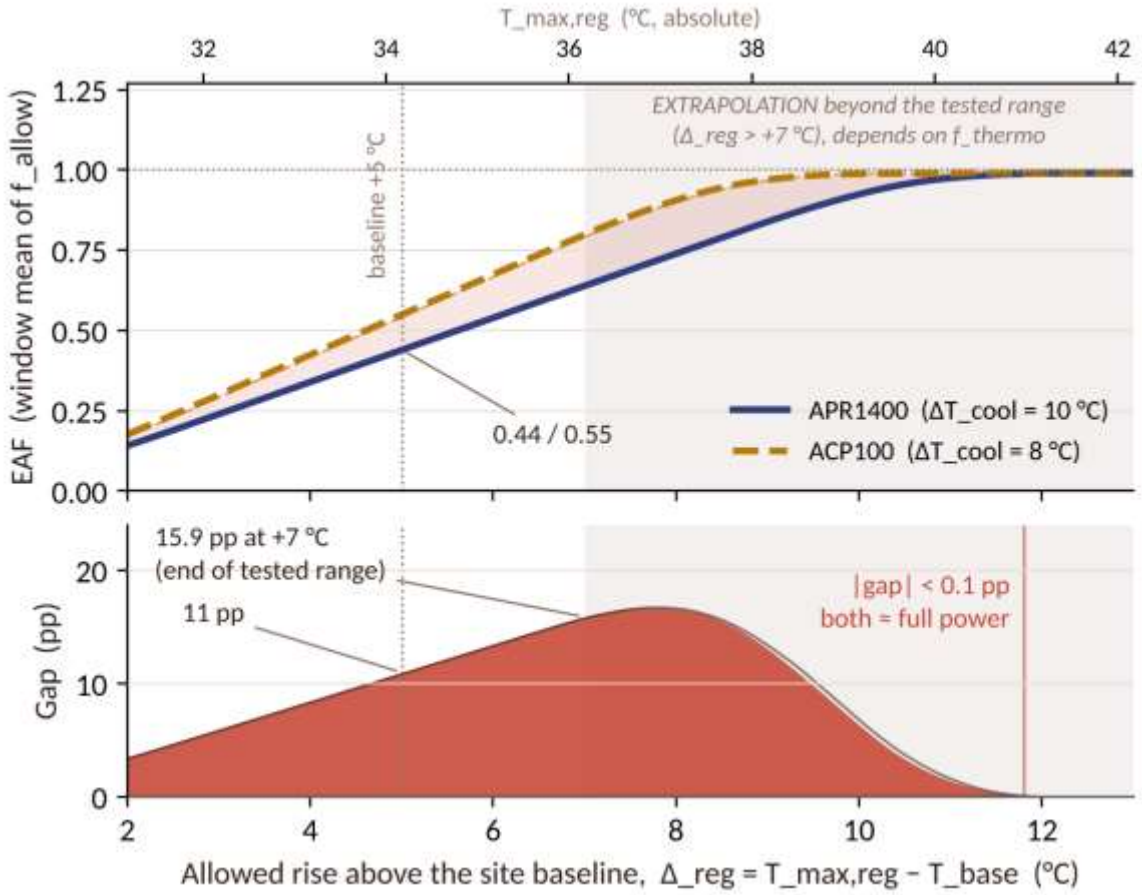
Window-mean EAF over 432 months; f_thermo never limits power in either form (minimum 0.975). Limit level: next slide.

Both give the same limit today (29.17 + 5 = 34.17 °C). As the sea warms, the fixed ceiling leaves less headroom; the allowed rise does not. Under the allowed rise, EAF stays constant, no month falls below the floor, and the gap is 12.5 pp instead of 11.

With the same +5 °C allowance, an allowed rise gives 6–8 pp higher EAF than a fixed ceiling. That is about ten times the difference between the two emission pathways (0.6–0.8 pp). **The regulator chooses the type of limit; its environmental effects are not assessed here.**

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

How the Gap Depends on the Limit Level



Within the tested range (+2 to +7 °C)

The gap widens as the limit is relaxed: 3.5 pp at +2 °C (both units below the floor), 11 pp at +5 °C, 15.9 pp at +7 °C.

A much higher limit removes the difference

Under the 40 °C cap of Permen LH 08/2009, both units run near full power (EAF ≈ 0.97 and 0.99): gap ≈ 2 pp.

Beyond +7 °C: extrapolated (shaded). The gap turns down after about +8 °C and closes near +12 °C, where thermodynamics, not the discharge limit, caps both units. Read as a trend, not a tested result.

Reading: no recommendation; ecological effects not assessed. *Monthly model, 432 months per pathway (SSP2-4.5 bold, SSP5-8.5 thin); EAF = mean of f_allow. Shaded: beyond the tested range; a different thermodynamic slope moves the curve there by ≤ 0.05 pp.*

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

What This Study Shows

BOTTOM LINE

In this model, at a tropical marine site under a constructed 34.17 °C limit, the discharge limit, not thermodynamics, sets how much power each reactor can deliver. The type and level of the limit change the result more than the emission pathway.

1

The limit sets the power; ΔT_cool decides which unit loses more

In all 432 months f_reg is lower than f_thermo. The design enters only through ΔT_cool (10 vs an estimated 8 °C), giving an 11-pp gap; reactor power, layout and safety class do not appear. The order reverses if the ACP100's ΔT_cool exceeds 10 °C, or if only the APR1400 raises its cooling-water flow by more than 25 %.

2

The type and level of the limit matter more than the emission pathway

With the same +5 °C, an allowed rise gives 6–8 pp higher EAF than a fixed ceiling, about ten times the pathway difference. Within the tested range the gap grows from 3.5 pp (+2 °C) to 15.9 pp (+7 °C); under a 40 °C cap it falls to ≈ 2 pp.

3

To our knowledge, no earlier application at an equatorial marine site

Earlier regulatory-versus-thermodynamic studies cover river-cooled plants in temperate climates (e.g. van Vliet et al., 2016). We found none for a seawater-cooled plant at an equatorial site using CMIP6 projections; our search covered English-language public sources only.

f_allow = min[f_reg, f_thermo, 1.0] · EAF = window-mean f_allow (2025–2060) · N_FO = months/yr below f_min,tech

CLOSING

Limitations & Future Work

The ACP100 cooling-water rise and TTD are estimates

No vendor design document confirms them. 8 °C comes from rejected heat and a published flow (7.5–7.9 °C); TTD is tested over 4–6 °C. The order holds below 10 °C and reverses above it.

A design-flow bound: raising the flow could reverse the order

If only the APR1400 raises its cooling-water flow by more than 25 %, it overtakes the ACP100. At the Gulf flow ratio of 1.54, its f_reg rises from 0.50 to 0.77 for about 17–51 MW of extra pump power. ACP100 pump data are not available; bypass mixing is not modelled.

One climate model and one grid cell

The trend uncertainty covers regression only, not the spread between climate models. A multi-model ensemble is the next step. Open: model derating slope 0.53 vs 0.41 %/°C (Kim & Jeong); cause untested, no effect on EAF.

Priority for future work: the ACP100 condenser design values and pump margin, from a published secondary-side design package.

Thank You

Questions & Discussion

Rachman Bagus Sujiatmoko & Hak-kyu Lim

rachman.bagus@kings.ac.kr · hklim@kings.ac.kr

This research was supported by the 2026 Research Fund of KEPCO International Nuclear Graduate School (KINGS), Republic of Korea.