Cloud Operations & Innovation ("CO+ I")

A Feasibility Framework for Waste Heat from Data Centres to a Water Capture System from Uravu Labs

Milestone-3 Report

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Contents

1. Introduction

The findings from Milestones 1 and 2 highlight how the Uravu system enables concurrent cooling and water production by harnessing waste heat from data centers. This report further explores the economic and environmental feasibility of integrating the Uravu system with data center operations. The chosen locations are the same as those reported in the Milestone-2 report: Frankfurt (FRK), Madrid (MRD), London (LON), Stockholm (SHM), Phoenix (PNX), Chicago (CHG), Seattle (STL), Houston (HSN), Hyderabad (HYD), Bengaluru (BLR), Mumbai (MUM), Chennai (CHN), and Singapore (SGP).

System Configurations:

i. ***Uravu-waste heat (Unblended)***: The system operates solely on the available data-center waste heat to drive the Uravu processes. Any additional cooling required for the facility water is supplied by the indirect evaporative cooler (IEC).
ii. ***Uravu-waste heat (blended)***: Similar to the unblended case, the Uravu unit is powered by waste heat. However, any remaining cooling demand for the facility water is met using a combination of IEC and a chiller, based on the target outlet temperature.
iii. ***Uravu-electric***: Waste heat is used only for pre-heating the desiccant, subject to ambient conditions. The remaining cooling requirement for the facility water is met through IEC and a chiller.
iv. ***Baseline-1 (Air-cooled chiller (ACC))***: The entire cooling load of the facility water is met using an air-cooled chiller.
v. ***Baseline-2 (Dry cooler (DC) + ACC)***: Facility water is cooled using a dry cooler, depending on the target temperature and ambient conditions. When the DC cannot meet the demand, the remaining cooling is provided by the air-cooled chiller.
vi. ***Baseline-3 (Cooling tower (CT) + ACC)***: Facility water is first cooled using a cooling tower based on the target temperature and local wet-bulb temperature (WBT). The air-cooled chiller meets any additional cooling demand.

Uravu system integration overview: The way Uravu integrates with a data center depends on the type of system being deployed, Uravu–Waste Heat or Uravu–Electric, as each is designed for different operating conditions.

Uravu–Waste Heat system: In this configuration, **the Uravu unit directly uses the waste heat released from the data center to produce water from air**. The captured

waste heat fully powers the core water-generation step, where water vapor is released from the liquid desiccant. Since the process relies entirely on available waste heat. As the **Uravu-waste heat unit fully utilizes the low-grade heat, there is no need for additional heating (through heat pumps or electrical input) for water production.**

Uravu–Electric system: This configuration is typically **used in humid locations where the available waste heat is relatively low (around 30–35°C)**. Under such conditions, waste heat alone may not be sufficient to continuously drive water production, especially during periods of unfavorable atmospheric conditions. To ensure reliable operation, the **waste heat is first used to warm the liquid desiccant**. The **remaining energy** required for water production is **then supplied by an electrically driven water vapor compressor, which recovers and reuses energy already present within the system**. This approach **maintains consistent water output without requiring upgrades to the waste heat through heat pumps**. A pictorial representation of all the configurations is shown in **Figure 1** for better clarity.

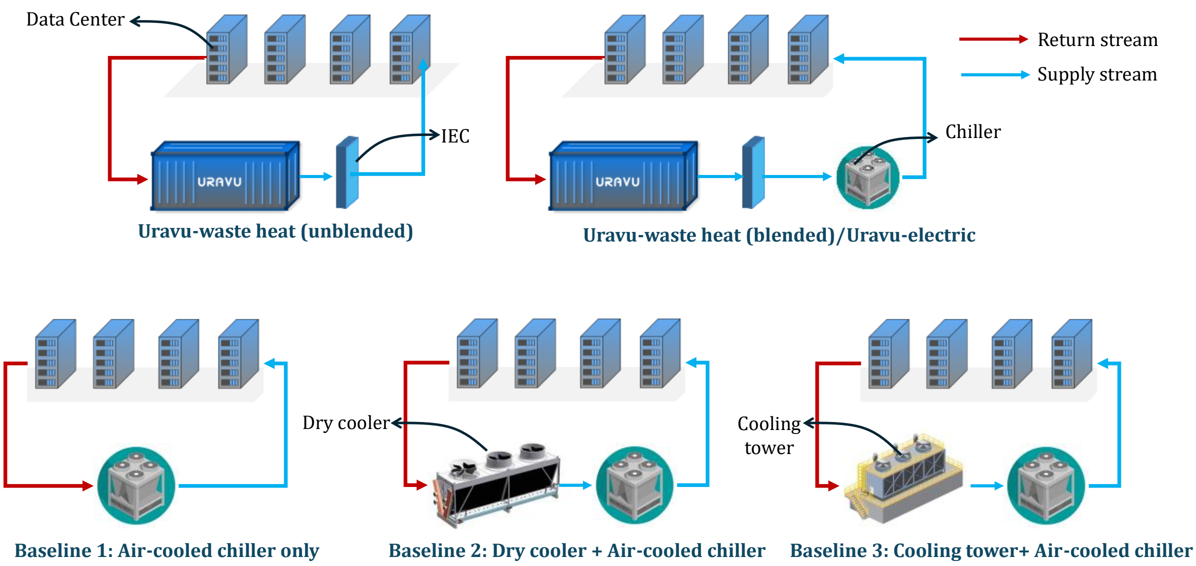

Figure 1: Pictorial representation of the different system configurations.

2. Key Assumptions for Environmental and Economic Evaluation

To facilitate a systematic and transparent evaluation, a set of baseline assumptions has been established to underpin both the environmental and economic analyses of the Uravu system integrated with data center operations. These assumptions delineate the key techno-economic parameters considered in the study. Establishing such assumptions ensures consistency in the comparative assessment, enhances the credibility of the analysis, and provides a coherent framework for interpreting the resulting environmental and economic performance indicators. The key assumptions considered for economic and environmental assessment are presented in **Table 1**.

2.1 Environmental assumptions and metrics

The environmental analysis is conducted under conditions representative of typical data center operations and the integration of the Uravu system for waste heat utilization. Environmental indicators assessed include the system's carbon footprint, water footprint, and sustainability performance relative to conventional cooling and water supply systems. Greenhouse gas emissions are estimated using region-specific grid emission factors, while the water footprint accounts for both direct (Scope-1) and indirect water (Scope-2) usage. The analysis also incorporates the potential environmental benefits associated with waste heat recovery and on-site water generation, which contribute to resource efficiency and reduced environmental impact.

Table 1: Summary of key parameters and assumed values.

Parameters	Value/source	Unit
Project lifetime	15	Years
Electricity cost	0.1 – 0.3 (source)	$/kWh
CO_2 Emission factor	0.02 – 0.45 (source-1 and source-2)	g/kWh
Water footprint factor	1 – 3.97 (source)	L/kWh
CAPEX (Uravu-waste heat)	500,000	$/MW
CAPEX (Uravu-electric)	650,000	$/MW
CAPEX (Air-cooled chiller)	350,000	$/MW
CAPEX (Dry-cooler)	100,000	$/MW
CAPEX (Cooling tower)	150,000	$/MW
Maintenance rate (Uravu unit)	2	%
Maintenance rate (Air-cooled chiller)	3	%

2.2 Economic assumptions and metrics

The economic evaluation considers representative cost parameters and operational conditions relevant to the integration of the Uravu data center for the selected cities. Key assumptions include the project lifetime, system throughput, and local electricity tariff. Capital expenditure (CAPEX) and operational expenditure (OPEX) are estimated based on available technology benchmarks and scaled to the system capacity.

a) ***Levelized cost of cooling (LCoC)***: This metric represents the average cost of delivering 1 unit of cooling (**typically in $/MWh**) over the whole lifetime of a cooling system. It accounts for all expenses — capital cost (equipment and installation), operating cost (electricity, fuel, water, maintenance), and replacements — divided by the total useful cooling delivered during its lifetime. By combining both upfront and ongoing costs into a single number, **LCoC enables a fair comparison between different cooling technologies (e.g., System configuration explained in Section 1),** regardless of their investment scale or operating patterns.

b) ***Net Value of Water (NVW)***: It is defined as the net economic outcome of producing water after incorporating the monetary credit associated with avoided cooling energy consumption (**measured in $\$/m^3$**). **NVW combines the cost of water production with the financial benefit** from displaced cooling-system operation, providing a unified metric to evaluate the overall economic performance of a system.

Table 2: Interpretation of Net Value of Water.

NVW Value	Meaning	Practical Interpretation
NVW $>$ 0	Net economic **cost**	Producing water results in a net expenditure; the cooling credit does not offset the full cost of water production.
NVW $=$ 0	**Cost–benefit neutral**	The savings from avoided cooling exactly balance the water production cost, resulting in an economic break-even.
NVW $<$ 0	Net economic **benefit**	The savings from avoided cooling exceed the cost of water production, resulting in an overall financial gain.

NVW provides a clear and intuitive economic indicator even when cooling-energy credits outweigh production costs. Unlike LCOW, NVW remains meaningful when the metric crosses zero or becomes negative, making it suitable for systems where thermal energy reuse yields substantial financial offsets.

3. Site-specific environmental and economic analysis

Based on the parameters listed in Table 1, economic and environmental analyses have been performed for different European Union (EU), United States (US), Indian and Singapore cities. As discussed in the Milestone-2 report, for the baseline, the facility water inlet temperature ($T_{\text{fac,in}}$) is maintained at 30°C, with a target outlet temperature (T_{target}) of 18°C. The facility water is maintained at a rate of 1.3 kg/s, and the desiccant flow rate is adjusted based on the available waste heat. Additionally, the Uravu system is programmed with a downtime trigger temperature (T_{trigger}) of 9.5°C, specific to 30°C operating conditions only. Based on the available waste heat temperature, the downtime trigger temperature can also be adjusted. The downtime trigger temperature indicates that Uravu's waste heat-based system is suspended whenever the ambient wet-bulb temperature (WBT) falls below this threshold. Also discussed in the Milestone-1 report, the facility water temperature should follow the given constraint, where $\boldsymbol{T_{\mathrm{fac,in}} \geq T_{\mathrm{vap}} + \Delta T_{\mathrm{system}} + BPE}$, where $\Delta T_{\mathrm{system}}$ is approximately 5°C, and the boiling point elevation (BPE) is around 12°C, along with saturation temperature (T_{vap}) which can be adjusted by controlling the vacuum according to the available waste heat temperature.

3.1 Levelized Cost of Cooling (LCoC)

United States: Across the US cities (Phoenix, Chicago, Houston, and Seattle), the LCoC for Uravu-based systems decreases sharply when the available waste-heat temperature rises.

At lower temperatures (near 30°C), the system's uptime is relatively low, resulting in a higher LCoC and often making it comparable to or slightly higher than existing baseline cooling systems. However, as the temperature increases beyond 40–45 °C, the Uravu-waste heat configurations become significantly more cost-effective, eventually reaching lower LCoC values of up to $10/MWh.

In simple terms: the hotter the waste heat, the cheaper the cooling becomes, and beyond 45°C, Uravu consistently is comparable to Baseline cooling systems in every US city studied.

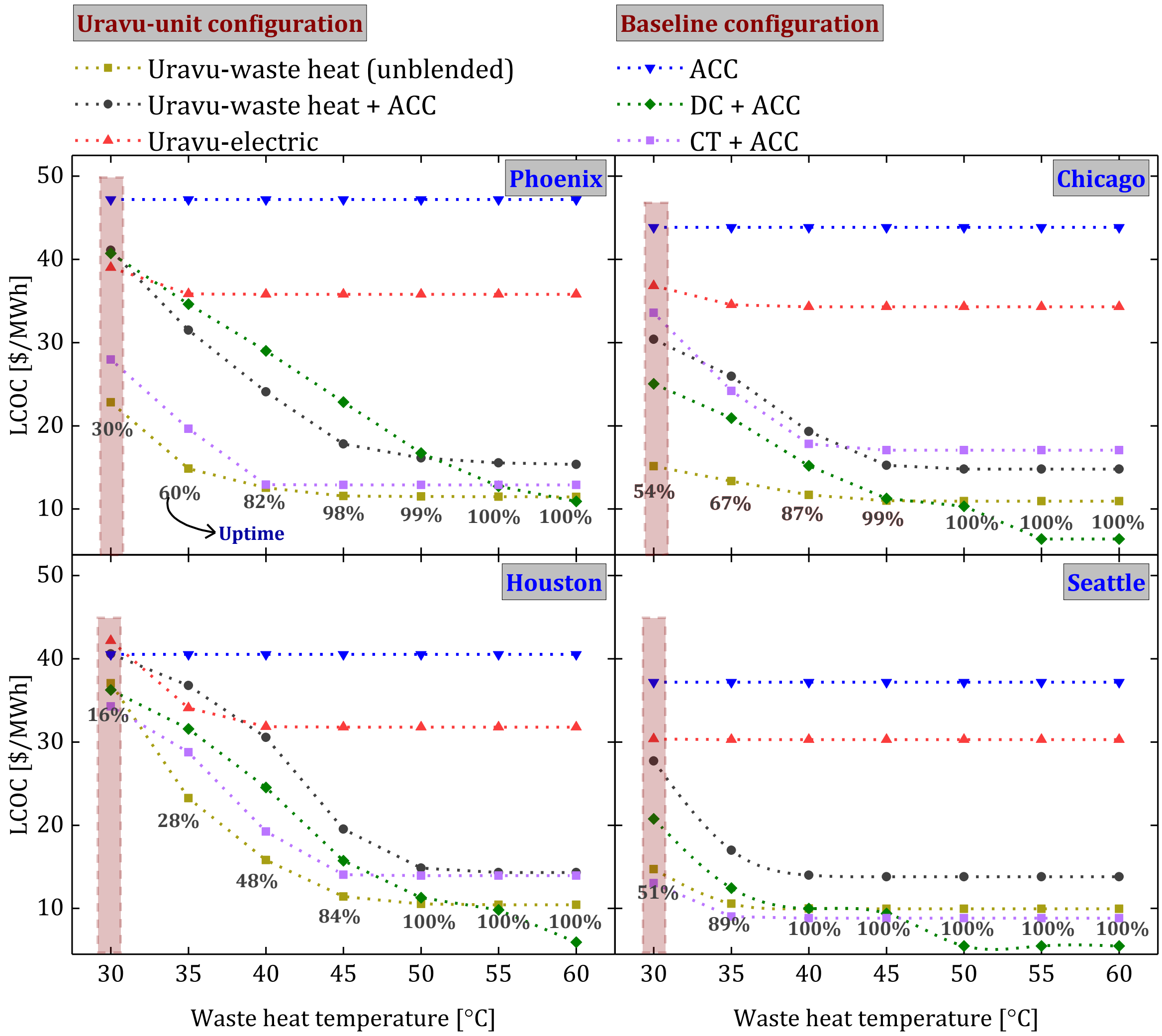

Figure 2: Variation of LCoC with waste heat temperature for US-based cities.

European Union: A similar trend is observed in EU cities (Frankfurt, Madrid, London, and Stockholm), although with slightly different starting points due to cooler climatic conditions. At a waste-heat temperature of 30–35°C, the LCoC is relatively high for the Uravu-waste heat (blended) system, because the system cannot run continuously. However, once the temperature exceeds 40–45°C, uptime approaches 100%, and the LCoC drops significantly.

When the waste-heat temperature is moderate or high, the Uravu-waste heat configuration delivers consistently lower LCoC than baseline cooling systems. The benefit becomes more pronounced beyond 45–50 °C, where the system runs continuously, and the cost advantage becomes stable.

In summary, Uravu becomes significantly more economical than traditional cooling in EU cities when waste heat reaches 45 °C or higher, regardless of whether the climate is warm (e.g., Madrid) or cool (e.g., Stockholm).

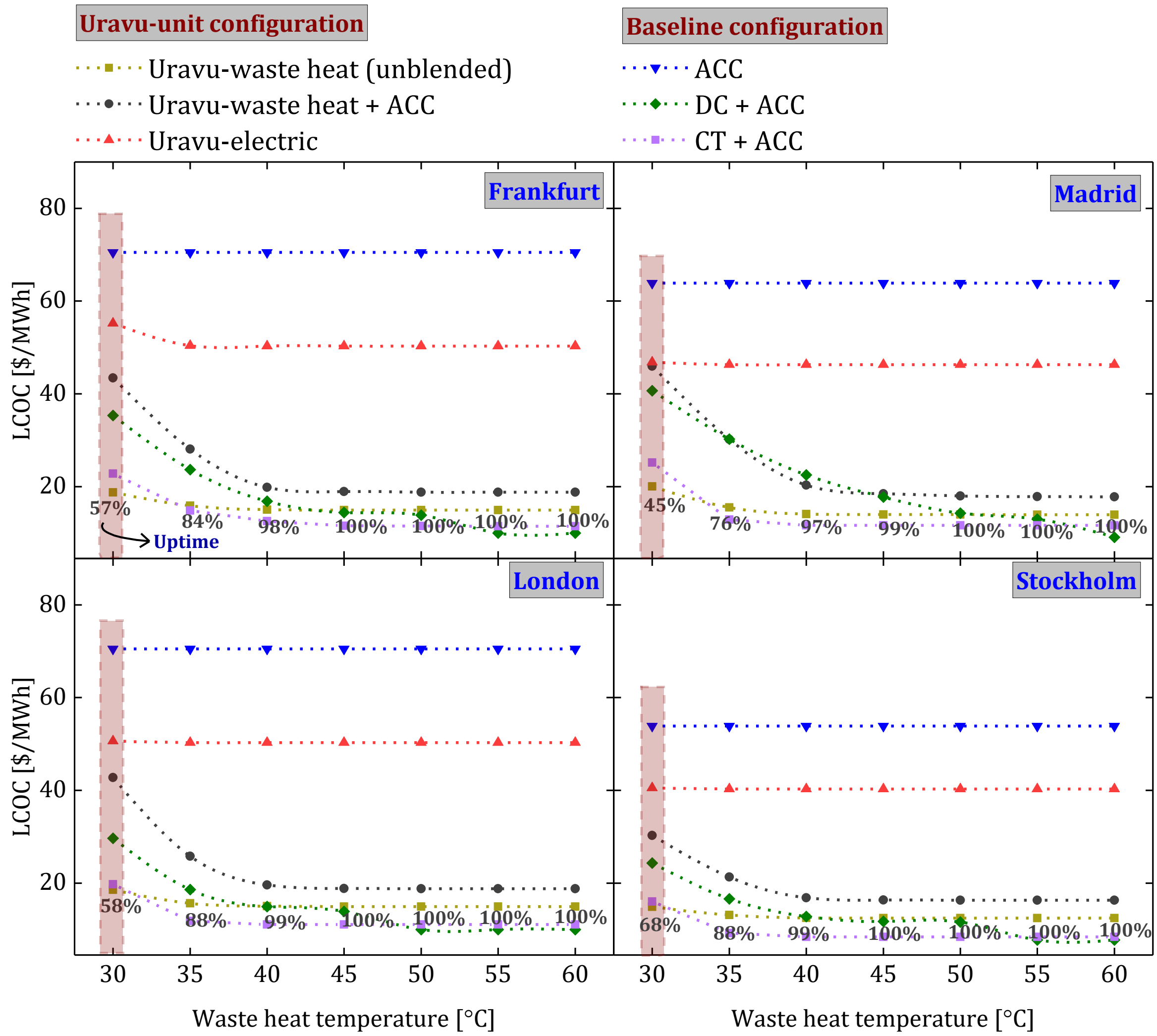

Figure 3: Variation of LCoC with waste heat temperature for EU-based cities.

India and Singapore: The drop in LCoC with rising waste-heat temperature is even more pronounced in Asian cities (Hyderabad, Bengaluru, Mumbai, New Delhi, Chennai, and Singapore). At lower temperatures, high humidity, and elevated cooling demand make the baseline systems expensive. When waste-heat temperature rises to around 40–45°C, the LCoC reduces rapidly because (i) Uravu systems reach full uptime and (ii) they replace a significant portion of mechanical cooling. At low-temperature waste heat in humid regions, the Uravu-electric system will result in comparable or lower LCoC than the baseline system.

Put simply, in Asia, the financial benefit of using Uravu increases most rapidly as waste heat temperature rises, especially in high-humidity climates such as Chennai and Singapore.

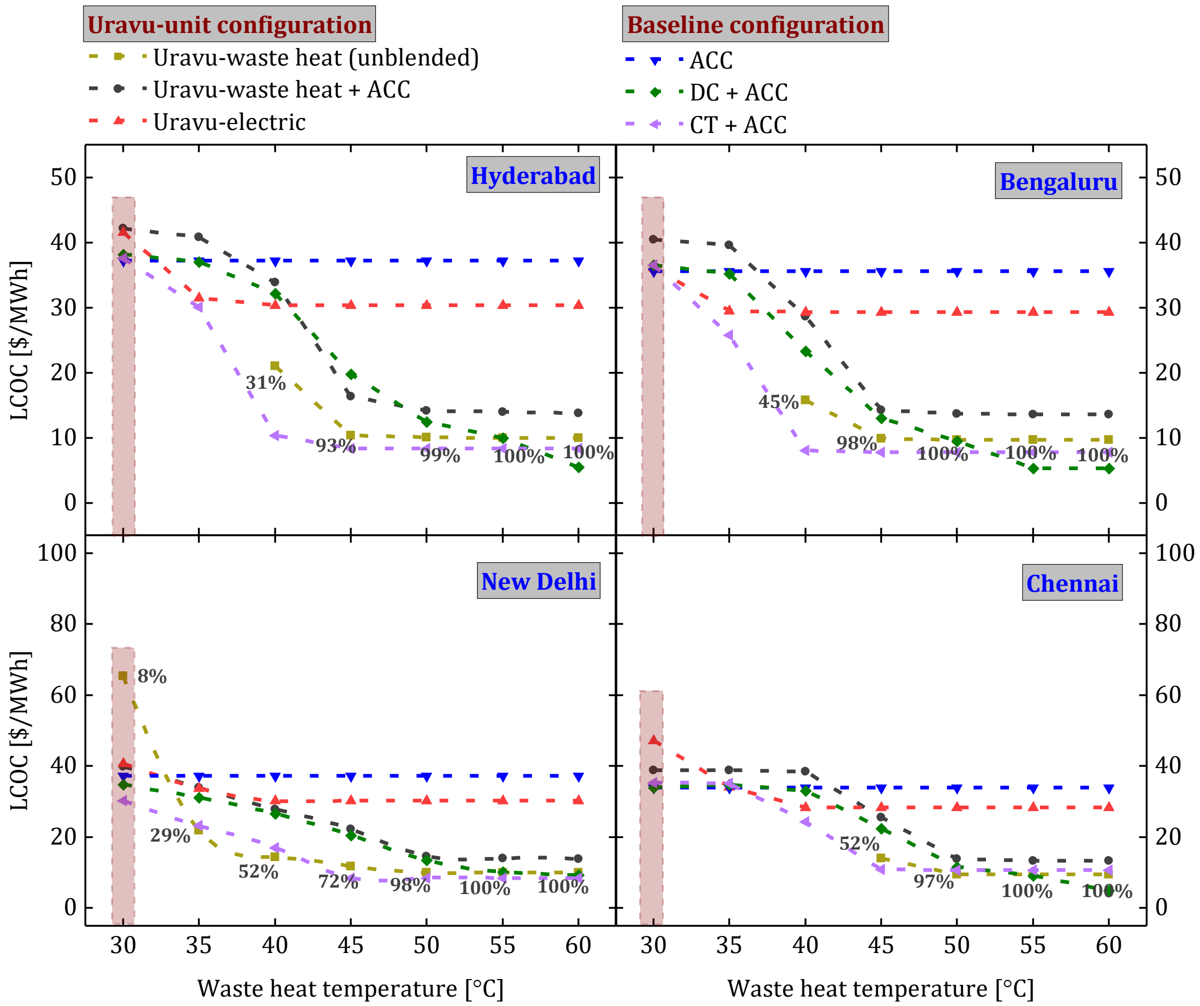

Figure 4: Variation of LCoC with waste heat temperature for Indian cities.

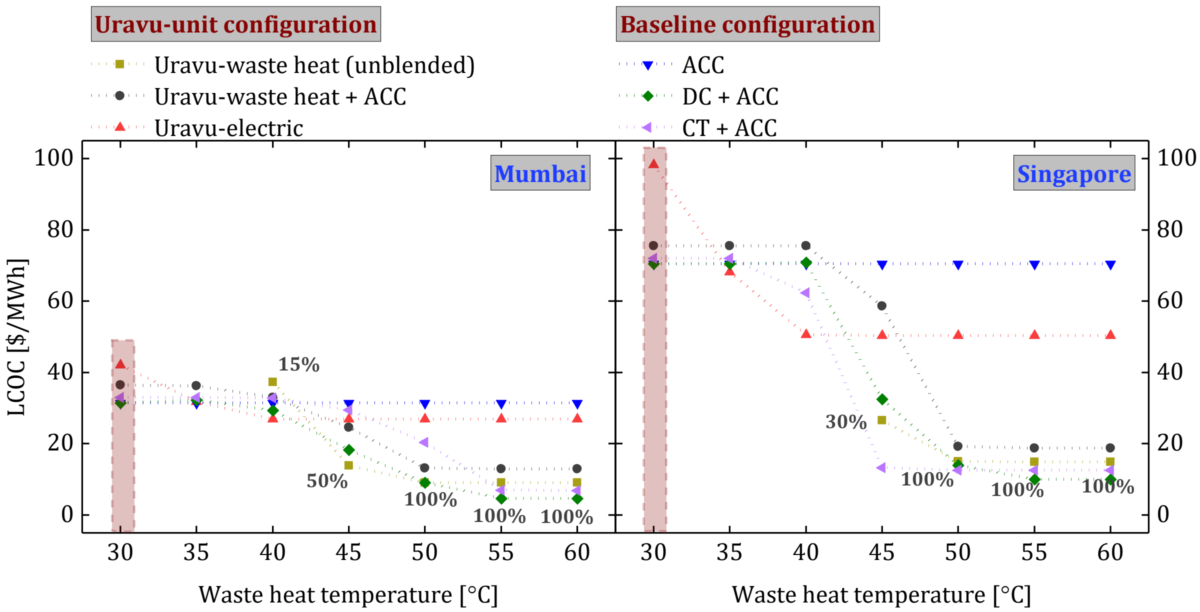

Figure 5: Variation of LCoC with waste heat temperature for Mumbai and Singapore.

Even though the starting LCoC varies from region to region due to climate and electricity market differences, a universal trend is visible:

Waste-heat temperature	LCoC trend for Uravu
30–35 °C	Highest cost – low uptime
35–45 °C	Substantial cost reduction – uptime rapidly increases
≥45 °C	Lowest cost – consistent, continuous operation

3.2 Net Value of Water

United States: In US cities, the NVW decreases gradually as waste-heat temperature increases. At low temperatures (30–35°C), all Uravu configurations exhibit a positive NVW, indicating that water production still incurs costs even when no cooling credits are applied. The credit lines (with respect to ACC and DC + ACC) lie below the "no-credit" line, reflecting additional financial value from cooling savings.

As the waste-heat temperature rises to 40–45°C, system uptime improves and the NVW begins to approach zero, indicating almost cost-neutral water production. At higher temperatures (≥45 °C), credit with respect to ACC increasingly pushes NVW into the negative range, indicating that the economic benefit from avoided cooling energy exceeds the cost of producing water. Higher waste-heat temperature steadily improves NVW, and monetizing cooling savings (credits) significantly enhances economic value.

European Union: The EU cities exhibit a similar pattern, albeit with slightly slower improvement, compared to the US at low temperatures, due to their cooler climate and lower cooling demand. At 30–35°C, NVW is still positive across all curves, and the credit lines are grouped moderately below the no-credit lines.

As the waste-heat temperature increases above 40°C, the differences between the curves become more pronounced — credits with respect to ACC and DC + ACC significantly improve the NVW, thereby reducing the net cost of water. At ~45°C and beyond, with Uravu-waste heat (blended) unit credit w.r.t. DC + ACC typically is close to zero NVW, demonstrating that in many EU locations, heat-driven Uravu systems can create net economic benefit when cooling energy savings are counted.

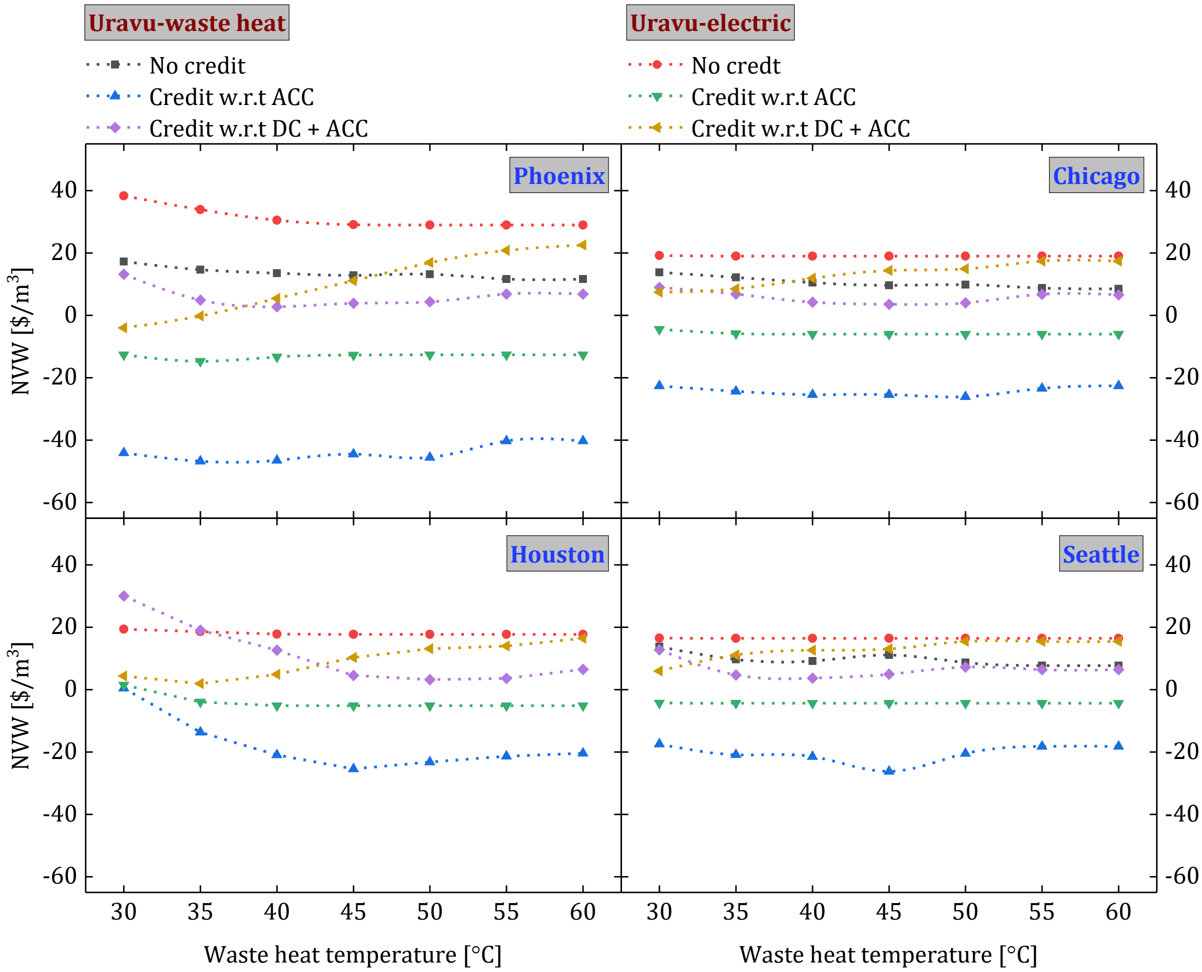

Figure 6: Variation of Net Value of Water with waste heat temperature for US-based cities.

India and Singapore: NVW trends in Asian cities are the most sensitive to waste-heat temperature due to high cooling demand and humidity. At low temperatures (30–35°C), NVW is significantly positive, especially in the no-credit case, because the unit cannot run continuously, and limited cooling savings are available. Only with the Uravu-electric unit is the credit line close to zero.

As the temperature rises, the NVW curves drop sharply. At around 40°C for humid regions like Chennai and Singapore, credit lines for the Uravu-waste heat system with respect to ACC and DC + ACC already approach zero NVW, and above 45°C, nearly every city shows negative NVW under both credit cases. This negative NVW means that cooling savings alone fully pay for the cost of producing water and even create additional financial value.

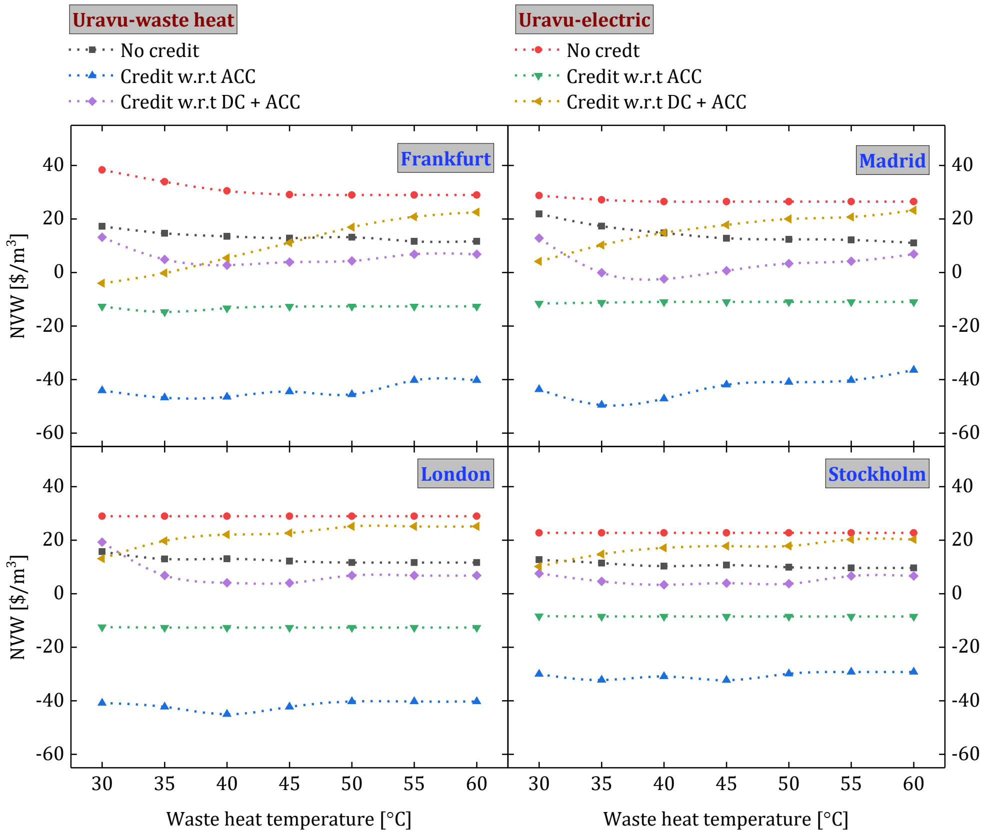

Figure 7: Variation of Net Value of Water with waste heat temperature for EU-based cities.

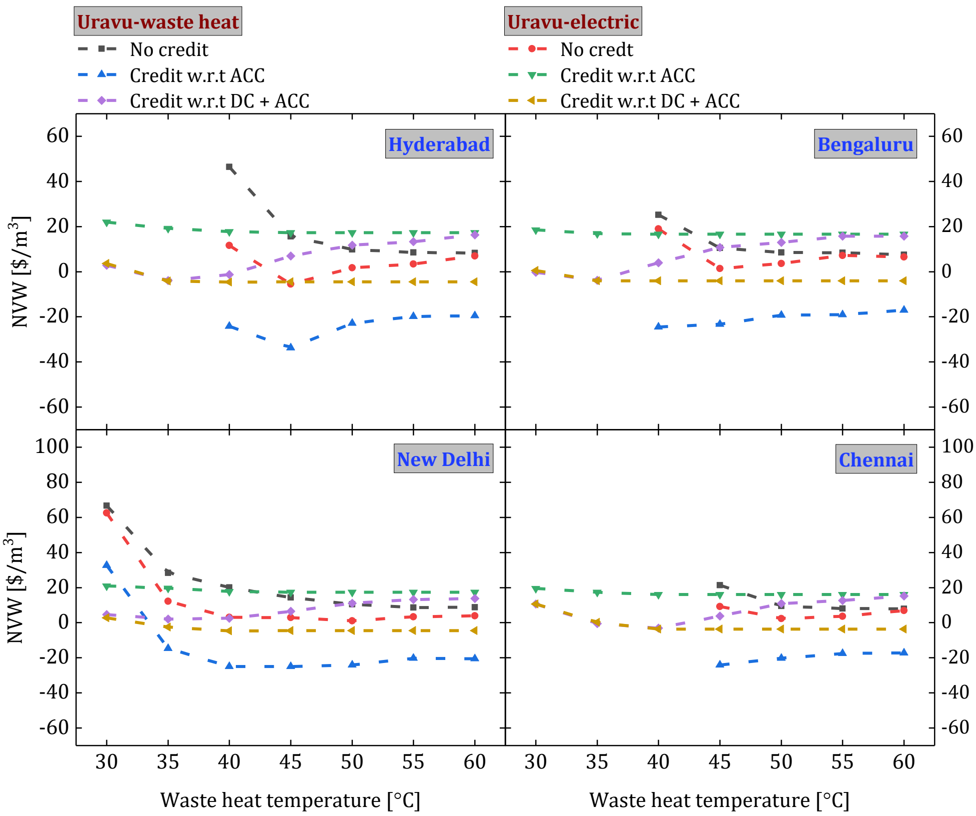

Figure 8: Variation of Net Value of Water with waste heat temperature for Indian cities.

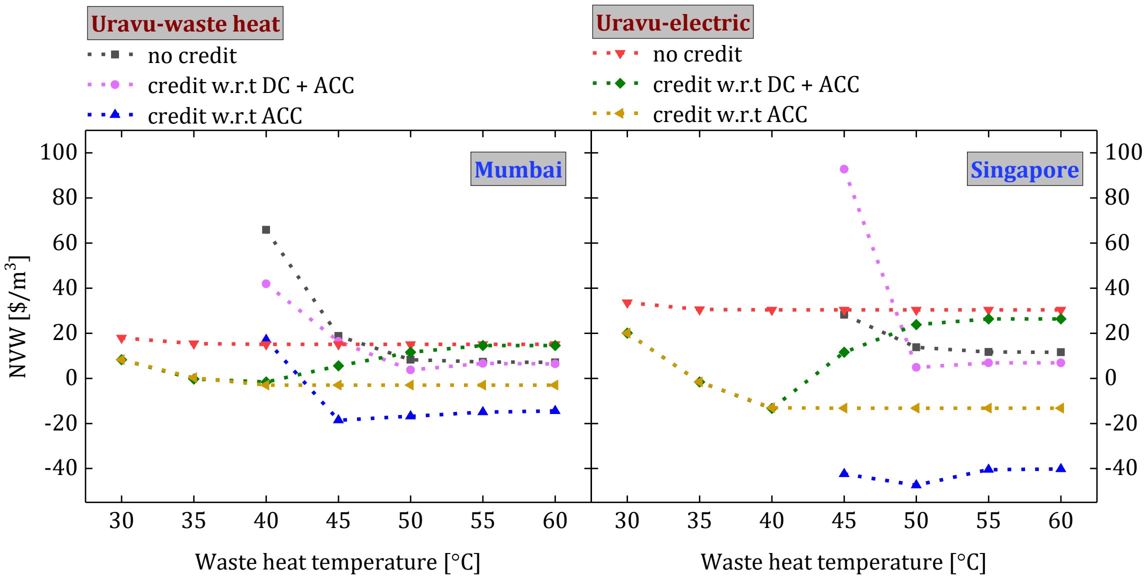

Figure 9: Variation of Net Value of Water with waste heat temperature for Mumbai and Singapore.

Table 3: City-wise decision table for NVW

City	Uravu-waste heat no credit	Uravu-waste heat w.r.t DC +ACC	Uravu-waste heat w.r.t ACC	Uravu-electric heat no credit	Uravu-electric w.r.t DC +ACC	Uravu-electric w.r.t ACC
Phoenix	NVW > 0	NVW > 0 (30 -35°C) NVW ≈ 0 (>35°C)	NVW < 0	NVW > 0	NVW < 0 (30 -35°C) NVW > 0 (>35°C)	NVW < 0
Chicago	NVW > 0	NVW > 0 (30 -35°C, 50-60°C) NVW ≈ 0 (35 -50°C)	NVW < 0	NVW > 0	NVW > 0	NVW < 0
Houston	NVW > 0	NVW > 0	NVW < 0	NVW > 0	NVW > 0	NVW < 0
Seattle	NVW > 0	NVW > 0 (30 -35°C) NVW ≈ 0 (>35°C)	NVW < 0	NVW > 0	NVW > 0	NVW < 0
Frankfurt	NVW > 0	NVW > 0 (30°C)	NVW < 0	NVW > 0	NVW < 0 (30°C)	NVW < 0

City	Uravu-waste heat no credit	Uravu-waste heat w.r.t DC +ACC	Uravu-waste heat w.r.t ACC	Uravu-electric heat no credit	Uravu-electric w.r.t DC +ACC	Uravu-electric w.r.t ACC
		NVW ≈ 0 (>30°C)			NVW > 0 (>30°C)	
Madrid	NVW > 0	NVW > 0 (30°C) NVW ≈ 0 (>30°C)	NVW < 0	NVW > 0	NVW > 0	NVW < 0
London	NVW > 0	NVW > 0 (30°C) NVW ≈ 0 (>30°C)	NVW < 0	NVW > 0	NVW > 0	NVW < 0
Stockholm	NVW > 0	NVW > 0	NVW < 0	NVW > 0	NVW > 0	NVW < 0
Hyderabad	NVW > 0	NVW > 0 (>40°C)	NVW < 0	NVW > 0	NVW ≈ 0 (30 -40°C)	NVW ≈ 0
Bengaluru	NVW > 0	NVW > 0 (40°C) NVW ≈ 0 (>40°C)	NVW < 0	NVW > 0	NVW ≈ 0	NVW < 0
Mumbai	NVW > 0	NVW > 0 (30 -35°C) NVW ≈ 0 (>35°C)	NVW > 0 (40°C) NVW < 0 (>40°C)	NVW > 0	NVW < 0 (30 -35°C) NVW > 0 (>35°C)	NVW < 0
New Delhi	NVW > 0	NVW > 0 (30 -35°C) NVW ≈ 0 (>35°C)	NVW < 0	NVW > 0	NVW < 0 (30 -35°C) NVW > 0 (>35°C)	NVW > 0 (30°C) NVW ≈ 0 (>30°C)
Chennai	NVW > 0	NVW > 0	NVW < 0	NVW > 0	NVW > 0 (30-35°C) NVW ≈ 0 (>35°C)	NVW > 0 (30°C) NVW ≈ 0 (>30°C)

City	Uravu-waste heat no credit	Uravu-waste heat w.r.t DC +ACC	Uravu-waste heat w.r.t ACC	Uravu-electric heat no credit	Uravu-electric w.r.t DC +ACC	Uravu-electric w.r.t ACC
Singapore	NVW > 0	NVW > 0 (45°C) NVW ≈ 0 (>45°C)	NVW < 0	NVW > 0	NVW < 0 (30 -35°C) NVW > 0 (>35°C)	NVW > 0 (30°C and >40°C) NVW < 0 (>30-35°C)

3.3 Power Usage Effictiveness (PUE)

United States: Across all four US cities, **PUE decreases steadily with higher waste-heat temperature**, but the improvement varies by cooling configuration.

- At **low waste-heat temperatures (~30–35°C)**, all systems show relatively **high PUE**, indicating higher overall power consumption for cooling.
- As the waste-heat temperature increases, Uravu-waste heat (blended) and CT + ACC exhibit a significant drop in PUE, reflecting a much lower cooling energy demand.
- **DC + ACC** also shows notable improvement as the temperature rises, but not as strongly as the Uravu and CT + ACC configurations.
- **Uravu-electric** shows a **moderate decline**, as it relies partly on electricity rather than waste heat.
- **ACC** remains almost **flat** across all temperatures, showing no dependence on waste-heat availability.

Higher waste-heat temperature enables significant reductions in PUE, and **Uravu-waste heat (blended) and CT + ACC** achieve the **lowest PUE values** at high temperatures.

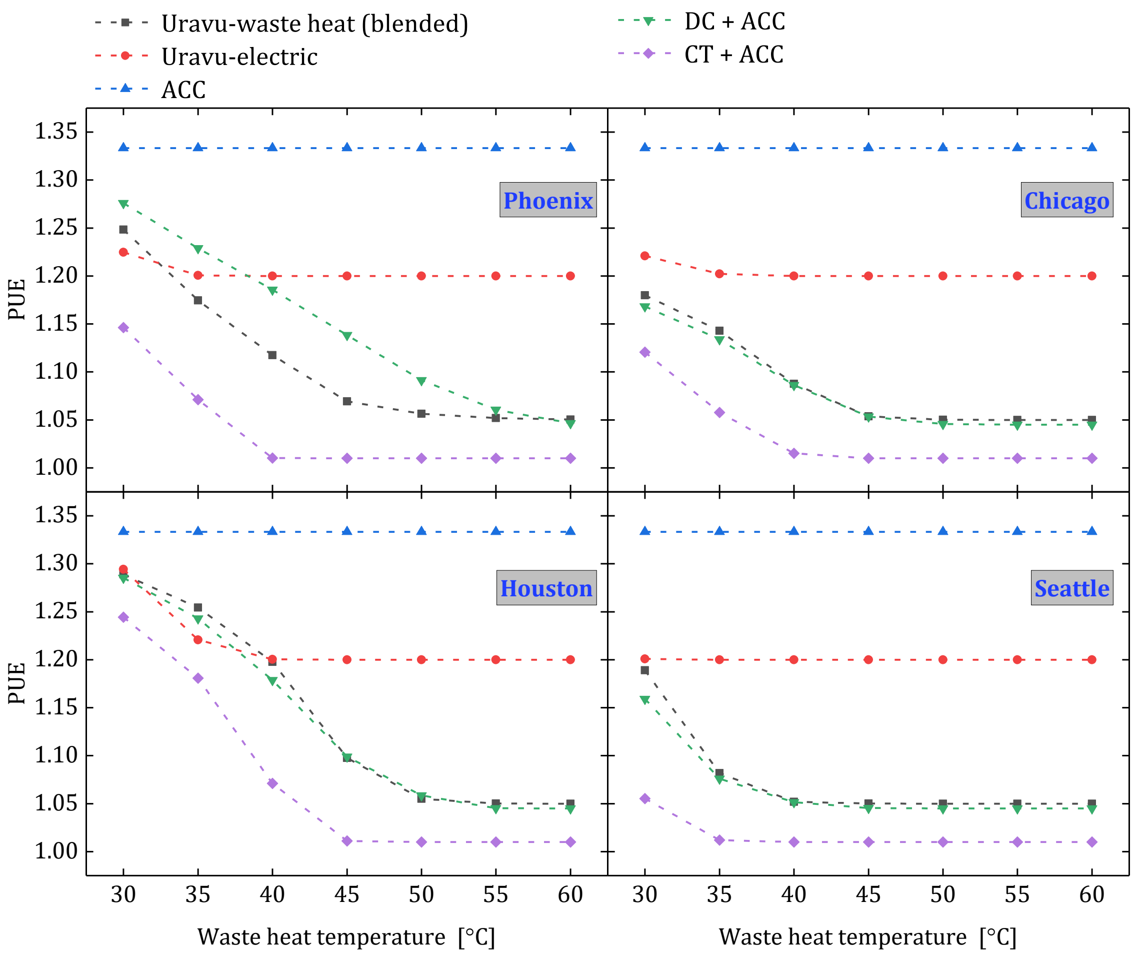

Figure 10: Variation of Power Usage Effectiveness with waste heat temperature for US-based cities.

European Union: The EU cities exhibit trends similar to those in the US, although the **reduction in PUE** resulting from temperature increases is slightly **more gradual** at lower temperatures due to comparatively milder climates.

- At temperatures around 30–35°C, all systems begin with **high PUE**, with **ACC** consistently being the most energy-intensive.
- At **40–45 °C**, **Uravu-waste heat (blended)** and **CT + ACC** show a rapid decline in PUE, marking the transition to highly efficient operation.
- **DC + ACC** follows a similar downward trend, converging with Uravu-waste heat at higher temperatures.
- **Uravu-electric** improves moderately but remains higher than the waste-heat-driven configuration.
- **ACC** stays constant at the top of the plot across the temperature range.

At elevated waste-heat temperatures, **Uravu-waste heat (blended)** becomes one of the most energy-efficient cooling options, pushing **PUE values close to 1.05, or slightly above, 1.01**, similar to CT+ACC.

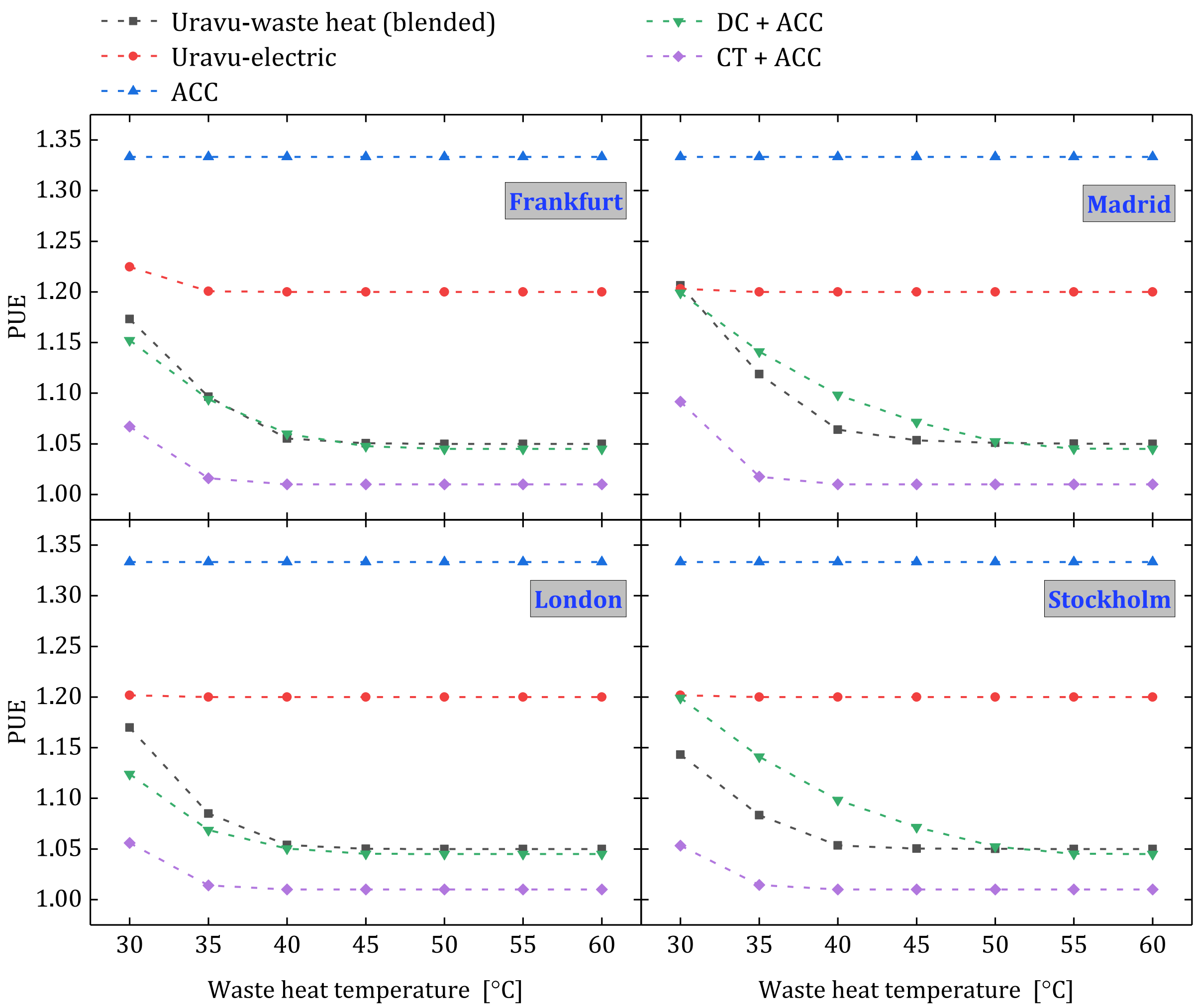

Figure 11: Variation of Power Usage Effectiveness with waste heat temperature for EU-based cities.

India and Singapore: The **Asian cities exhibit the strongest sensitivity to waste-heat temperature due to** high cooling demand and humid environments.

- At **30–35°C**, PUE is **highest overall**, especially for **ACC** and **Uravu-electric**.
- As waste-heat temperature increases, the PUE drops faster and more significantly than in the US and EU cases.
- **Uravu-waste heat (blended)** and **CT + ACC** achieve **the lowest PUE values**, frequently reaching **≈1.01-1.05**, meaning nearly all IT power goes to computing rather than cooling.
- **DC + ACC** also shows significant improvement, but plateaus slightly above the other two.
- **Uravu-electric** becomes more favorable at lower temperatures but stays above the waste-heat-driven configuration.
- **ACC** remains nearly flat and consistently the highest PUE case.

Asian cities achieve the **most significant reduction in PUE** when high-temperature waste heat is available, particularly for **Uravu-waste heat (blended)** and **CT + ACC**, making them the most energy-efficient cooling options in this region.

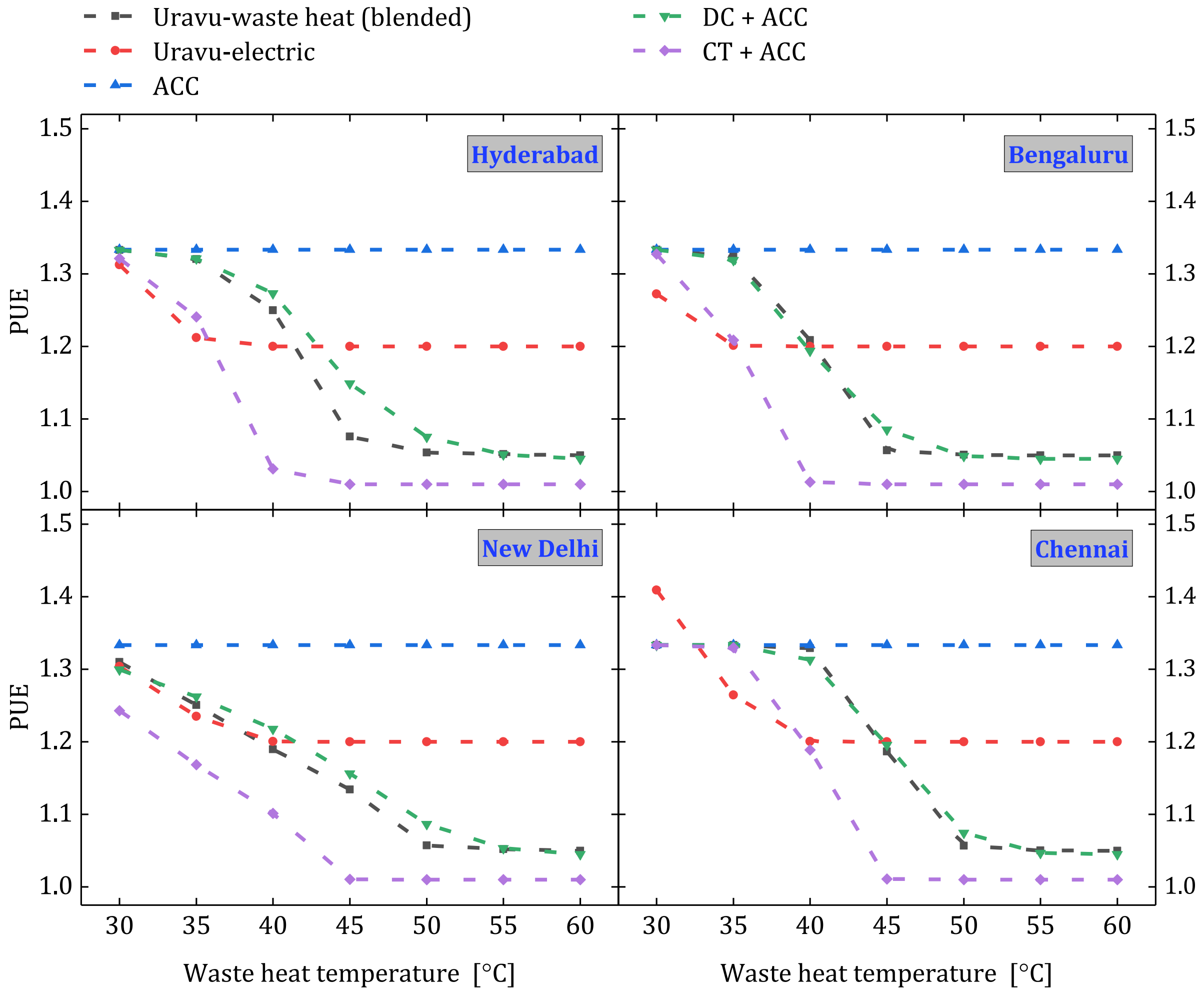

Figure 12: Variation of Power Usage Effectiveness with waste heat temperature for Indian cities.

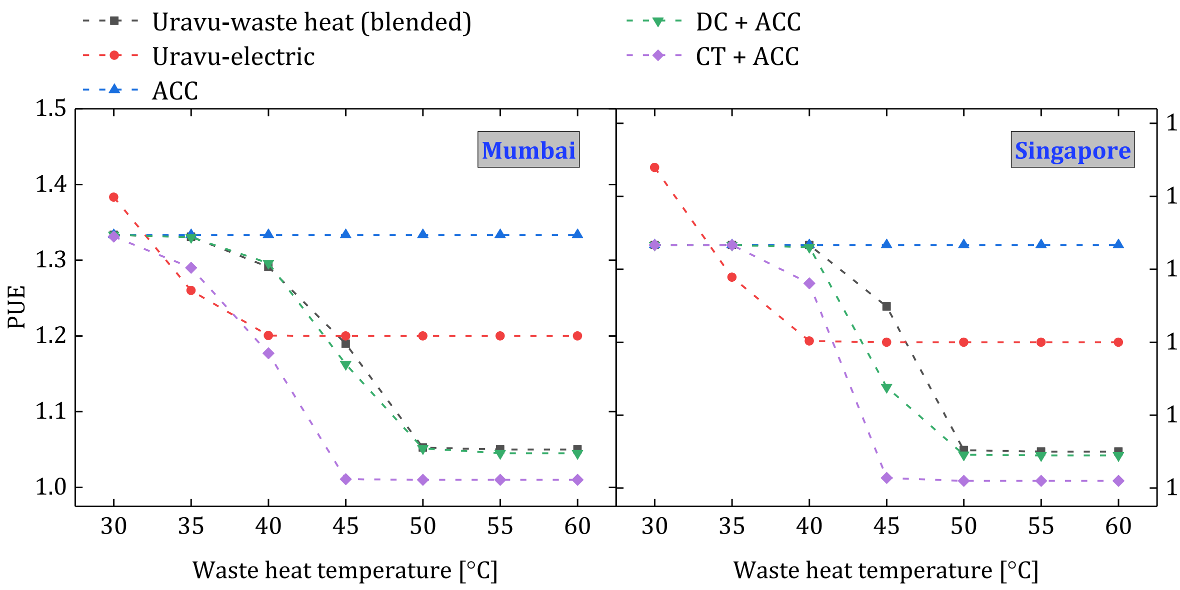

Figure 13: Variation of Power Usage Effectiveness with waste heat temperature for Mumbai and Singapore.

Table 4: Universal takeaway of PUE across regions.

Waste-heat temperature	Cooling energy requirement	PUE outcome
30–35°C	Highest	highest across all configurations
40–45°C	Rapid decrease	begins to converge for efficient configurations
≥45°C	Lowest	Uravu-waste heat and CT + ACC → lowest PUE

3.4 CO_2 emissions

United States: Across US cities, **CO_2 emissions decrease steadily with increasing waste-heat temperature** for all Uravu configurations. At low waste-heat temperatures (30–35°C), **Uravu-waste heat (blended)** and **DC + ACC** still depend partially on electrically driven cooling, resulting in relatively high emissions. As the waste-heat temperature rises, more cooling demand is met purely through heat-driven regeneration, resulting in a significant reduction in CO_2 emissions.

At temperatures **of 45°C or higher**, **Uravu-waste heat (blended)** consistently achieves the **lowest CO_2 emissions**. **Uravu-electric** shows smaller reductions because it still requires electricity regardless of heat availability. **ACC** remains almost flat (with the highest emissions), while **CT + ACC** achieves low emissions due to its low electricity consumption. With district heating uptime varying from 2,200 to 4,400 hours in the US, the CO_2 emissions are comparable to those of the Uravu waste heat system.

Higher waste-heat temperature → greater displacement of air-cooled chillers → significantly lower CO_2 emissions, especially for Uravu-waste heat.

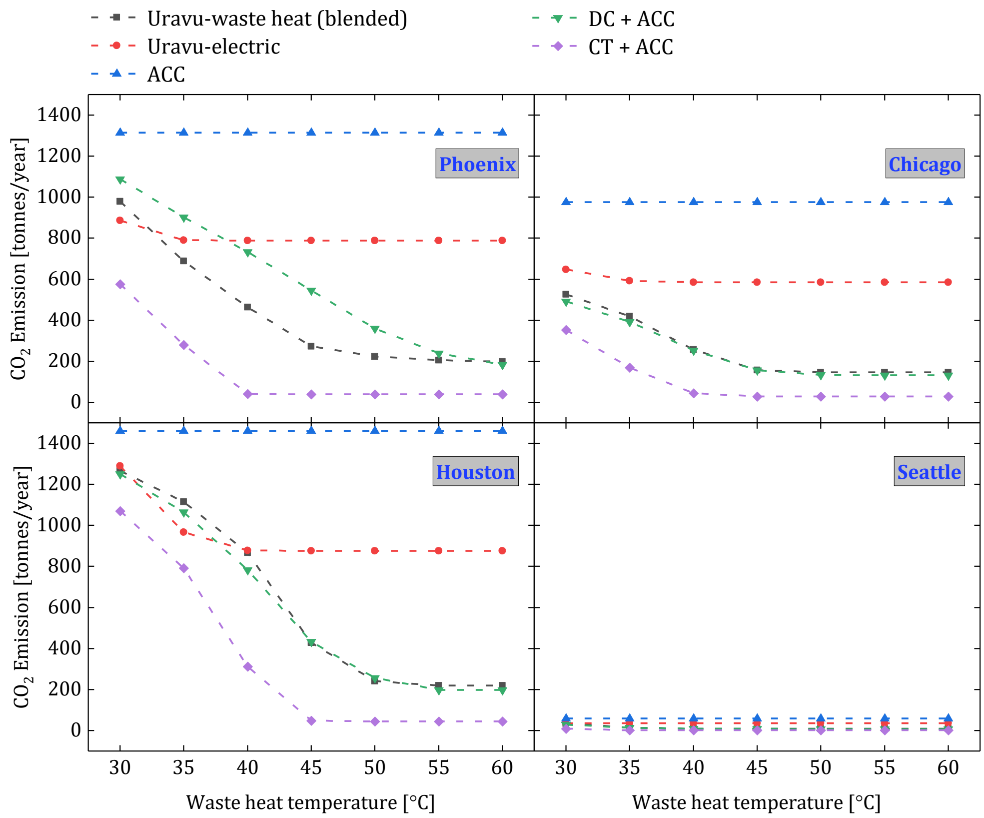

Figure 14: Variation of CO_2 emissions with waste heat temperature in US-based Cities.

European Union: EU cities exhibit a similar pattern, but with lower overall starting emissions due to cleaner energy mixes. At 30–35°C, **ACC** produces the highest emissions, followed by **Uravu-electric**, which remains above waste-heat-driven configurations. As waste-heat temperature rises, **Uravu-waste heat (blended)** and **CT + ACC** show substantial reductions in CO_2 emissions.

At ≥45°C, **Uravu-waste heat (blended)** achieves the **lowest emissions**, often approaching zero, indicating that reliance on electricity-based cooling becomes minimal at high grades of waste heat. Uravu-electric remains relatively constant across the temperature range. Due to higher district heating uptime in EU regions, the CO2 emissions are higher at low-waste heat temperatures and comparable to Uravu-waste heat configurations at high-waste heat temperatures.

At higher waste-heat temperatures, CO_2 emissions drop drastically, with the Uravu waste-heat configuration becoming the most climate-friendly cooling option.

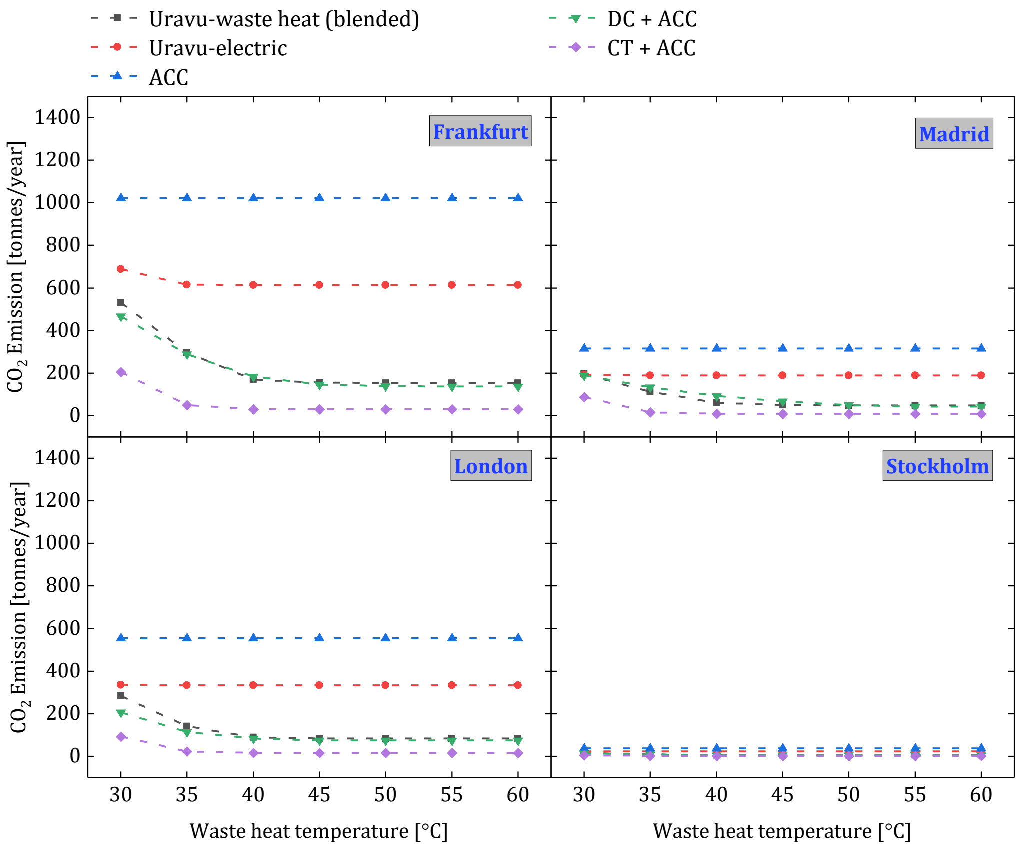

Figure 15: Variation of CO_2 emissions with waste heat temperature in EU-based Cities.

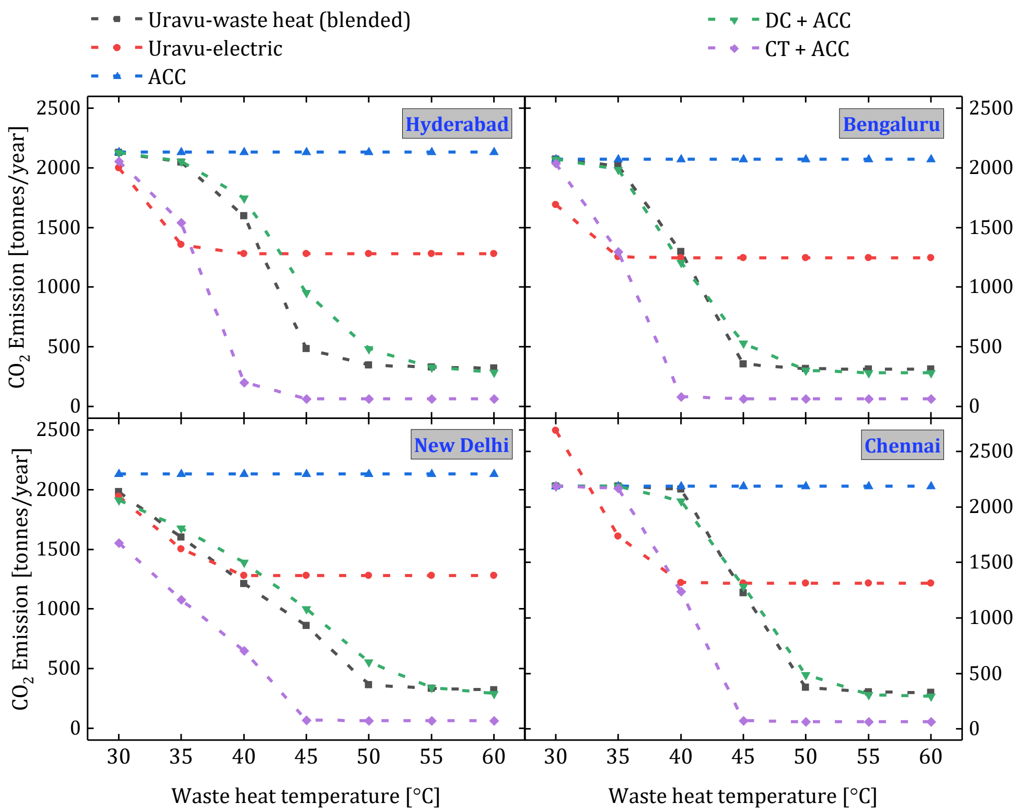

Figure 16: Variation of CO_2 emissions with waste heat temperature in Indian cities.

India and Singapore: Asian cities exhibit the most significant magnitude of CO_2 Emission reduction, despite rising waste heat temperatures, due to their high baseline cooling loads and grid emission intensities. At low temperatures (30–35°C), emissions from electrically driven cooling are high, especially for **ACC** and **Uravu-electric**.

As the waste-heat temperature increases, **Uravu-waste heat (blended)** rapidly displaces air-cooled chiller, causing a steep decline in CO_2 emissions. At around 45°C, emissions drop below 500 tonnes/year in most cities, and at temperatures of ≥50°C, emissions approach **100** tonnes/year because nearly all cooling demand is met through waste-heat regeneration rather than electricity.

High-temperature waste heat produces the **most significant absolute reduction in CO_2 emissions, with Uravu** waste heat eliminating most of the cooling-related emissions in warm and humid climates.

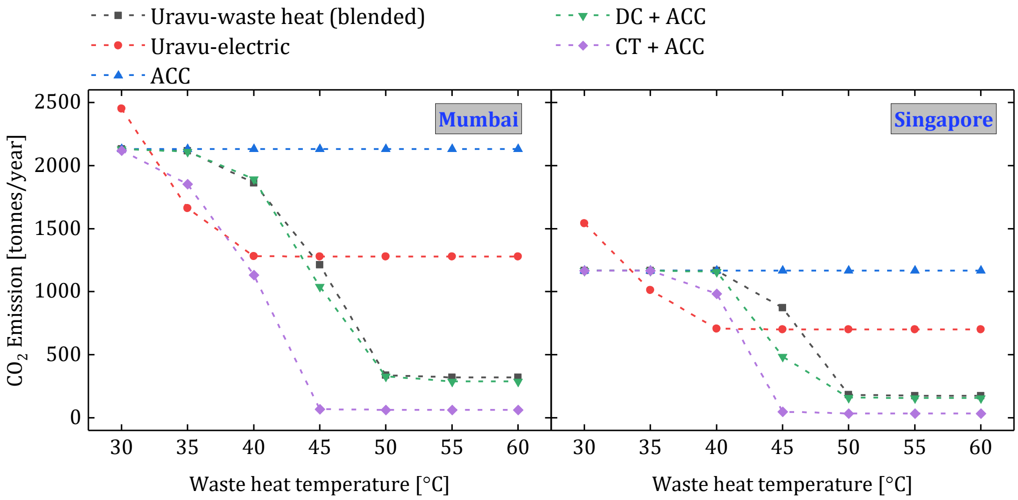

Figure 17: Variation of CO_2 emissions with waste heat temperature in Mumbai and Singapore.

Table 5: Universal takeaway of total CO_2 emissions across regions.

Waste-heat temperature	**CO_2-emission outcome**	**Explanation**
30–35 °C	High emissions	Cooling still relies partly on electricity
40–45 °C	Rapid drop in emissions	Increasing displacement of mechanical cooling
≥45 °C	Lowest emissions	Cooling becomes almost entirely waste heat-driven

Figure 18 compares the percentage reduction in CO_2 emissions achieved by three systems, **Uravu-waste heat (blended), Uravu-electric, and district heating using a heat pump**, relative to conventional natural-gas-based district heating. This comparison aims to assess how effectively each technology converts available waste heat into tangible

decarbonization benefits, particularly under varying waste-heat temperature conditions. The comparison is carried out only for cities with a district heating requirement of more than 5,000 hours annually.

In the 30–40°C waste-heat temperature range, both Frankfurt and London demonstrate that the Uravu-waste heat (blended) configuration already yields a noticeable reduction in CO_2 emissions, even though this range corresponds to low-grade heat that is generally considered difficult to reuse. For Stockholm, the drop is more pronounced due to a cleaner grid energy mix. In contrast, **Uravu-electric** and **heat-pump-based district heating** systems produce only modest and nearly constant emission reductions across this temperature band, as both systems continue to rely significantly on electricity rather than heat recovery. These results highlight that **even moderate-temperature waste heat can be effectively utilized by the Uravu-waste heat system to deliver meaningful climate benefits, reinforcing the advantage of direct thermal utilization over electricity-dependent approaches when the waste** heat temperature is relatively low.

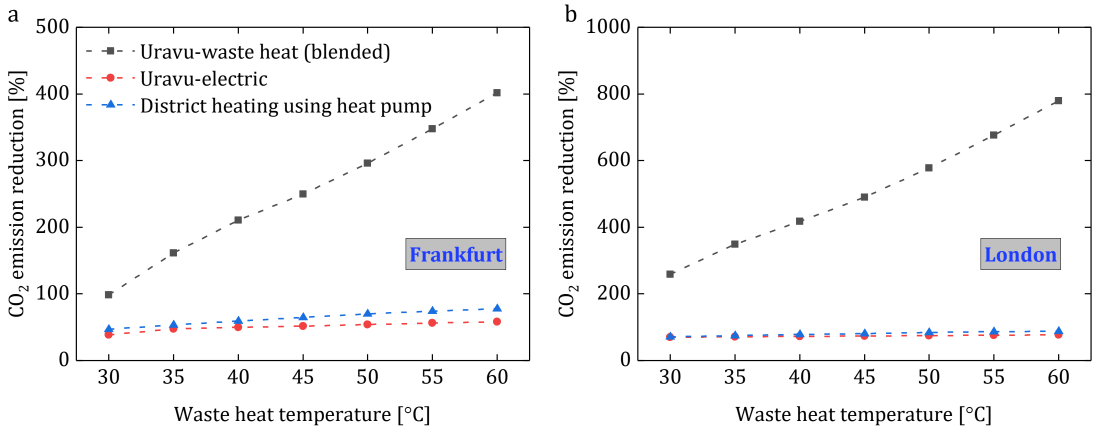

Figure 18: CO_2 emission reduction relative to natural-gas district heating in Frankfurt and London across varying waste-heat temperatures.

3.5 Water Usage Effectiveness (WUE)

In standard cooling systems, WUE is positive because water is used (for example, in cooling towers). However, when a technology reduces or eliminates evaporative water consumption or produces water, the WUE value can fall below zero, as seen in the case of Uravu systems.

United States: WUE improves (becomes more negative) as the waste-heat temperature increases. At low temperatures (30–35°C), **Uravu-waste heat** and **Uravu-electric** both exhibit modest water savings (slightly negative WUE), indicating that the system reduces direct water usage compared to traditional cooling. As the waste-heat temperature rises, **Uravu waste heat shows a strong downward trend, demonstrating a** rapidly increasing water-use efficiency.

At temperatures above ~45°C, **Uravu-waste heat** consistently achieves the **most significant water savings**, reaching values below –1.5 L/kWh in some cities. **Uravu-electric** remains nearly constant throughout the temperature range, meaning that while it avoids water losses, its water savings do not scale with temperature as strongly because it depends partly on electricity rather than waste heat.

Waste-heat-driven operation significantly reduces water use at higher temperatures, while electric-based operation offers moderate but steady water savings.

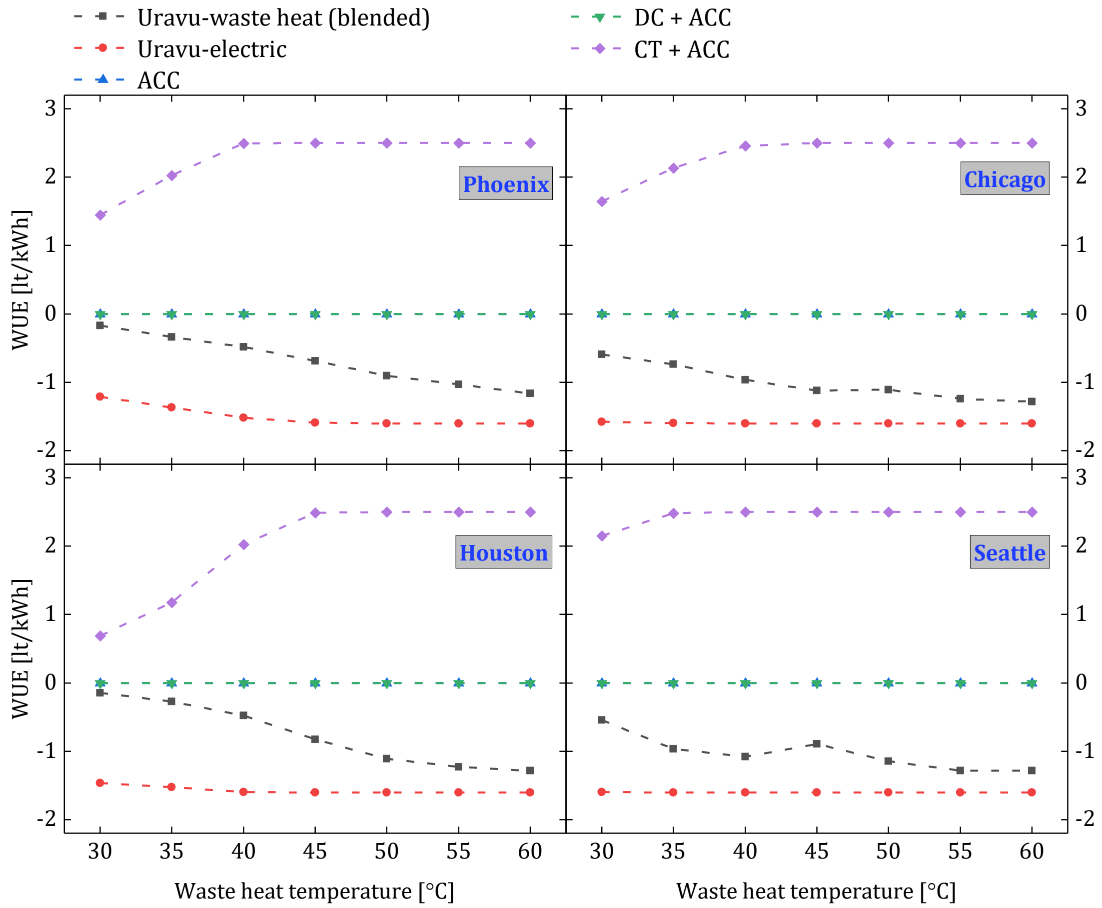

Figure 19: Variation of Water Usage Effectiveness with Waste Heat Temperature in US-based Cities.

European Union: The EU cities show a similar but slightly more gradual pattern. At lower temperatures (30–35°C), both **Uravu-waste heat** and **Uravu-electric** provide modest water savings. As the waste-heat temperature increases, Uravu waste heat shows a sharp reduction in WUE, indicating significant **improvements in water savings**.

Above ~45°C, **Uravu-waste heat** becomes highly water-efficient, approaching -1.2 L/kWh. Meanwhile, **Uravu-electric** remains nearly flat and does not benefit further from temperature increases. This distinction highlights that **waste-heat-driven regeneration, rather than electrically driven regeneration, is responsible for the significant change in water savings.**

Increasing the waste-heat temperature enhances water-saving performance, with Uravu waste heat showing the steepest improvement once high-temperatrue waste heat is available.

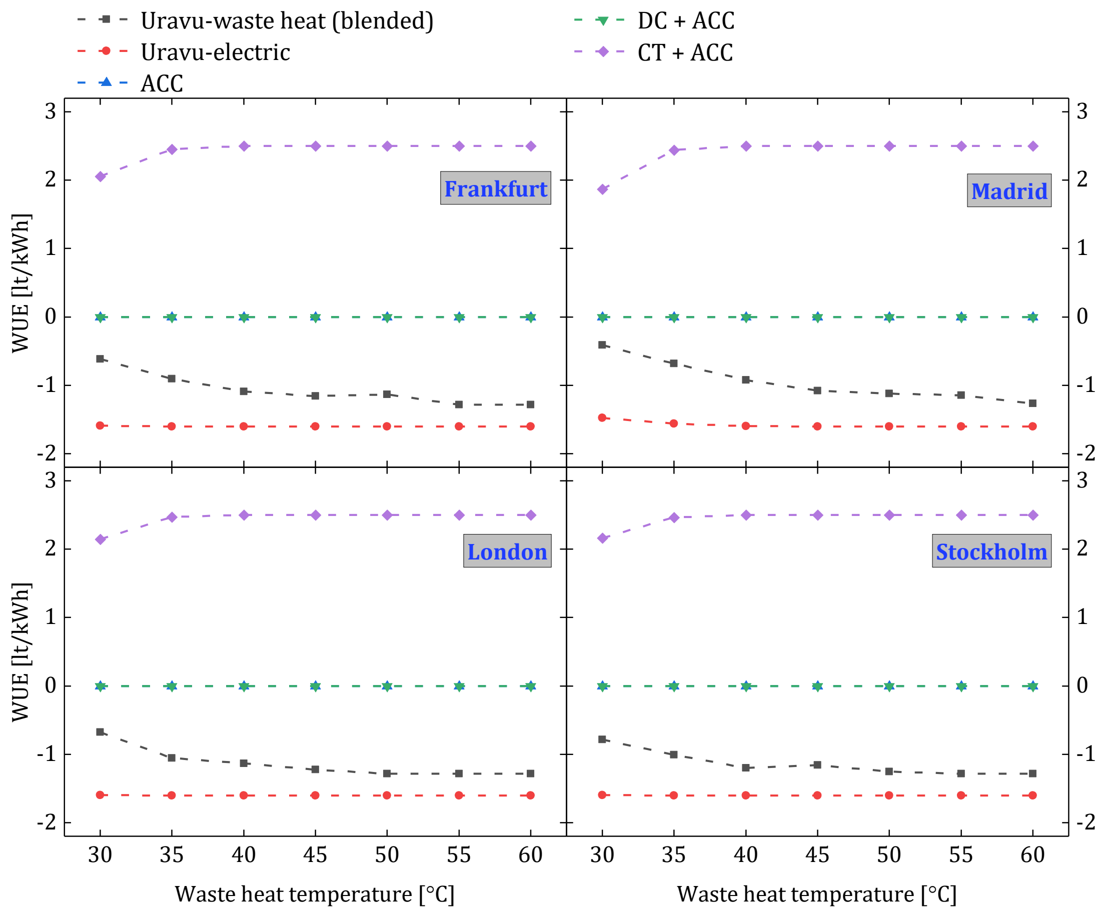

Figure 20: Variation of Water Usage Effectiveness with Waste Heat Temperature in EU-based Cities.

India and Singapore: WUE trends in Asian cities are the **strongest and most temperature-sensitive.** At low waste-heat temperatures, WUE is already slightly negative because high cooling loads allow notable water savings even in partial-uptime operation.

As the waste-heat temperature increases to 40–45 °C, Uravu waste heat exhibits a significant and rapid decrease in WUE, reflecting high system uptime and substantial quantities of water saved through reduced evaporative (CT) losses. At temperatures of ≥45°C, WUE values drop dramatically, -1.5 L/kWh, and remain in that range, highlighting that Uravu-waste heat can save substantial water in hot and humid climates, **where conventional cooling uses the most water.**

Uravu-electric again exhibits minor sensitivity to temperature, remaining nearly constant across different regions.

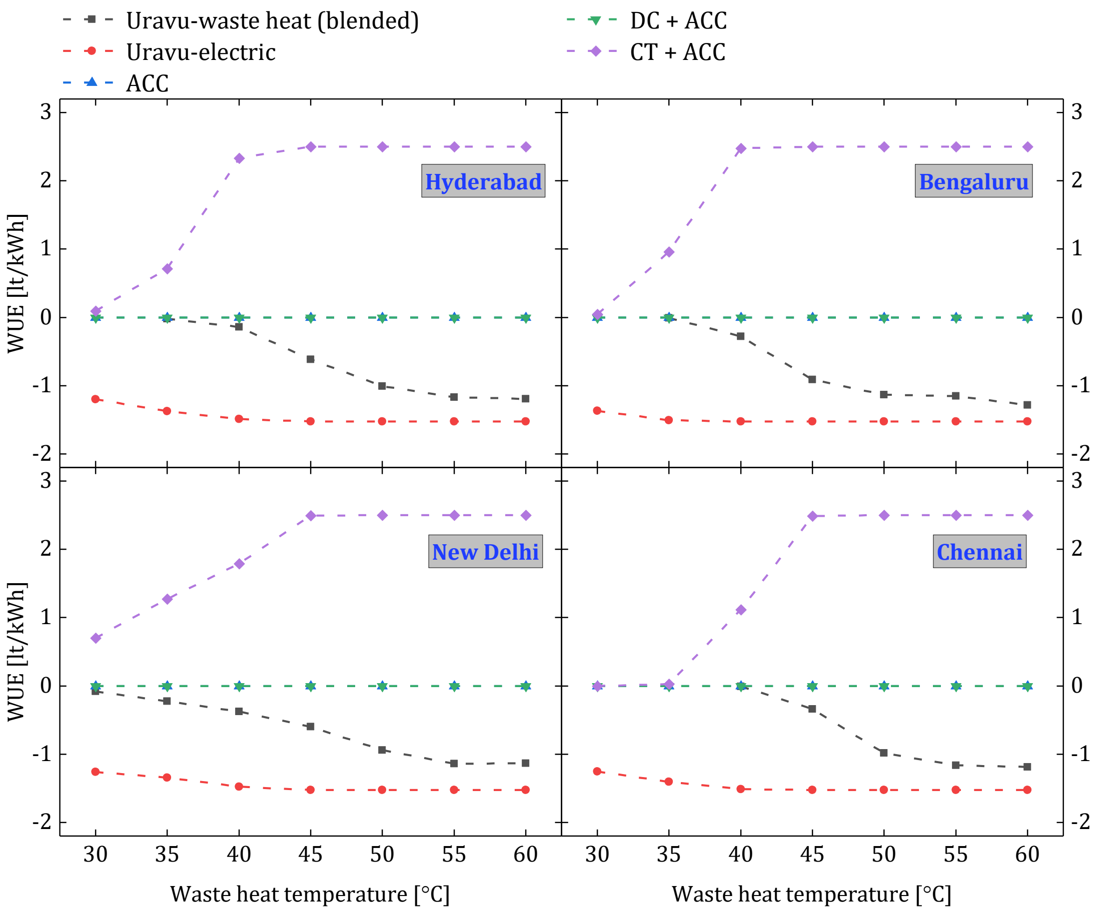

Figure 21: Variation of Water Usage Effectiveness with Waste Heat Temperature in Indian Cities.

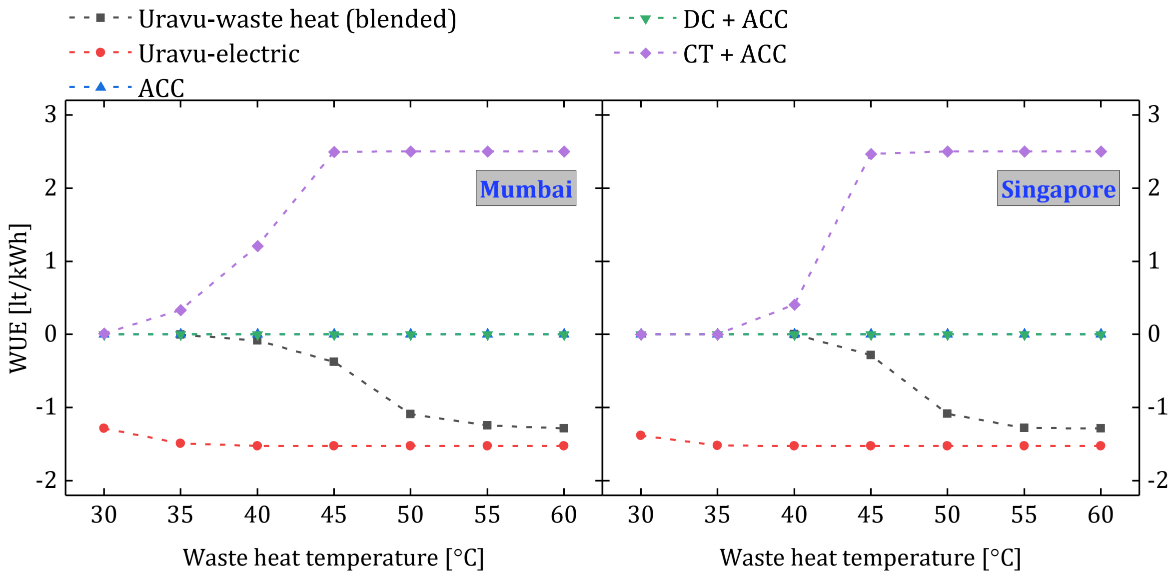

Figure 22: Variation of Water Usage Effectiveness with Waste Heat Temperature in Mumbai and Singapore.

Higher waste-heat temperatures produce the most significant water savings globally, especially in climates where evaporative cooling (CT + ACC) typically consumes large volumes of water.

Table 6: Universal takeaway of WUE across regions.

Waste-heat temperature	WUE trend	Reason
30–35 °C	Slightly negative (modest water savings)	Partial uptime → partial displacement of direct water usage
40–45 °C	Substantial decline (rapid improvement)	Significant displacement of direct water use
≥45 °C	Most negative (maximum water savings)	Full uptime → maximum avoidance of direct water usage

3.6 Indirect Water Usage

Indirect water usage (Scope-2 water) represents the off-site water consumed to generate the electricity required to operate the cooling system. Because each cooling configuration relies on grid electricity—and electricity production itself requires water—this metric captures the hidden water footprint associated with power use. This section examines how indirect water usage varies with waste-heat temperature across different cooling system configurations.

United States: Across all four US cities, the **secondary water footprint consistently decreases with higher waste-heat temperatures, indicating a** reduced reliance on grid electricity to run the cooling systems.

- **Uravu-waste heat (blended)** and **DC + ACC** show the **most substantial reduction**, dropping from ~5,000–7,000 m^3/year at 30 °C to nearly **1,000 m^3/year or lower at 55–60 °C**.
- **CT + ACC** provides an even sharper decline due to low power consumption for most cities beyond 45–50°C (especially Houston and Seattle).
- **Uravu-electric** remains moderately high and mostly **flat with temperature**, showing only marginal improvement because it continues to depend heavily on grid electricity.
- The **ACC-only** configuration consistently has the **highest secondary water footprint** and is nearly temperature-independent, highlighting its heavy dependence on electrical power.

Higher waste-heat temperatures drastically decrease indirect water consumption for Uravu-waste heat, DC + ACC, and CT + ACC, while Uravu-electric and ACC provide limited benefits.

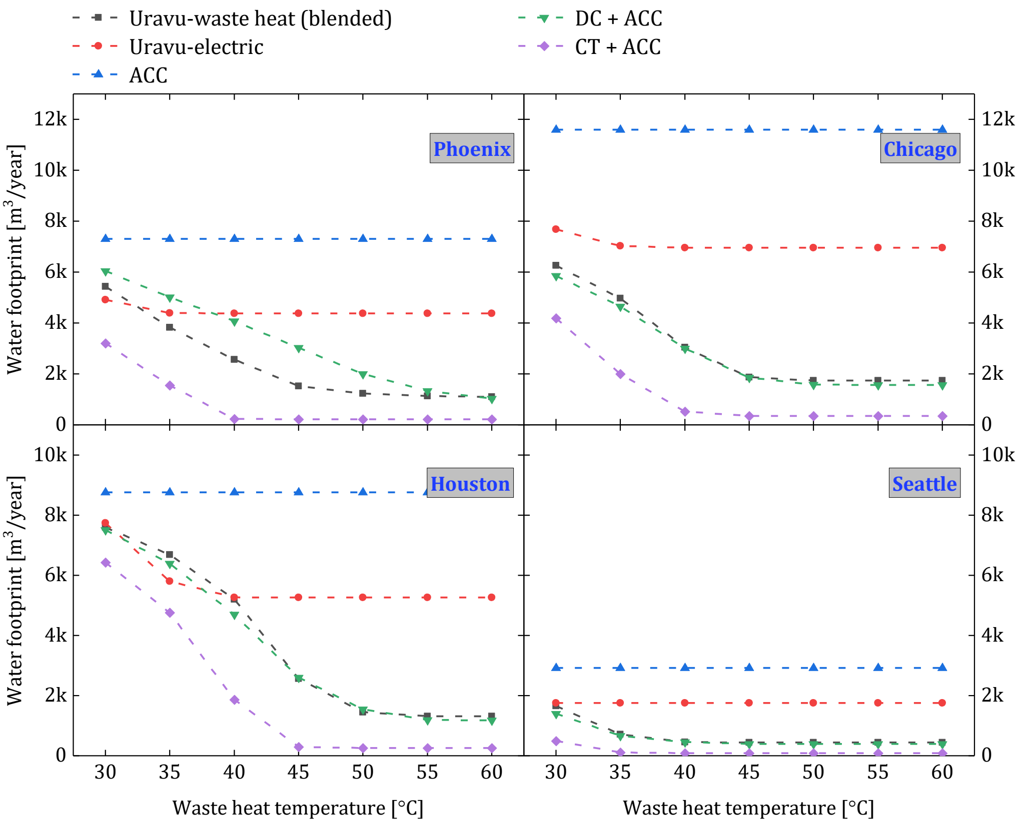

Figure 23: Variation of secondary water footprint with waste heat temperature in US-based Cities.

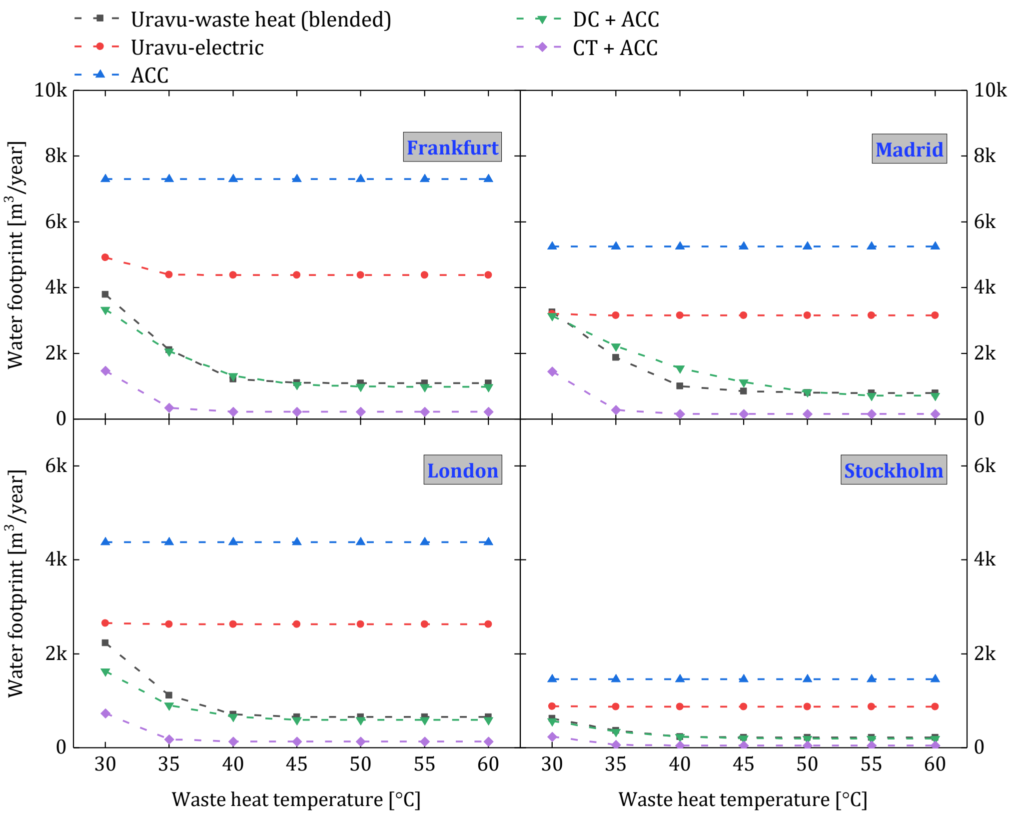

Figure 24: Variation of secondary water footprint with waste heat temperature in EU-based Cities.

European Union: A **similar trend to the US**, but with an even faster drop in secondary water footprint at moderate temperatures.

- **Uravu-waste heat (blended)** and **DC + ACC** decrease steeply from ~4,000–6,000 m³/year at 30 °C to **below 1,000 m³/year by 45–50 °C**.
- **CT + ACC** consistently reaches **up to 160 m³/year at 40–45 °C**, highlighting its high efficiency in mild European weather conditions.
- **Uravu-electric** remains almost constant, with only small reductions after 40 °C.
- **ACC-only** again remains the **worst performer**, staying above ~6,000 m³/year in all EU cities.

The secondary water footprint improves rapidly with temperature, and CT + ACC is the most effective combination at high waste-heat temperatures, followed by Uravu waste heat and DC + ACC.

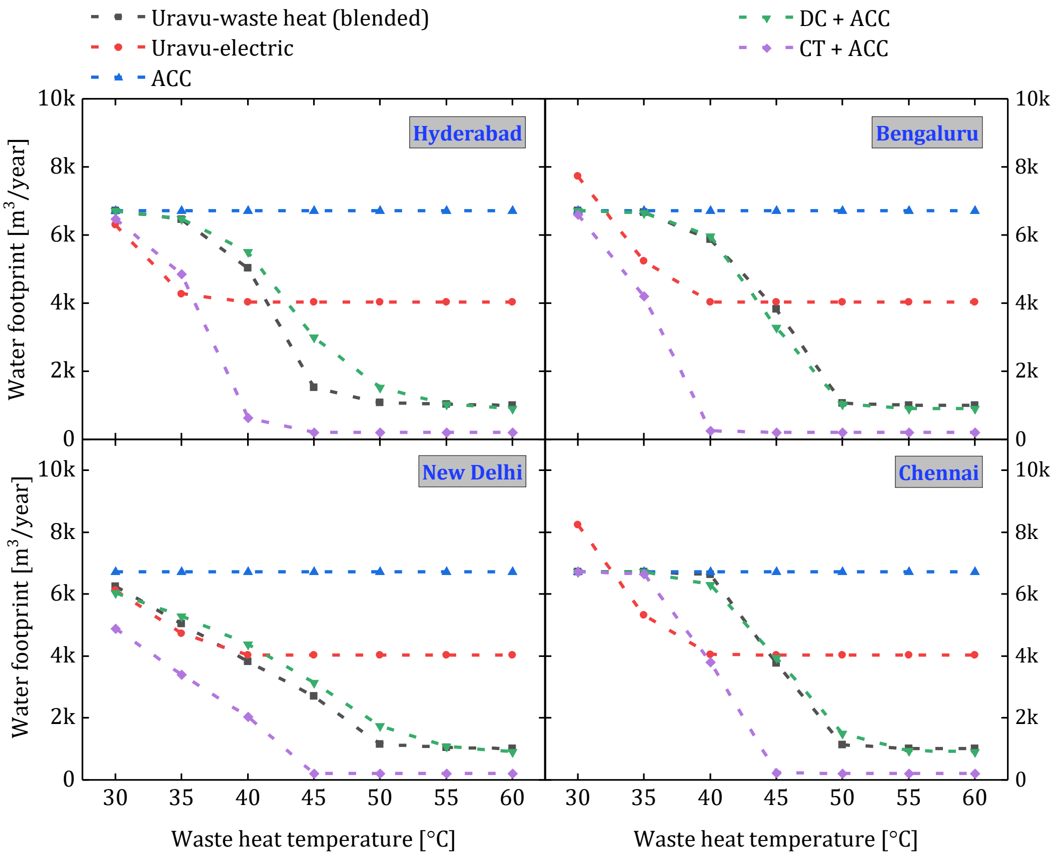

Figure 25: Variation of secondary water footprint with waste heat temperature in Indian Cities.

India and Singapore: Asian cities show **the strongest sensitivity** to waste-heat temperature due to high cooling demand and electricity consumption.

- **Uravu-waste heat (blended)** and **DC + ACC** plummet dramatically from ~6,000–8,000 m^3/year at 30 °C to **below 1,000 m^3/year beyond 50 °C**, indicating an extreme reduction in dependence on the electrical grid.
- **CT + ACC** becomes **~150 m^3/year** as early as **40–45 °C** for most cities — earlier than any other region.
- **Uravu-electric** decreases slightly but remains at a **moderate water footprint**, demonstrating that electricity dependency limits water savings.
- **ACC-only** again generates consistently **high water footprint**, independent of temperature.

Secondary water savings are the largest among all regions; CT + ACC offers the fastest drop to zero footprint, followed by Uravu-waste heat and DC + ACC.

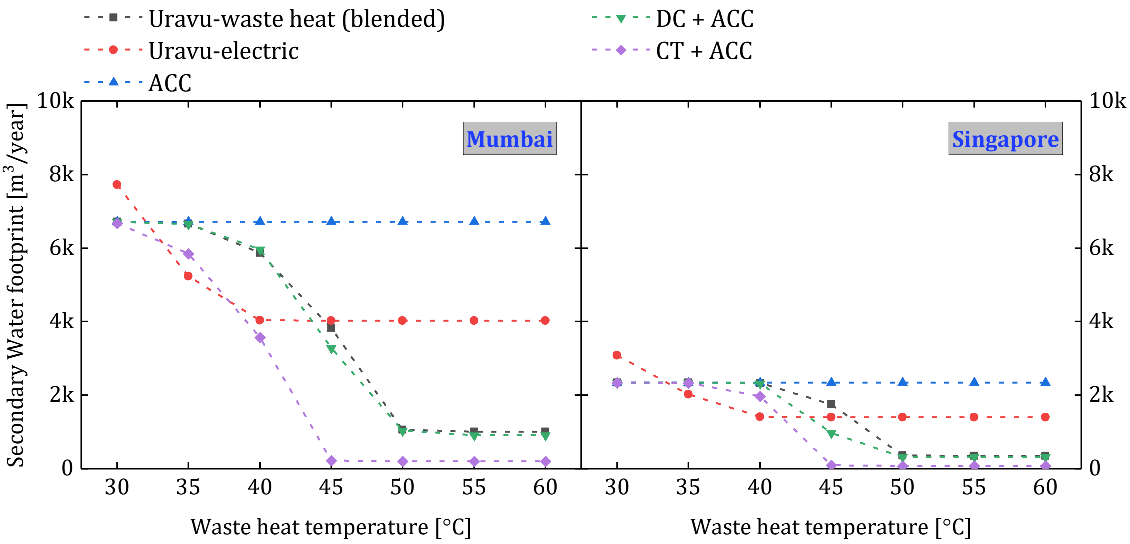

Figure 26: Variation of secondary water footprint with waste heat temperature in Mumbai and Singapore.

Table 7: Universal takeaway of total water footprint across regions.

Waste-heat temperature	Water footprint trend	Reason
30–35 °C	Moderate to high water consumption	Partial displacement of evaporative cooling
40–45 °C	Sharp decrease in water footprint	A large share of cooling is met via the Uravu unit
≥45 °C	Lowest water footprint	Full uptime → minimal/no cooling-tower losses

Table 8: Summary insight of total water footprint.

System configuration	Sensitivity to temperature	Long-term water (Scope-1 and Scope-2)savings potential
Uravu-waste heat (blended)	High	★★★★★ (strong decline with temperature)
Uravu-electric	Low	★★★ (small reduction due to electrical reliance)
DC + ACC	High	★★★★ (similar to Uravu-waste heat)
CT + ACC	Very high	★★ (strong decline of Scope-2 water footprint with temperature but still have high direct water usage)
ACC	None	★★★ (no direct water usage but has the highest Scope-2 water footprint at all temperatures)

4. Concluding remarks

This study shows that integrating the Uravu water-from-air system with data-center operations can convert waste heat into a valuable resource. By utilizing otherwise discarded heat, the system reduces cooling costs and environmental impact. It also lowers dependence on electricity-driven cooling and minimizes water consumption. Overall, Uravu enables data centers to operate more sustainably while generating on-site freshwater.

Overview of Compared Configurations

Configuration	Heat Source	Water Requirement	Electricity Need	Freshwater Production	Typical Use Case
Uravu-waste heat	Waste heat (≥35°C)	None	Very low	Yes	Sites with usable waste heat
Uravu-electric	Grid electricity	None	Moderate	Yes	Sites with low/no waste heat
ACC	Grid electricity	None	High	No	Water-scarce regions
DC + ACC	Grid electricity	Very low	High	No	Moderate climates
CT + ACC	Grid electricity	Very high	Moderate	No	Hot & humid climates
Heat Pump District Heating	Electricity	None	High	No	Heating-dominated regions

Performance Snapshot

Metric	Uravu-Waste Heat	Uravu-Electric	ACC	DC + ACC	CT + ACC
Cooling Cost	⭐⭐⭐⭐⭐ (Lowest beyond 40°C)	⭐⭐⭐	⭐⭐⭐	⭐⭐⭐	⭐⭐⭐⭐
Water Savings	⭐⭐⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐	⭐⭐⭐⭐	⭐⭐
CO_2 Reduction	⭐⭐⭐⭐⭐	⭐⭐⭐	⭐	⭐⭐⭐	⭐⭐⭐
Low grid energy consumption	⭐⭐⭐⭐⭐	⭐⭐⭐	⭐	⭐⭐⭐	⭐⭐⭐
Scalability	⭐⭐⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐⭐	⭐⭐⭐	⭐⭐
Total Value to Data Center Operator	**Very High**	High	Medium	Medium	Low

Why Uravu-Electric deserves special attention ?

Unlike waste-heat configurations, **Uravu-electric works anywhere**, even when waste heat is unavailable or insufficient. This positions it as:

- A **drop-in sustainability accelerator**
- A **bridge technology** until heat-recovery upgrades are added
- A **zero-water-consumption cooling pathway** for hyperscalers

Where is Uravu-Electric is especially advantageous ?

Scenario	Benefit
Low waste-heat temperature (<35°C)	Provides water production + sustainability gains when Uravu-waste heat uptime is limited especially in humid regions
New data centers	Enables cooling + water neutrality from day 1
Retrofit sites	Deployable without major HVAC reconfiguration

Key Advantages

Value Category	Uravu-Waste Heat	Uravu-Electric
Cooling OpEx savings	⭐⭐⭐⭐⭐	⭐⭐⭐
Water neutrality	⭐⭐⭐⭐⭐	⭐⭐⭐⭐
On-site freshwater	⭐⭐⭐⭐	⭐⭐⭐⭐⭐
CO_2 reduction	⭐⭐⭐⭐⭐	⭐⭐⭐
Works without heat loop	❌	✔
Works with renewables	✔	✔✔ (best pairing)

Future Implications for Data-Center Strategy

Trend	Impact
Water-neutral pledges	Favors Uravu solutions
Cooling decarbonization regulations	Uravu reduces grid load & CO_2
Heat recovery mandates	Uravu-waste heat becomes economically inevitable
Growth of edge data centers	Uravu-electric enables distributed deployment
AI + HPC thermal loads	Higher waste heat → higher uptime → higher NVW

🔥 **With waste heat:**

Cooling becomes cheaper as servers get hotter — while generating fresh water on-site.

⚡ **Without waste heat:**

Uravu-electric delivers sustainable water-neutral cooling anywhere with no water risk.