Scenario-Robust Siting of Semiconductor Fabrication Plants: A Geospatial Decision Analysis of Germany and Taiwan

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Resumo

Nesta dissertação de mestrado, *Scenario-Robust Siting of Semiconductor Fabrication Plants: A Geospatial Decision Analysis of Germany and Taiwan*, Georg Hoch analisa de que forma as alterações climáticas estão a alterar o perfil de risco da fabricação de semicondutores. Extremos de calor, secas persistentes e o acoplamento água-energia ameaçam a continuidade operacional das fábricas. Dada a elevada intensidade de capital e a longa vida útil destas instalações, a seleção do local deixa de ser uma decisão meramente orientada por custos e assume um caráter estratégico ajustado ao risco. A tese desenvolve um enquadramento consciente do clima e da água para a localização robusta de fábricas na Alemanha e em Taiwan entre 2024-2048.

O estudo aplica uma análise de decisão multicritério geoespacial (MCDA) que integra exposição climática, stress hídrico e risco de seca à escala da bacia, bem como proxies de acessibilidade a infraestruturas energéticas e logísticas. Os indicadores são harmonizados em grelhas nacionais e agregados com ponderações objetivas estimadas pelo método CRITIC. As condições atuais são ancoradas na reanálise ERA5, enquanto as trajetórias futuras seguem os cenários CMIP6 SSP2-4.5-SSP5-8.5 em quatro horizontes temporais. O risco hídrico é operacionalizado com o Aqueduct 3.0.

Os resultados mostram reordenações relevantes dos locais candidatos. Na Alemanha, corredores do norte e noroeste mantêm vantagem sob maior forçamento climático. Em Taiwan, bacias interiores do centro-norte destacam-se, enquanto o sul e o leste deterioram. Diagnósticos de robustez baseados em rankings identificam zonas estáveis e geram shortlists para orientar *due diligence* em água, rede elétrica, licenciamento e resiliência.

Palavras-chave: Fabricação de semicondutores, localização de fábricas, risco climático, escassez de água, análise geoespacial, análise de decisão multicritério, Alemanha, Taiwan.

Abstract

This Master's thesis, *Scenario-Robust Siting of Semiconductor Fabrication Plants: A Geospatial Decision Analysis of Germany and Taiwan*, Georg Hoch examines how climate change reshapes the operational risk profile of semiconductor fabrication, as rising heat extremes, drought persistence, and water-power interdependencies threaten operational continuity. Given the capital intensity and multi-decade lifetimes of fabrication plants, site selection becomes a risk-adjusted strategic decision rather than a cost-driven exercise. This thesis develops a climate- and water-aware framework for scenario-robust fab siting in Germany and Taiwan over 2024-2048.

The study applies a geospatial multi-criteria decision analysis (MCDA) that integrates climate exposure, basin-scale water stress and drought risk, and constant-accessibility proxies for power and logistics infrastructure. Indicators are harmonized to national analysis grids, direction-aligned, and aggregated using objective within-group weights derived via the CRITIC method, which emphasizes high-contrast, low-redundancy information. Present-day conditions are anchored to ERA5 reanalysis, while future trajectories follow CMIP6 SSP2-4.5 and SSP5-8.5 across four decision horizons. Basin-scale water risk is operationalized using Aqueduct 3.0, with a transparent extrapolation for the late-2040s where no official release exists.

Results show that climate and water constraints materially re-rank candidate locations in both countries. In Germany, northern and northwestern corridors remain consistently favorable as hot-dry persistence increases under higher forcing. In Taiwan, central-north interior basins with reservoir buffering recur frequently among top-ranked zones, while southern and eastern basins deteriorate. Rank-based robustness diagnostics identify zones that remain attractive across years and scenarios, yielding decision-ready shortlists to guide due diligence on water rights, grid capacity, permitting, and resilience investments.

Keywords: Semiconductor manufacturing, fab siting, climate risk, water stress, geospatial analysis, multi-criteria decision analysis, Germany, Taiwan.

Table of Content

Tabel of Figures:

1. Introduction

As the risk of heat and drought intensifies due to climate change, the production of semiconductors becomes increasingly exposed to disruptions in the supply of water and power. As fabs are central to many downstream industries, such disruptions can propagate beyond the plant level, creating supply chain and macroeconomic effects. Recent evidence supports this view in two ways. First, climate shocks are transmitted through supplier customer networks, reducing downstream operating income and increasing relationship terminations (Pankratz & Schiller, 2024). Secondly, trade linkages can amplify the macroeconomic costs of extreme heat, with indirect losses potentially equalling direct impacts in mid-century scenarios (Sun et al., 2024).

These tensions are particularly salient for a Germany Taiwan dual focus. Western Europe has experienced an accelerated rise in heat extremes, with evidence linking observed trends to changes in atmospheric circulation persistence that favour prolonged warm spells ("persistent states"), thereby elevating cooling loads and increasing stress on river systems and power grids (Rousi et al., 2022; Vautard et al., 2023). Importantly, compound hot dry risk depends not only on temperature but also on precipitation dynamics: mean precipitation trends and dryness persistence strongly influence how often concurrent warm-and-dry months occur in the future (Bevacqua et al., 2022). Taiwan, meanwhile, is highly drought-sensitive due to uneven rainfall seasonality and strong reliance on storage and allocation regimes. Recent work documents increasing drought risk and the operational relevance of dry-spell persistence in key basins, emphasizing that water availability and buffering capacity are central for industrial continuity (Hofste et al., 2019; Vo & Liou, 2024; Narvaez & Interconnected Disaster Risks team, 2022). In both geographies, chronic water stress and multi-month dry spells are first-order threats for fab uptime through their effects on process-water availability, cooling, and indirectly electricity reliability.

At the infrastructure level, drought risk couples directly to electricity reliability. Empirical evidence shows that thermoelectric generation in Europe and the United States is vulnerable to reduced summer river flows and elevated intake temperatures, which can reduce available generation during periods when cooling demand peaks (van Vliet et al., 2012). For continuous-process, water- and cooling-dependent manufacturing such as semiconductor fabrication, this water power coupling increases exposure to derates and curtailment risk and therefore raises the expected costs of operational disruptions. Complementing this, global assessments highlight that severe water scarcity already affects billions of people, underscoring the need to plan large industrial water users within basin-level constraints rather than relying on national averages (Mekonnen & Hoekstra, 2016; Vörösmarty et al., 2010).

Methodologically, this thesis integrates climate, water, and infrastructure evidence through geospatial multi-criteria decision analysis (MCDA) with objective weighting. All indicators are harmonized to a national analysis grid for each country and direction-aligned so that higher values indicate higher suitability. Criterion weights are derived within thematic groups using the CRITIC method (Criteria Importance Through Intercriteria Correlation), which combines contrast intensity (dispersion) and inter-criterion conflict (correlation) to produce a data-driven baseline that reduces subjective bias in weight selection (Diakoulaki, Mavrotas, & Papayannakis, 1995). Climate conditions are benchmarked using ERA5, a widely validated global reanalysis providing physically consistent atmospheric fields since 1979 (Hersbach et al., 2020). Forward trajectories are evaluated using CMIP6-consistent projections under SSP2-4.5 and SSP5-8.5) across four decision horizons (2024, 2028, 2038, 2048), following the CMIP6 and ScenarioMIP design papers (Eyring et al., 2016; O'Neill et al., 2016). Basin-scale water stress, variability, and drought risk are operationalized using Aqueduct Global Maps 3.0 indicators (Hofste et al., 2019). To guard against model risk, robustness and sensitivity are assessed within the additive MCDA framework using transparent perturbations of indicator weights and group-budget assumptions, alongside stability diagnostics across years and scenarios (Saltelli et al., 2008).

Finally, the thesis frames siting as reliability aware. Classical deterministic location models are insufficient when climate- and water-driven disruptions impose material expected costs. Reliability-aware facility-location research shows that when expected failure costs (e.g., downtime, yield loss, emergency mitigation) are internalized, preferred footprints shift toward diversification and proximity to backup capacity an implication directly relevant for fab portfolios facing water- and grid-related constraints (Snyder & Daskin, 2005). This logic provides the economic bridge from robustness metrics to decision relevance: scenario-robust zones are interpreted as candidates with lower expected failure-cost exposure and lower required resilience premiums over multi-decade investment horizons.

The present thesis tackles the following 3 research questions:

RQ1: How do climate, water, and drought exposures change fab suitability in Germany and Taiwan from 2024 to 2048?

RQ2: Which zones remain robust across a moderate emission scenario (SSP2-4.5) versus a high emission scenario (SSP5-8.5)?

RQ3: What are the business-relevant implications of selecting the scenario-robust shortlist versus plausible alternatives interpreted through operational failure drivers (downtime, yield loss, emergency mitigation) and mitigation levers that affect OPEX/CAPEX (e.g., reuse, storage, resilient grid access)?

By addressing these 3 research questions, this thesis advances methods and practice. Specifically, methodologically it (i) implements objective-weight geospatial MCDA (CRITIC) combining climate, water, and infrastructure indicators into a transparent suitability index; (ii) develops delta-mapping and robustness diagnostics (e.g., exceedance shares and Top-K stability) to prioritize zones that remain attractive across years and scenarios; and (iii) interprets rankings through a reliability-aware lens that links robustness to expected failure costs and resilience premiums (Diakoulaki et al., 1995; Saltelli et al., 2008; Snyder & Daskin, 2005). Managerially, it (iv) produces decision-ready Top-5 shortlists for Germany and Taiwan across 2024/2028/2038/2048; (v) validates plausibility via overlays with existing and planned fabs; and (vi) provides a due-diligence pathway that translates spatial screening outputs into bankable next steps on water rights, grid capacity, land permitting, and resilience investments.

The present analysis focuses on land-based siting for Germany and mainland Taiwan, integrating temperature and precipitation-based hydro-climate indicators, basin-scale water risk, and infrastructure proximity layers. It is designed for national screening and shortlist generation rather than micro-site engineering or end-to-end supply-chain optimization. Key limitations include proxy-based water-risk representation and resolution constraints, which are mitigated through scenario brackets, robustness checks, and explicit sensitivity testing (Hofste et al., 2019; Saltelli et al., 2008).

This thesis is structures as follows: Chapter 2 reviews the literature on semiconductor siting, hydro-climate risk, water scarcity, and MCDA. Chapter 3 documents study areas and data sources. Chapter 4 details preprocessing, indicator construction, CRITIC weighting, robustness metrics, and validation. Chapter 5 presents suitability maps and rankings for Germany and Taiwan (2024 - 2048) under SSP2-4.5 and SSP5-8.5 and derives scenario-robust shortlists. Chapter 6 discusses managerial implications, limitations, and decision governance. Chapter 7 concludes with answers to the research questions and outlines extensions (ensemble-explicit uncertainty and a reliability-adjusted economic module).

2. Background & Literature Review

2.1 Semiconductor value chains and why site selection is a portfolio decision

Semiconductors are at the heart of modern value chains, and recent journal articles show that climate shocks spread through supplier customer networks rather than remaining local. When the realised climate exposure at supplier locations exceeds expectations, the operating income of downstream customers falls and relationship terminations become more likely, effectively rewiring supply networks (Pankratz & Schiller, 2024). For semiconductor fabrication, an interconnected sequence of lithography, deposition, etching, cleaning/rinsing and metrology that depends on continuous utilities (power, ultrapure water and process gases) this implies that site selection and capacity planning must consider network contagion and utility uptime, as well as on-site engineering constraints.

At the macro level, extreme heat increases costs due to health impacts and lower labour productivity. It also causes indirect losses through trade, such as production interruptions at upstream suppliers, delayed deliveries, inventory shortages and output losses in downstream manufacturing. For sectors reliant on chips, especially the automotive sector with its tight takt times and just-in-time logistics, therefore, fab siting becomes a systemic risk decision with clear profit-and-loss implications (Sun et al., 2024).

2.2 Climate signal: Europe's hot-dry acceleration and East Asia's compound risks

Observational attribution shows that heat extremes in Western Europe have intensified at an unusually fast rate and are linked to dynamical changes, such as the occurrence of more persistent "double-jet" states. This circulation persistence increases the probability of hot spells lasting several weeks, which drive up demand for cooling, put stress on rivers and grids, and thus raise the risk of fab downtime (Rousi et al., 2022; Vautard et al., 2023). Taken together, these circulation-driven heat extremes in Western Europe and the rising probability of compound warm dry months in East/Southeast Asia increase the expected failure costs for continuous-process industries such as semiconductor fabrication, by raising the likelihood of simultaneous cooling, water, and power constraints (Snyder & Daskin, 2005; Bertsimas & Sim, 2004)

Beyond single hazards, the frequency of compound hot dry months (concurrent warmth and dryness) is a key industrial driver. Detection and attribution studies show that there have been significant increases in anthropogenic forcing, which is relevant for both Germany and East/Southeast Asia. In a warmer world, trends in mean precipitation rather than temperature will control the occurrence of hot dry periods in the future, making it increasingly important to track basin-scale water availability for water-intensive fabs (Bevacqua et al., 2022).

2.3 Water scarcity as first order constraint for fabs

Global diagnostics indicate that billions of people already live in areas of severe water scarcity. River systems that underpin industrial water security exhibit spatial mismatches between demand centres and reliable supply (Mekonnen & Hoekstra, 2016; Vörösmarty et al., 2010). For semiconductor fabrication facilities, this constraint is particularly acute: manufacturing requires large volumes of ultrapure water (UPW) for repeated cleaning and rinsing steps, as well as for controlling contamination across hundreds of wet benches and tools. Indeed, the environmental intensity of microchip production, including significant water usage, has long been documented (Williams, Ayres & Heller, 2002). Recent reviews detail the quality requirements of UPW and the treatment processes involved, which themselves entail energy usage and waste handling implications (Zhang et al., 2021). From a managerial perspective, this translates into higher expected Operational Expenditures (OPEX) for treatment/reuse and Capital Expenditures (CAPEX) for storage/redundancy. As well as potential exposure to curtailment under drought allocations. At basin scale, such scarcity directly translates into mitigation CAPEX/OPEX. For example, investments in reuse, on-site storage, and contractual buffers which shape the risk-adjusted value of siting options in a reliability-aware framework (Mekonnen & Hoekstra, 2016; Vörösmarty et al., 2010; Zhang et al., 2021; Snyder & Daskin, 2005; Bertsimas & Sim, 2004).

2.3 Drought power coupling and uptime economics

Thermoelectric power plants in Europe and the United States may experience a reduction in available capacity during hot, dry summers due to lower river flows and warmer intake water. This reduces generation at a time when cooling demand is at its peak (van Vliet et al., 2012). In the context of semiconductor manufacturing, this water-power coupling increases the anticipated cost of disruptions: water constraints can restrict the supply of ultrapure water, while power constraints can escalate the risk of outages or necessitate curtailments. These failure costs, including downtime, yield loss/scrap and emergency logistics, are the types of penalties that reliability-aware facility location models explicitly account for when comparing sites (van Vliet et al., 2012; Snyder & Daskin, 2005). Consequently, drought-related water and power restrictions should be considered part of the expected 'cost of service' when making location decisions (van Vliet et al., 2012).

2.4 Indicators for water stress and drought risk (Aqueduct) and why they fit

The operationalisation of water risk follows Aqueduct data indicators. Containing baseline water stress, seasonal and interannual variability, and drought hazard/risk layers capturing meteorological deficits and exposure. These constructs are grounded in global shortage and river-system diagnostics (Mekonnen & Hoekstra, 2016; Vörösmarty et al., 2010). Compound-event attribution and detection studies indicate that anthropogenic forcing has increased the likelihood of concurrent warm and dry months relevant to basin-scale water stress (Bevacqua et al., 2022; Chiang et al., 2022). In semiconductor manufacturing, these basin-level signals translate into higher ultrapure water (UPW) related treatment and buffering needs (Zhang et al., 2021). From a managerial perspective, the resulting mitigation CAPEX/OPEX (reuse systems, storage, contractual buffers) provides the economic bridge to risk-adjusted siting decisions. Consistent with reliability aware manufacturing facilities and robust decision-making under uncertainty (Snyder & Daskin, 2005; Bertsimas & Sim, 2004).

2.6 Operational resilience and risk economics

In siting research for hazard-exposed industries, results are commonly interpreted through reliability-aware facility-location models, whose objective functions explicitly include the expected costs of service interruptions (e.g., downtime, yield loss, expedited logistics). These models tend to Favor diversified footprints and proximity to backup capacity because such configurations reduce the expected penalties associated with outages (Snyder & Daskin, 2005). Complementarily, robust optimization explains why paying small steady-state premiums (e.g., for redundant utilities or more reliable basins) can be economically rational when they reduce downside risk (Bertsimas & Sim, 2004). For semiconductor fabs, these trade-offs are grounded in physical constraints: basin-scale water scarcity and drought persistence increase the likelihood of process-water curtailments (Mekonnen & Hoekstra, 2016), while heat and low river flows can derate thermoelectric generation precisely when cooling demand peaks (van Vliet et al., 2012).

2.7 Methods landscape: MCDA, objective weighting, robustness, and reliability

The evaluation of location for complex facilities is typically a multifaceted process that incorporates diverse forms of evidence. Including environmental exposures, water availability, and infrastructure access. MCDA facilitates transparent aggregation of incommensurate indicators and supports governance needs around traceability and auditability of choices, as documented across energy and infrastructure reviews that adopt multi-criteria approaches for planning and screening decisions (Pohekar & Ramachandran, 2004).

A recurrent methodological issue in MCDA pertains to the process of assigning weights to criteria. In an attempt to reduce subjectivity, the literature frequently turns to objective weighting schemes. The latter derive weights from the data rather than from preferences alone. Among these, CRITIC (CRiteria Importance Through Intercriteria Correlation) is a widely referenced method because it rewards indicators that carry high contrast (dispersion) while penalising redundancy (high correlation) across alternatives. This process prioritises information-rich, non-overlapping signals. The original formulation in Computers & Operations Research established CRITIC as a robust, data-driven baseline for weight setting that complements (rather than replaces) managerial judgment (Diakoulaki, Mavrotas, & Papayannakis, 1995).

It is imperative that siting outcomes demonstrate resilience to uncertainty; hence, the MCDA literature underscores the significance of robustness analysis as an integral component of optimal practices. A number of standard checks are employed in such cases, including sensitivity tests on individual criteria and on weight structures, as well as scenario-stability assessments. The latter are used to ascertain whether top-ranked options remain attractive under plausible futures. Empirical reviews suggest that broad spatial patterns are often stable under moderate weight variation, motivating explicit sensitivity and stability diagnostics (Pohekar & Ramachandran, 2004).

In conclusion, the interpretation of MCDA results is enhanced by two adjacent operations research strands. The analysis of facility location with consideration for reliability demonstrates that when anticipated failure costs (e.g., downtime, yield loss, expedited logistics) are internalised, optimal networks undergo a shift towards diversification and proximity to backup capacity. This insight finds direct application in the context of hazard-exposed industrial siting (Snyder & Daskin, 2005). Robust optimization formalizes the associated governance trade-off: small steady-state premiums can be justified if they materially reduce downside risk, guiding decision-makers to favour options that remain above threshold across scenarios (Bertsimas & Sim, 2004). Collectively, these literatures furnish a conceptual framework for interpreting MCDA rankings as portfolio decisions rather than as isolated annual selections.

2.8 Physical baselines and scenario-coherent projections

All climate-aware spatial analytics depend on consistent baselines and internally coherent scenarios.

This study uses the ERA5 reanalysis dataset as a benchmark for historical and near-present climate conditions that is consistent from a physical perspective (Hersbach et al., 2020). Future climate trajectories are represented using CMIP6 projections under SSP2-4.5 and SSP5-8.5, in accordance with the ScenarioMIP framework. This ensures consistency across models, variables, and forcing pathways over the 2024 to 2048 timeframe (Eyring et al., 2016; O'Neill et al., 2016). These scenarios encompass plausible mid-century conditions that are relevant to managerially significant exposures, including rising cooling demand and the persistence of dry or compound warm-dry periods, which impact water availability and power system reliability.

2.9 Germany: implications for fab suitability and business outcomes

Germany lies within Western Europe's accelerated heat regime, where attribution studies show a disproportionate intensification of heat extremes linked to changes in atmospheric circulation. More persistent circulation states ("double-jet" configurations) increase the likelihood of multi-week hot spells. For semiconductor fabrication, the operationally relevant factor is therefore not peak temperature, but the duration of heat exposure. Which drives sustained cooling demand and amplifies pressure on water resources and electricity systems (Rousi et al., 2022; Vautard et al., 2023).

These dynamics interact with physical constraints in the power system. Thermoelectric generation remains a key source of firm capacity in Europe and is vulnerable to reduced summer river flows and elevated intake temperatures. Empirical studies show that such conditions can materially reduce available generation capacity precisely during periods of peak cooling demand (van Vliet et al., 2012). For fabs, this heat water power coupling raises expected failure costs via a higher probability of derates, load-shedding exposure, and constrained process cooling.

The MCDA results translate these mechanisms into risk-adjusted siting trade-offs. Zones with slightly higher baseline costs can dominate economically if they reduce exposure to persistent hot dry conditions and associated utility constraints.

Structural factors reinforce this logic. Germany's position at the intersection of multiple TEN-T core corridors supports reliable access to markets, suppliers, and skilled labour (European Commission., 2024). Combined with strong demand from automotive and industrial sectors and recent fab investments in eastern Germany (TSMC, 2023). These conditions frame fab siting as a risk adjusted investment decision rather than a pure cost minimization exercise.

2.10 Taiwan: implications for fab suitability and business outcomes

Recent evidence suggests an increasing likelihood of concurrent warm and dry conditions in the region relevant to Taiwan, which can simultaneously tighten water availability and raise cooling demand (Chiang et al., 2022). These conditions simultaneously tighten process water availability and raise cooling demand, directly challenging fab uptime. This compound event signal is robust and anthropogenic, and it is especially relevant for Taiwan's basin scale planning (Chiang et al., 2022).

Looking forward, the occurrence of such compound hot dry states is controlled primarily by mean precipitation trends rather than temperature alone. Hence mid-century pathways that dry regional rainfall materially erode siting headroom even if absolute heat increases are similar (Bevacqua et al., 2022). In practical terms, precipitation driven change sharpens spatial differences within Taiwan's catchments. Making reservoir adjacency and reuse potential decisive tie breakers in otherwise comparable locations.

Power reliability is the second lever. Heat and low flows reduce thermoelectric output precisely when cooling loads peak, so proximity to resilient grid nodes mitigates expected reduce and curtailment exposure. Distance-to-grid thus functions as an operational proxy for summer adequacy in the ranking, complementing water-stress layers (van Vliet et al., 2012).

Managerially, these dynamics translate into higher expected OPEX for ultrapure-water treatment/reuse and for contingency buffers, and into a premium on sites that pair moderate drought persistence with short logistics to ports/airports. Interpreted through reliability aware location theory. Zones that remain above a decision threshold across scenarios central north interior basins with reservoir/grid access deserve priority over single year "winners" located in more volatile southern/eastern catchments (Bevacqua et al., 2022; Chiang et al., 2022; van Vliet et al., 2012).

2.11 Research gaps and how this study positions its contribution

The present work tackles 3 key research gaps:

The first gap pertains to single-hazard snapshots. A significant number of siting studies evaluate a single year/hazard; however, the present study emphasises delta-mapping (present to future) and scenario robustness (SSP2-4.5 vs. SSP5-8.5), consistent with decade-scale investment under uncertainty (O'Neill et al., 2016; Eyring et al., 2016).

The second gap pertains to the qualitative management of water risk. Water is frequently regarded as a mere checklist item. The integration of basin-scale stress/variability with compound hot dry likelihoods, in conjunction with their correlation to ultrapure water (UPW) centric fab operations, serves to establish a nexus between hydrologic reality and uptime/cooling. This linkage facilitates the translation of risk to CFOs through the conceptual lens of expected-failure-cost logic (Mekonnen & Hoekstra, 2016; Bevacqua et al., 2022; Zhang et al., 2021).

The third gap pertains to the correlation between MCDA outputs and reliability economics. It is noteworthy that there is a paucity of spatial studies that establish a connection between rankings and reliability-aware facility-location theory. The utilisation of exceedance shares and validation overlays (existing/planned fabrication facilities, e.g. Dresden) serves to reinforce the argument for the defence of a shortlist as an investable portfolio, as opposed to a static map. This approach has been demonstrated to enhance the quality of decisions made for automotive-exposed firms (Snyder & Daskin, 2005).

3. Data & Study Areas

3.1 Study areas and rationale (Germany & Taiwan)

The present study examines Germany and Taiwan, two countries that play a pivotal role in European value chains, yet exhibit contrasting hydro climate regimes and infrastructure systems. Western Europe has experienced an unusually rapid rise in summer heat extremes associated with circulation persistence ("double-jet" states). Elevating cooling demand and stressing rivers and grids. East/Southeast Asia shows a growing likelihood of concurrent warm dry conditions relevant for industrial water reliability. These signals provide the climate context for site screening, while detailed mechanisms and evidence are discussed in Chapter 2 (Rousi et al., 2022; Vautard et al., 2023; Chiang et al., 2022).

Germany is selected as a strategically central EU economy with dense, multimodal connectivity (TEN T corridors linking ports and continental markets) and a large, chip intensive industrial base (notably automotive). This centrality and logistics optionality make Germany a high-leverage testbed for comparing suitability under varying hydro climate pressures while keeping access to European demand consistent (European Commission., 2024.; ACEA., 2024).

Taiwan is included as a globally critical fabrication hub whose siting constraints are dominated by drought and storage. Basin scale water stress, pronounced rainfall seasonality, and reservoir dependence provide a stringent setting to evaluate water robust siting and infrastructure proximity for continuous fab operations, complementing the European case with a distinct hydro climate profile (Chiang et al., 2022).

3.2 Variables, Data Architecture, and Sources

The analysis integrates three evidence modules that jointly shape fab uptime and accessibility: (i) climate/hydro, (ii) water stress & drought, and (iii) infrastructure & accessibility. All indicators are harmonized onto a common national analysis grid and direction aligned so that higher values indicate higher suitability. Dataset families and provenances are listed below.

(i) Climate/Hydro

Near-surface air temperature (tas) and precipitation (pr) are used to represent the present climate and scenario consistent futures. Historical and near-present indicators are benchmarked against the fifth (and latest) generation global reanalysis from the European Centre for Medium Range Weather Forecast (ERA5), a widely validated dataset providing physically consistent atmospheric observations since 1979 (Hersbach et al., 2020). Forward climate trajectories follow the CMIP6 design to ensure scenario coherence. Specifically, projections under SSP2-4.5 and SSP5-8.5 are evaluated at four decision prediods (2024, 2028, 2038, 2048) in line with the CMIP6 overview and ScenarioMIP protocol (Eyring et al., 2016; O'Neill et al., 2016).

(ii) Water stress & drought

Basin scale scarcity and variability are represented with indicators capturing chronic pressure (withdrawals relative to renewable supply) and event persistence (multi-month precipitation/temperature deficits). The operational data source employed in this study is the World Resources Institute's Aqueduct Global Maps 3.0 indicators (Baseline Water Stress, Interannual and Seasonal Variability, and Drought Risk), which are then harmonised with the study grid (Hofste et al., 2019). The choice of these constructs is grounded in scientific evidence showing widespread severe water scarcity and river system threats (Mekonnen & Hoekstra, 2016; Vörösmarty et al., 2010). In compound event research indicating that future hot dry occurrences are strongly shaped by precipitation trends. Attribution work further documents an anthropogenic increase in concurrent warm and dry months relevant for East/Southeast Asia (Manning et al, 2019; Chiang et al., 2022).

(iii) Infrastructure & accessibility

Datasets cover high voltage/thermal generation nodes, reservoirs, long-distance highways, seaports, and airports to reflect connection options, redundancy, and outbound service. Their inclusion is motivated by evidence that heat and low flows can derate thermoelectric generation when cooling loads peak, linking siting to power adequacy during hot periods (van Vliet et al., 2012).

Validation points

Geocoded locations of existing and announced semiconductor fabs in Germany and Taiwan are compiled as point features for later external checks (listed in the Validation section).

3.3 Pre-processing and harmonization

To ensure spatial and conceptual comparability prior to analysis, all datasets are harmonised to a common national reference frame per country. All layers are reprojected to a single metric CRS (Germany: ETRS89 / UTM; Taiwan: TWD97 / TM2) and aligned to one national analysis grid, ensuring that distance-based indicators and spatial overlays are internally consistent (Pohekar & Ramachandran, 2004).

Vector datasets (roads, ports, reservoirs, airports, and power infrastructure) are reprojected and rasterised onto this grid. Infrastructure accessibility is represented through Euclidean distance-to-nearest-feature raster's. Climate inputs (tas and pr) are resampled to the target grid using conservative resampling (bilinear for continuous variables; nearest-neighbour for categorical masks) to avoid artificial extremes and to preserve spatial gradients relevant for subsequent indicator construction.

A feasible-land mask is applied so that non-developable cells do not receive suitability scores. The national land and coastline outlines are sourced from OpenStreetMap's administrative boundaries and coastline geometry (via OSMnx / OSM), and are used to exclude near-shore ocean pixels particularly important for Taiwan, where coastal cells can be close to infrastructure but are not buildable at national screening scale.

All indicators are direction-aligned so that higher values consistently imply higher suitability, and are min-max normalised to a common 0-1 scale prior to aggregation. Detailed implementation choices (grid resolution, raster construction, distance transformations and proximity scoring, NoData handling, and map-only smoothing) are reported in Section 4.2.

3.4 Target years and scenarios

The study concentrates looking at the years 2024, 2028, 2038, and 2048 to figure out the short-term and long-term planning and investment horizons. The combination of SSP2-4.5 (avg. emission scenario) and SSP5-8.5 (extreme emission scenario) creates a defensible scenario bracket that fits with the CMIP6/ScenarioMIP design (Eyring et al., 2016; O'Neill et al., 2016). The specific years match the release of Aqueduct 3.0 projections used in this study, which shows water-risk indicators at set time intervals. By using the available time slices as a base for the analysis, we can avoid temporal interpolation and keep the hydrologic indicators consistent across modules (Hofste, Reig, & Schleifer, 2019; World Resources Institute., 2019). The design makes it easy to compare the present with the future and check for scenario stability without adding any new timing assumptions.

3.5 Indicator derivation

- **Heat exposure:** Annual/summer *tas* means, plus persistence counts for consecutive hot months motivated by Western Europe's circulation-driven acceleration of heat extremes (Rousi et al., 2022; Vautard et al., 2023).
- **Precipitation and "hot-dry.":** *pr* means/percentiles and the co-occurrence of warm-dry months using literature-based thresholds. Future frequencies are mainly controlled by precipitation trends, not temperature alone (Bevacqua et al., 2022; Chiang et al., 2022).
- **Water stress/drought:** Basin scale baseline stress, seasonal/interannual variability, and drought hazard/risk to capture deficits and duration conceptually anchored in global scarcity diagnostics and river system security and operationalized with Aqueduct 3.0-style indicators (Mekonnen & Hoekstra, 2016; Vörösmarty et al., 2010; Hofste, Reig, & Schleifer, 2019; World Resources Institute., 2019).
- **Power accessibility:** Distance to high-voltage nodes/thermal capacity as a proxy for connection and redundancy, motivated by observed drought-related derates (van Vliet et al., 2012).
- **Logistics.** Distances to highways, seaports, and airports as proxies for constant accessibility and service levels to downstream customers.

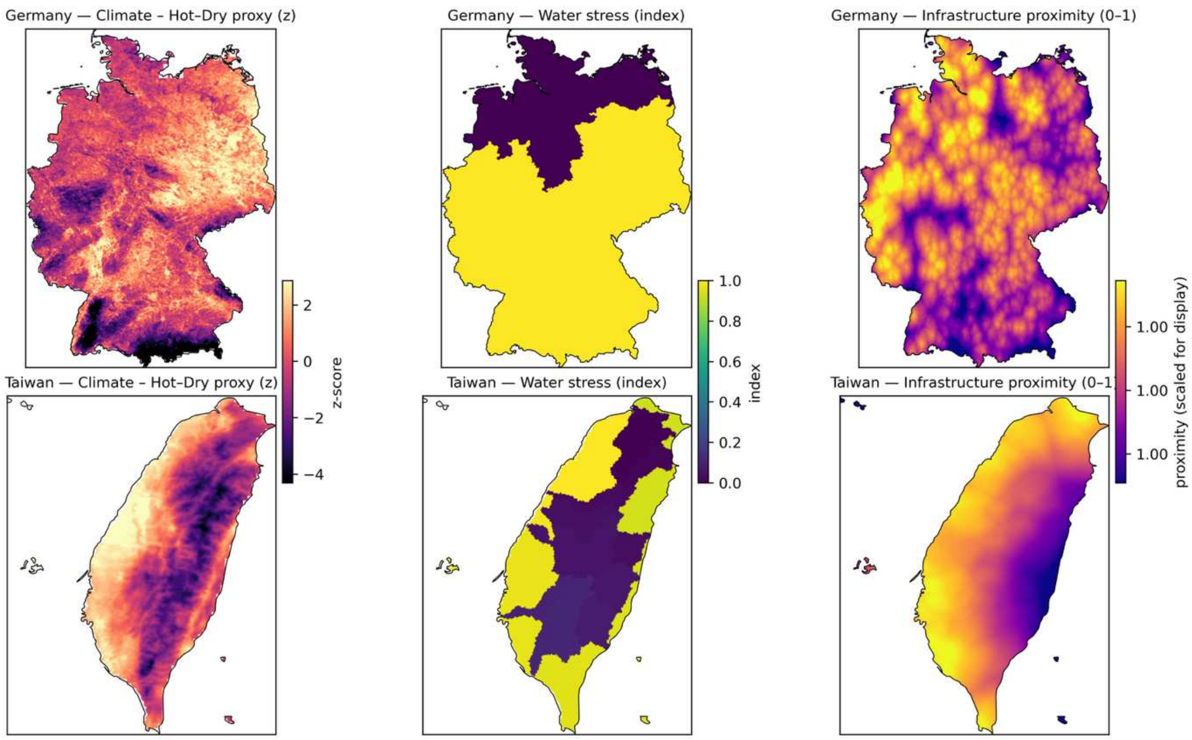


Figure 1: Indicator layers used in the MCDA: climate exposure, water stress, and infrastructure accessibility

3.6 Quality control and validation

The following three classes of checks are conducted: (i) plausibility tests on raster ranges and spatial patterns against ERA5-based climatology for the study period (Hersbach et al., 2020). (ii) Overlay validation with existing and announced fabs in Germany and Taiwan reporting ranked for positions known clusters (e.g. Dresden). (iii) Robustness diagnostics within the additive MCDA: one at a time indicator removals, +- shifts to criterion and group-budget weights as perturbations around the CRITIC baseline (without re-estimating CRITIC).

In the context of managerial interpretation, results are interpreted through the lens of reliability-aware facility-location and robust-optimisation economics. That is to say, when expected failure costs (downtime, yield loss, expedited logistics) are significant, diversified footprints and proximity to backup capacity are favoured, and small steady-state premiums can be rational if they reduce downside risk (Snyder & Daskin, 2005; Bertsimas & Sim, 2004). The aforementioned diagnostics evaluate the robustness and plausibility of the indicators in question without effecting any alterations to the definitions of said indicators or the objective CRITIC weighting.

3.7 Data/method limitations and mitigation

It is evident that resolution and downscaling continue to present a significant challenge. Climate fields are characterised by a coarser resolution compared to infrastructure vectors, resulting in scale mismatches. This effect is mitigated through the implementation of a consistent target grid, conservative resampling, and the application of smoothing exclusively for the purpose of visualisation. ERA5 is utilised as a physically consistent baseline for the purpose of conducting plausibility checks on near-present spatial patterns (Hersbach et al., 2020).

The global indicators employed to analyse water stress and drought do not utilise fully coupled hydro energy models. Nevertheless, these proxies are supported by evidence linking basin-scale scarcity, warm dry persistence, and thermoelectric derates to industrial risk (Mekonnen & Hoekstra, 2016; Bevacqua et al., 2022; van Vliet et al., 2012).Results are interpreted within an operational-resilience framework, focusing on expected failure costs (downtime, yield loss, expedited logistics) and mitigation CAPEX/OPEX (e.g., reuse, storage, PPAs). End-to-end routing or shipping-policy interactions are intentionally out of scope for the spatial scoring and therefore not modeled. The quality-control and sensitivity checks in Section 3.6 comprising plausibility validation against ERA5, overlay checks with existing and announced fabs, and robustness analysis based on Top-5 stability under weight perturbations mitigate the practical implications of these limitations.

4. Methodology

4.1 Design principles and alignment with the research questions

The methodological design translates heterogeneous geospatial evidence into decision ready maps and a defensible shortlist of Top-5 zones, for new semiconductor fabrics in Germany and Taiwan. The pipeline is built to answer the following three research questions: how dose climate and water exposures alter fab suitability until 2048 (RQ1), which zones remain robust across SSP2-4.5 vs. SSP5-8.5 (RQ2), and what the business relevant implications of robust, climate aware siting are for operational reliability and investment value (RQ3). The approach emphasizes physical consistency, scenario coherence, and managerial interpretability. ERA5 serves as a physically consistent baseline for plausibility checking; CMIP6/ScenarioMIP provides forward trajectories under SSP2-4.5 and SSP5-8.5 (Hersbach et al., 2020; Eyring et al., 2016; O'Neill et al., 2016). Water scarcity and drought are operationalized using Aqueduct 3.0 indicators at basin scale (Hofste et al., 2019), while utility and logistics continuity are captured via proximity to relevant infrastructure. The method combines objective, data-driven weighting within indicator groups with transparent, governance-friendly group priorities, producing composite suitability maps, change (delta) maps, robustness diagnostics, and a Top-5 shortlist supported by plausibility and overlay checks per country and time slice.

4.2 Preprocessing and raster foundation

All inputs are harmonized to a single national analysis grid per study area using one metric CRS per country, ensuring comparable distance measures across layers as standard in geospatial MCDA (Pohekar & Ramachandran, 2004). Land and coastline masks prevent near shore ocean pixels from receiving suitability scores particularly important for Taiwan, where many coastal pixels fall close to infrastructure yet are not developable. The target grid resolution is chosen as a compromise between climate data fidelity and infrastructure detail, and all layers are resampled or rasterized onto this common grid.

Vector datasets (e.g., roads, ports, reservoirs, power plants/substations, airports) are reprojected to the common CRS and rasterized onto the analysis grid. Accessibility surfaces are derived via Euclidean distance to nearest feature rasters, a common proxy for infrastructure proximity in siting contexts (Pohekar & Ramachandran, 2004). Distances are transformed into proximity scores in (0,1) using an exponential decay with feature-specific distance caps, and then combined into a composite infrastructure proximity surface.

Climate rasters are resampled to the target grid using conservative methods to preserve value distributions used in analysis; ERA5 provides a physically consistent reference for plausibility checking of near present spatial patterns (Hersbach et al., 2020). NoData handling is enforced consistently so masked cells do not enter scoring or normalization.

Beyond land and coastline masking, no additional hard constraints (e.g., protected areas, slope, or land-use exclusions) are imposed at this screening stage; developability considerations are deferred to zone-level due diligence. All continuous indicators are min/max normalized to (0,1) and direction aligned so higher values always indicate higher suitability, consistent with additive MCDA practice (Diakoulaki et al., 1995). Any visual smoothing is applied solely for cartographic readability; all computations use the unsmoothed rasters.

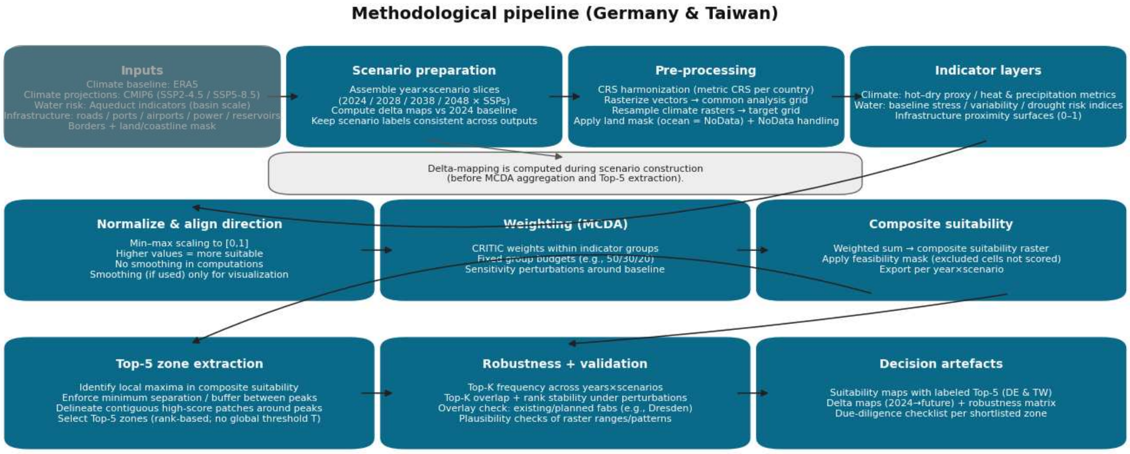


Figure 2: End-to-end methodological pipeline for suitability mapping and Top-5 site selection

4.3 Indicator construction

4.3.1 Climate and compound hot dry signals

It is evident that effective operational performance is contingent on effective cooling systems and the avoidance of prolonged supply constraints. To this end, the derivation of climate indicators is undertaken to capture both intensity and persistence, with the utilisation of a proxy-based approach. For each time slice (2024, 2028, 2038, 2048), the construction of standardised temperature and precipitation indicators is undertaken, and these are then combined into a spatial hot-dry proxy that reflects concurrent warmth and dryness. Rather than explicitly tracking individual events, persistence is represented implicitly through aggregated climate signals that emphasise sustained warm and dry conditions relevant for industrial continuity.

These constructs reflect two robust results from scientific literature: (i) Western Europe has experienced an accelerated increase in heat extremes, driven by circulation persistence ("double jets"), resulting in prolonged periods of high temperature that exert stress on cooling systems and energy grids (Rousi et al., 2022; Vautard et al., 2023). (ii) The future frequency of compound hot-dry events are primarily influenced by precipitation trends rather than temperature alone, underscoring the importance of precipitation pathways in mid-century planning (Bevacqua et al., 2022). The climate indicators in the scoring system therefore emphasise concurrent warmth dryness and persistence as operationally relevant risk proxies, rather than event-level climatological extremes.

4.3.2 Basin-scale water stress and drought risk (Aqueduct-style)

Semiconductor fabrication is water-intensive; uninterrupted access to ultrapure water and cooling reserves is a prerequisite for uptime. The operationalisation of water-related exposure is achieved through the implementation of Aqueduct-style, basin-scale indicators, which are widely utilised for the screening of large industrial water users. The following elements are to be considered: baseline water stress (withdrawals relative to the supply of renewable resources), seasonal and interannual variability (volatility that must be mitigated through storage, contracts, or reuse), and drought hazard/risk layers (capturing deficit likelihood and severity). Collectively, these indicators signify chronic scarcity and variability-driven supply risk at the basin level, in accordance with global diagnostics of water scarcity and river-system pressure (Mekonnen & Hoekstra, 2016; Vörösmarty et al., 2010). Looking at Taiwan, it is proposed that drought related exposure is to be interpreted in conjunction with the findings of research into detection and attribution. It indicates an increased likelihood of concurrent warm and dry conditions under the influence of anthropogenic forcing. These conditions have the potential to intensify both co-occurring cooling demand and water constraints (Chiang et al., 2022). The basin framing is intentional: decisions for large water users should reflect basin-level constraints and competition for supply rather than national averages.

4.3.3 Constant accessibility (uptime proxies)

In addition to exposures, the reliability of fabrication is contingent upon the consistent availability of power and logistics. In order to expand upon this, proximity to grid/plant nodes is included (as a proxy for connection options), in addition to reservoirs (local buffering capacity), and major roads/ports/airports (outbound accessibility). Infrastructure vectors are converted into distance-to-nearest-feature rasters and transformed into bounded proximity scores on a 0-1 scale to reflect diminishing relevance with distance. As demonstrated in the relevant literature, there is a demonstrable correlation between heat and drought, on the one hand, and reduced thermoelectric generation when cooling demand peaks, on the other. This, in turn, increases the likelihood of power-system constraints during periods of high temperature (van Vliet et al., 2012). These distance-based proxies serve to complement climate and water indicators, thereby ensuring the establishment of practical continuity conditions for site screening.

It has been demonstrated that climate, water, and infrastructure layers are not aggregated in their raw form, but rather only after domain-consistent normalisation and transformation into commensurable indicators. This renders the MCDA aggregation more defensible and serves to reduce the risk of "black-box" criticism.

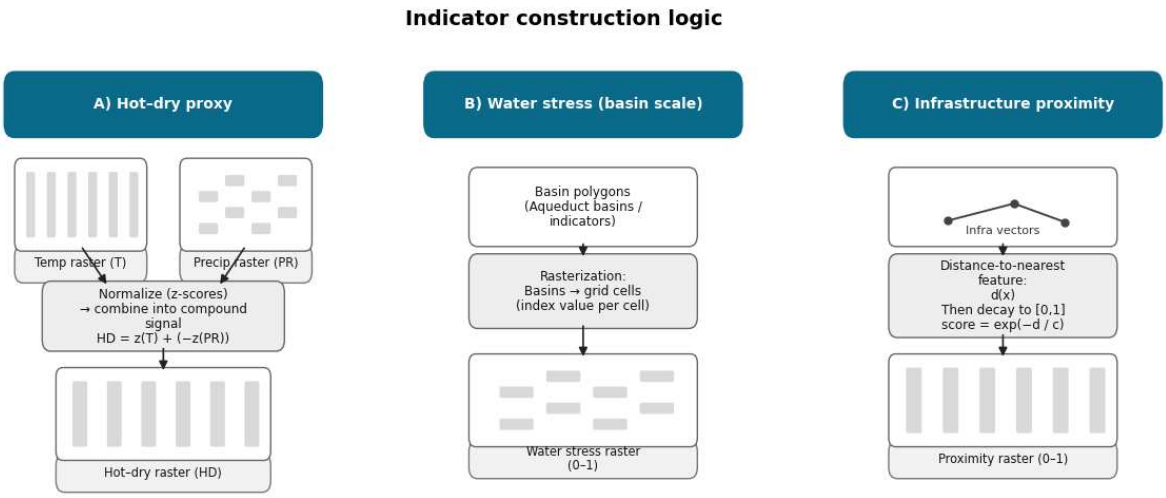


Figure 3: Transformation of raw climate, water, and infrastructure data into MCDA indicators

4.4 Weighting: objective CRITIC + hierarchical group priorities

To minimize subjective bias while retaining managerial interpretability, I combine objective, data-driven weighting with a transparent hierarchical structure. Within each thematic group (Climate & Water; Logistics; Remainder), The CRITIC weights are derived from indicators that exhibit strong spatial contrast and low redundancy with others. (Diakoulaki et al., 1995). In addition, fixed group budgets are imposed to reflect common governance trade-offs between risk exposure and feasibility:

- **Climate & Water (50%)**: temperature, precipitation, hot-dry proxy/persistence, baseline water stress, variability, drought risk;
- **Logistics (30%)**: roads and ports;
- **Remainder (20%)**: grid/plant proximity, reservoirs, airports, and other second-order enablers.

This hierarchy ensures that half of the total weight consistently reflects environmental constraints that threaten uptime, while logistics preserve their central role for semiconductor value chains and the remainder captures additional siting enablers. Rather than manually perturbing weights, robustness of the weighting scheme is assessed by comparing alternative CRITIC-derived weighting specifications (i.e., alternative CRITIC runs under slightly different indicator-grouping or input-structure configurations). This tests whether the resulting suitability patterns and Top-5 zones are materially sensitive to the specific CRITIC specification, while keeping the weighting logic objective and traceable.

4.5 Composite suitability and candidate delineation

Normalized indicators and final weights are combined into a composite suitability surface for each country, scenario, and time slice using a standard GIS-based MCDA suitability-mapping approach (Leake, C., & Malczewski, J. (2000); Malczewski, J., 2006). Hard constraints (e.g., protected areas or evidently infeasible terrain) are applied by setting suitability to zero in excluded areas. To translate continuous scores into a shortlist, I define a decision threshold as an upper quantile of the national score distribution, held constant across years and scenarios, to delineate "candidate" areas, consistent with common GIS-MCDA screening practice (Malczewski, J., 2006). Where helpful, adjacent high-scoring pixels are merged into contiguous patches, and practical descriptors (approximate footprint, centroid, distance to grid and logistics) are computed. From this candidate set, I extract the Top-5 zones based on the weighted composite suitability score defined in §4.4 and present them on the maps with labels for stakeholders. This procedure corresponds to the figures generated by the analytical pipeline and used for internal validation and presentation.

4.6 Scenario design and delta mapping

The present study evaluates four decision-relevant time slices (2024, 2028, 2038, and 2048) for each country under two forcing pathways, SSP2-4.5 and SSP5-8.5. The near-present baseline is anchored to ERA5-based indicators, which provide a physically consistent representation of recent climate conditions. While future forcing follows the CMIP6 framework and ScenarioMIP protocol to ensure internal scenario coherence across models and variables (Hersbach et al., 2020; Eyring et al., 2016; O'Neill et al., 2016).

For each climate indicator (temperature and precipitation) and for the composite suitability score, maps of change ("delta") are computed relative to the 2024 baseline. These delta maps are a valuable addition to absolute projections, as they provide a clear visual representation of the areas where suitability pressures are likely to intensify or ease over the investment horizon.

This feature enables a more informed and comparative interpretation of the data, rather than relying on single year snapshots.

Aqueduct 3.0 provides basin-scale water-risk indicators for a baseline period and discrete future horizons up to the late 2030s. These layers are used directly for 2024, 2028, and 2038 (Hofste et al., 2019). For the late-2040s horizon (2048), no official Aqueduct release is available. In order to preserve temporal coverage without the introduction of a fully coupled hydrological model, a transparent estimate is constructed. Specifically, basin-level tendencies observed between 2028 and 2038 are extrapolated to 2048 under the assumption of persistence in relative index-level changes, and then scaled using the late-2040s CMIP6 precipitation signal. This design choice is consistent with detection and attribution evidence showing that future compound hot-dry occurrences are governed primarily by precipitation trends rather than temperature alone (Bevacqua et al., 2022).

All 2048 water-risk layers are explicitly flagged as estimated and are examined within the robustness assessment across years and scenarios This ensures that decision-makers can assess how strongly the resulting suitability patterns and shortlists depend on the extrapolation, while maintaining consistency with the basin-scale water-risk framework applied to earlier time slices.

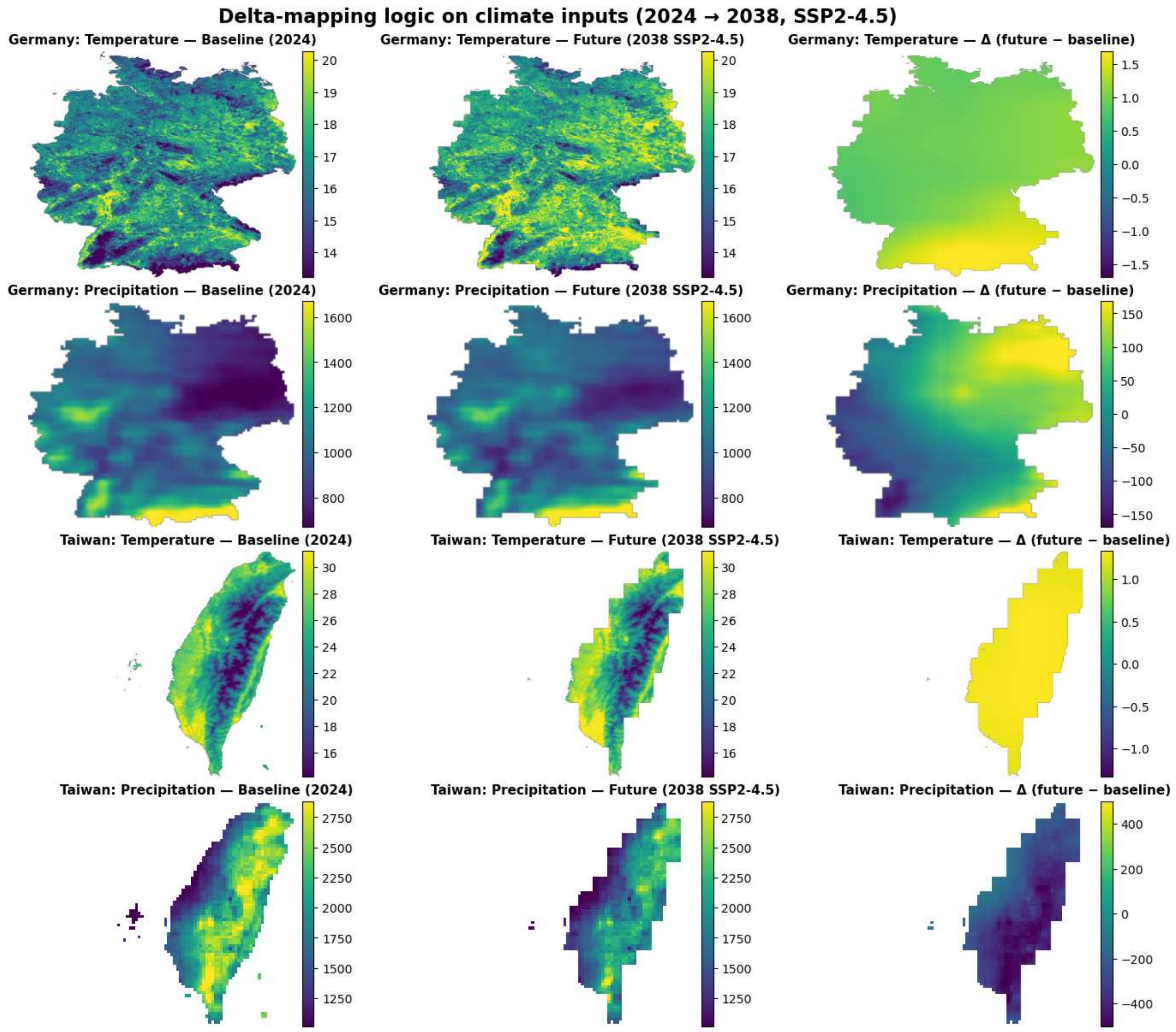


Figure 4: Delta-mapping logic for climate inputs (2024 → 2038, SSP2-4.5)

4.7 Robustness across years and scenarios

Because decision-makers seek locations that perform well and remain attractive under plausible futures. Robustness is assessed using complementary, rank-based diagnostics across years and scenarios, consistent with robust decision-making principles. That emphasize performance across multiple plausible futures rather than single-scenario optima (Lempert, Popper, & Bankes, 2003).

First, robustness is evaluated through repeated Top-5 occurrence: for each year × scenario realization. The five highest-ranked local maxima of the composite suitability surface are extracted (subject to the minimum separation rule). Zones that recur frequently among these Top-5 sets across SSP2-4.5 and SSP5-8.5 and across all evaluated time slices are interpreted as robust candidates, reflecting GIS-MCDA screening logic under multiple criteria and futures (Malczewski, J., 2006).

Second, set stability is assessed by comparing Top-K intersections across (i) years within a scenario and (ii) scenarios within a given year. Testing whether the same spatial clusters repeatedly appear among the highest ranked zones (Malczewski, J., 2006).

Third, robustness is interpreted through rank stability of shortlisted zones across time slices and scenarios. Instead of conducting formal, parameter-sweep sensitivity experiments, stability is evaluated as a diagnostic of how consistently the decision-relevant rankings persist under changing assumptions about climate forcing and temporal horizons. This approach aligns with the role of sensitivity/uncertainty analysis as a complement to point estimates in decision models (Saltelli et al., 2008).

Together, these diagnostics identify scenario-robust candidate zones and reduce reliance on single-year "winners."

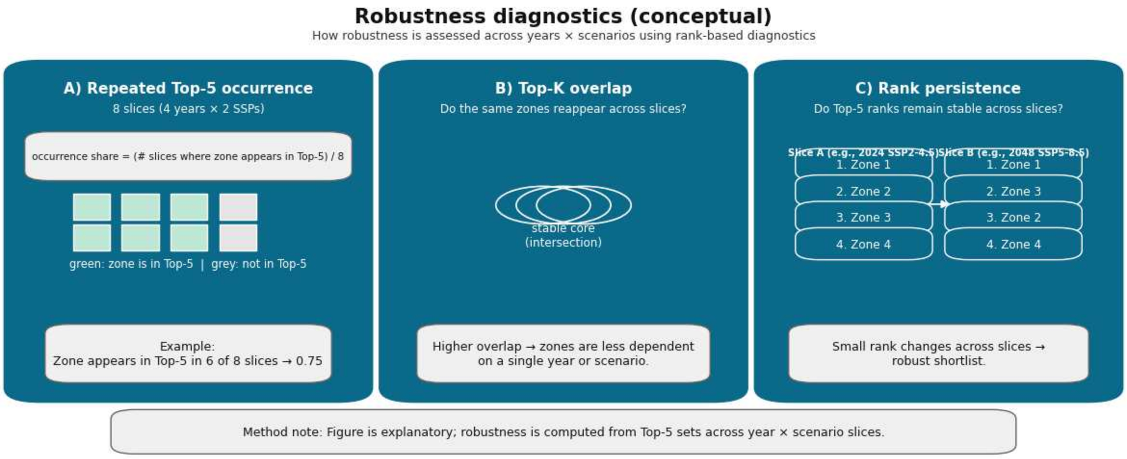


Figure 5: Robustness diagnostics for scenario- and time-consistent site selection

4.8 Validation and sensitivity analysis

The validation of the suitability maps is conducted by comparing them with existing and announced semiconductor fabrication facilities in Germany and Taiwan. Two diagnostics are reported: (i) a hit-rate measuring the share of fab locations falling in the upper tail of the national suitability distribution, and (ii) rank bias, comparing fab-point ranks to ranks from randomly sampled points within the feasible land mask. Alignment with known clusters (e.g., Dresden) supports plausibility, while deviations are interpreted in light of the model's emphasis on climate and water constraints rather than traditional cluster or talent arguments (Malczewski, J., 2006).

Uncertainty and robustness are assessed primarily through scenario and time-slice consistency rather than formal global sensitivity analysis. Results are compared across SSP2-4.5 and SSP5-8.5 and across all evaluated time slices (2024, 2028, 2038, 2048), emphasizing stability of high-ranking zones across plausible futures (Lempert, Popper, & Bankes, 2003). Rank-based checks are consistent with GIS-MCDA screening practice, where the objective is to identify stable candidate zones rather than estimate marginal effects precisely (Leake, C., & Malczewski, J. (2000); Malczewski, J., 2006; Pohekar & Ramachandran, 2004).

Finally, robustness is interpreted through an investment lens: reliability-aware facility location highlights how internalizing expected failure costs shifts preferred sites toward lower-disruption risk and greater redundancy (Snyder & Daskin, 2005), while robust optimization explains why small cost premiums can be justified if they reduce downside risk under uncertainty (Bertsimas & Sim, 2004).

4.9 From maps to a Top-5 shortlist

The methodology is operationalized into three decision artefacts for each country:

1. Suitability maps by year and scenario with clearly labeled Top-5 zones;
2. A robustness matrix reporting Top-5 recurrence across years × scenarios and Top-K intersections (overlap of the K highest-ranked zones/clusters across time slices and scenarios);
3. A concise due-diligence checklist for each shortlisted zone.

Together, these outputs preserve traceability: each shortlist item is linked to transparent indicators, weights, and robustness diagnostics while remaining accessible for decision-makers. They reflect how location alternatives are typically evaluated in practice: what is attractive today, how attractiveness evolves under plausible futures, and whether priority zones remain stable when years and scenarios change.

4.10 Methodological limitations (scoped)

Two scope-related limitations deserve emphasis. First, the water module relies on Aqueduct-style basin indicators and a transparent extrapolation for 2048. These measures are suitable for national screening, but they cannot replace local hydrological studies or utility-specific contracts; therefore, 2048 layers are flagged as estimated and tested for sensitivity (Hofste et al., 2019; Mekonnen & Hoekstra, 2016). Second, the climate module uses scenario-coherent CMIP6 projections, capturing large-scale signals under SSP2-4.5 and SSP5-8.5 but not microclimates or all circulation nuances. Robustness checks and validation overlays help keep the resulting shortlists conservative and decision-useful for early-stage siting (Eyring et al., 2016; O'Neill et al., 2016; Saltelli et al., 2008).

5. Results

5.1 Orientation and reading guide

This section reports the spatial suitability outcomes for Germany and Taiwan across four decision horizons (2024, 2028, 2038, 2048) under SSP2-4.5 and SSP5-8.5, as produced by the methodology described in Chapter 4. Results are presented as (i) national suitability maps with Top 5 candidate zones, (ii) delta maps versus 2024 to highlight trajectories of improvement and deterioration, (iii) a robustness view based on repeated Top 5 occurrence and rank persistence across years and scenarios, and (iv) validation against existing and planned fabrication sites.

Throughout the chapter, spatial patterns are interpreted from a business decision perspective, emphasizing implications for operational reliability, water and energy availability, expected downtime risk, and long-term site viability. The results are intended to support location screening and portfolio-level siting decisions, rather than to optimize end-to-end supply chains.

5.2 Germany

5.2.1 Germany baseline 2024

The 2024 suitability map shows a relative north-northwest advantage within the national distribution, arising from three interacting indicator signals:

- **Hot dry exposure:** lower frequencies of concurrent warm-and-dry months outside the continental interior reduce summertime cooling stress and water co-constraints (Bevacqua et al., 2022; Rousi et al., 2022; Vautard et al., 2023).

- **Water stress & variability:** lower basin-level stress and more favorable variability in northern catchments imply lower curtailment risk for ultrapure-water and cooling needs (Mekonnen & Hoekstra, 2016; Vörösmarty et al., 2010).

• **Constant accessibility:** shorter distances to major road corridors and ports along the North Sea/Baltic gateways (plus resilient inland logistics) support outbound service reliability.

Together, these factors lift northwestern and some central corridors. While parts of the south/southeast score lower where tighter water margins coincide with higher warm-spell persistence and summertime power-cooling constraints (van Vliet et al., 2012).

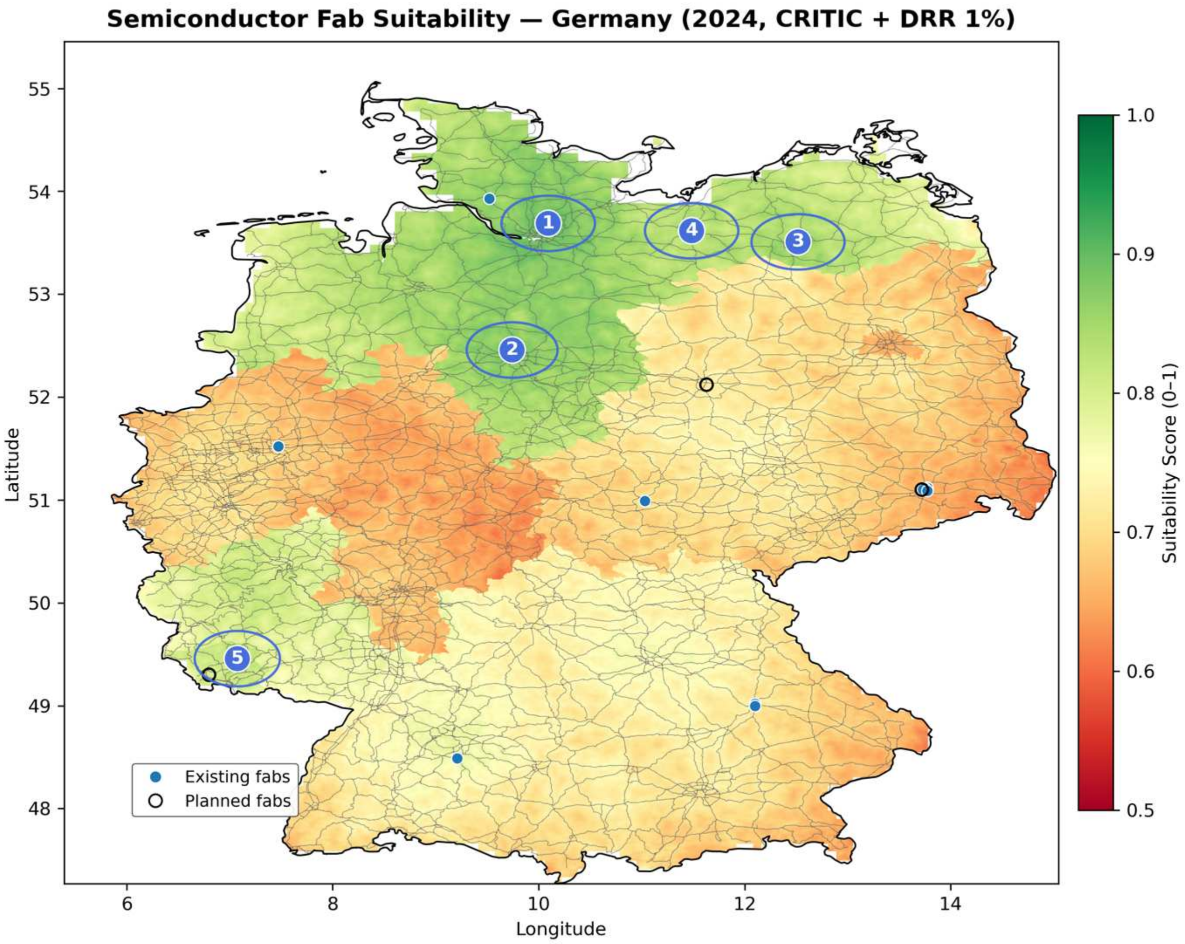


Figure 6: Germany baseline suitability (2024)

5.2.2 Germany projection 2028 and 2038

In the period 2028, there is a modest shift in the spatial gradient. The highest ranked northern corridors remain largely unchanged, with incremental gains where proximity to logistics and reservoirs enhances existing advantages. In accordance with SSP5-8.5, a number of southern cells are predicted to deteriorate relative to 2024 as the warm dry signal strengthens. Thereby increasing the likelihood of overlapping water and grid constraints (Bevacqua et al., 2022; van Vliet et al., 2012).

Looking at the year 2038, the distinction between various possible future scenarios becomes increasingly evident. Accordingly, with SSP2-4.5, the majority of 2024 Top 5 zones maintain their elevated rankings. While certain central eastern regions demonstrate enhancements, with infrastructure proximity compensating for moderate hydro stress. As outlined in the relevant literature. SSP5-8.5 demonstrates a tendency for more significant declines in the south and southeast. Which is a phenomenon attributed to elevated levels of warm dry pressure and augmented exposure to the vulnerabilities of power systems during periods of peak cooling (Rousi et al., 2022; Vautard et al., 2023; van Vliet et al., 2012).

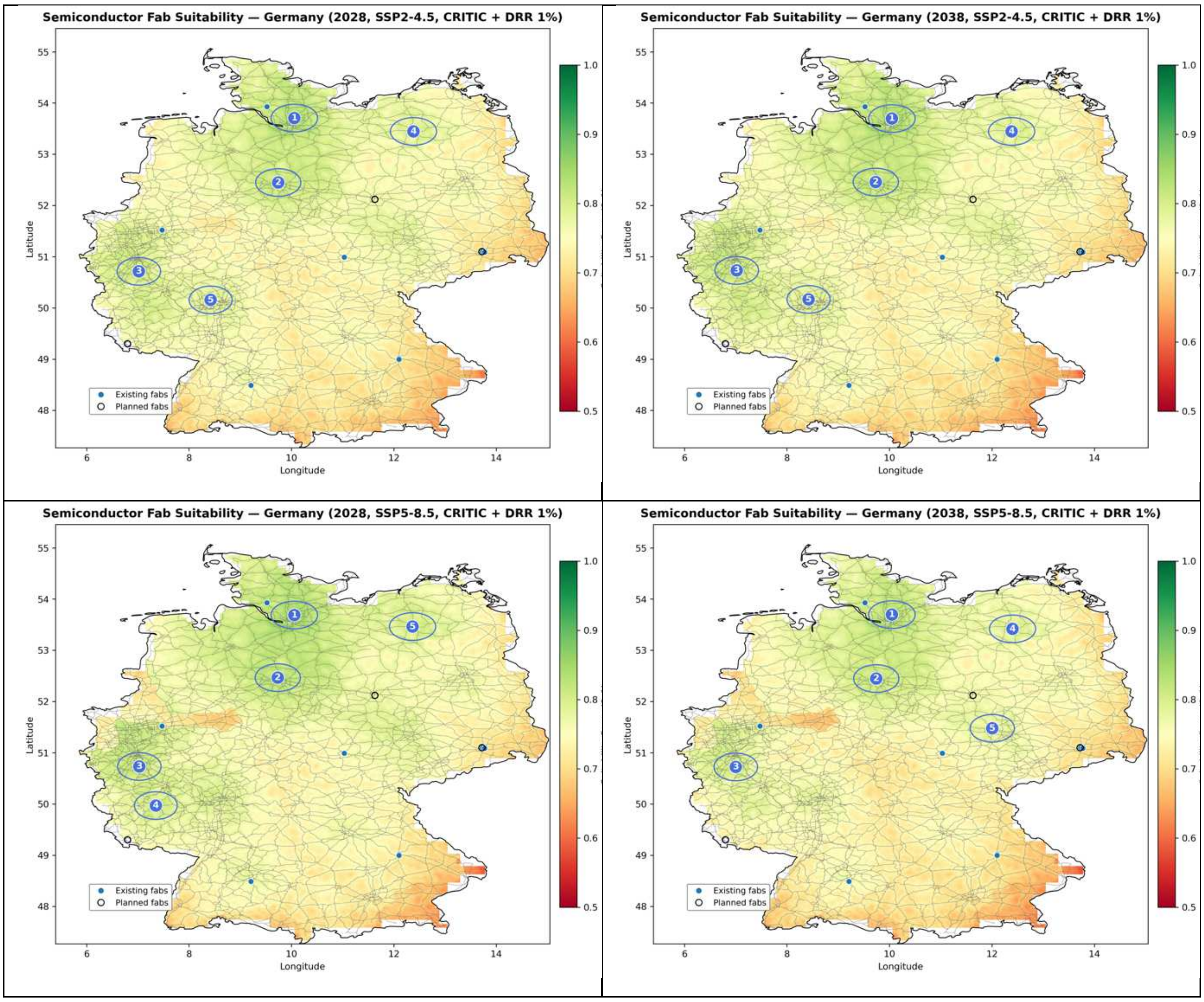


Figure 7a: Germany suitability projection for 2028 under SSP2-4.5.
Figure 7b: Germany suitability projection for 2038 under SSP2-4.5.
Figure 7c: Germany suitability projection for 2028 under SSP5-8.5.
Figure 7d: Germany suitability projection for 2038 under SSP2-4.5.

5.2.3 Germany projection 2048 (estimated water-risk layer)

For 2048, the basin-scale water-risk layer is estimated from 2028 to 2038 trends scaled by CMIP6 precipitation deltas (see §4 Methods), preserving scenario coherence while making uncertainty explicit (Eyring et al., 2016; O'Neill et al., 2016). Under both SSPs, the northwestern corridors largely retain their relative advantage. Under SSP5-8.5, several central and southern areas lose relative rank compared to earlier horizons and no longer appear among the nationally highest-scoring Top-5 zones used for robustness assessment (see §4.7). A subset of coastal-adjacent corridors combining strong road and port accessibility with nearby reservoirs consistently appears among the Top-5 across scenarios, supporting their inclusion in the shortlist. Appears among the Top-5 across scenarios, supporting their inclusion in the shortlist.

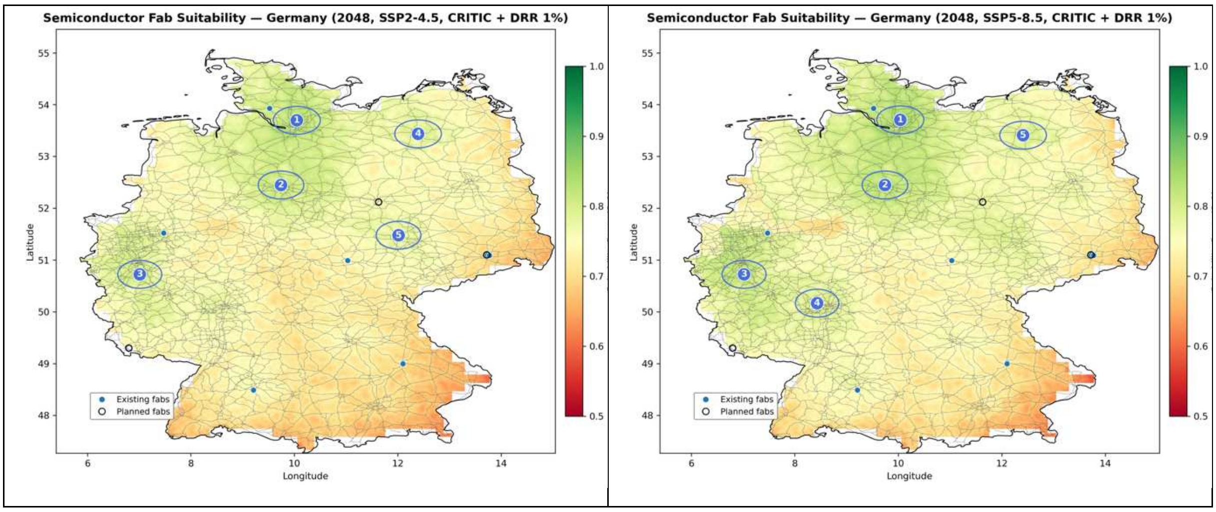


Figure 8a: Germany fab suitability (2048, SSP2-4.5): estimated basin-scale water-risk layer
Figure 8b: Germany fab suitability (2048, SSP5-8.5): estimated basin-scale water-risk layer under high forcing

5.2.4 Germany: Top-5 and spatial narrative

Across years and scenarios, Top 5 zones consistently concentrate in:

1. **North and northwest**: characterized by relatively resilient basins and strong road and port accessibility;
2. **Selected central belts**: where proximity to grid and generation assets and reservoir buffering complement moderate climate exposure;
3. **An avoidance of southern basins**: where hot-dry persistence coincides with tighter water margins and elevated power-cooling constraints.

Interpreted through a reliability-aware siting lens, these zones exhibit lower exposure to expected failure-cost drivers such as water scarcity, compound hot-dry persistence, and thermoelectric derates and therefore require comparatively less mitigation CAPEX and OPEX to sustain continuous operations. This supports their attractiveness for risk-adjusted, long-horizon industrial investments, including climate-sensitive manufacturing supply chains (Snyder & Daskin, 2005; Bertsimas & Sim, 2004; van Vliet et al., 2012).

5.3 Taiwan

5.3.1 Taiwan baseline 2024

The 2024 suitability map highlights Taiwan's drought sensitivity and dependence on surface-water storage within the national distribution, arising from three interacting indicator signals:

- Water stress & drought persistence: central-north interior areas perform better than many southern and eastern areas where baseline basin stress and drought persistence signals are less favourable, increasing curtailment risk for ultrapure-water and cooling needs (Hofste et al., 2019; Vo & Liou, 2024).

- The capacity of a reservoir to buffer is as follows: The proximity of a storage facility to major reservoirs has been demonstrated to have a significant impact on its suitability. This is conditional upon the assurance of both realistic ultrapure water (UPW) buffering and short-term operational flexibility. The findings of Narváez et al. (2022) underscore the role of storage infrastructure as a primary site selection criterion on the island.

- The concept of constant accessibility is predicated on the premise that shorter distances to major ports and primary road corridors differentiate otherwise similar hydro-climatic cells. It is evident that interior zones that remain within efficient logistics reach of northern industrial agglomerations tend to rank higher than more remote eastern or southern areas.

Together, these factors lift central-north corridors where storage access and logistics coincide, while parts of the south and east score lower where tighter water margins and weaker accessibility compound suitability constraints (Narvaez et al., 2022).

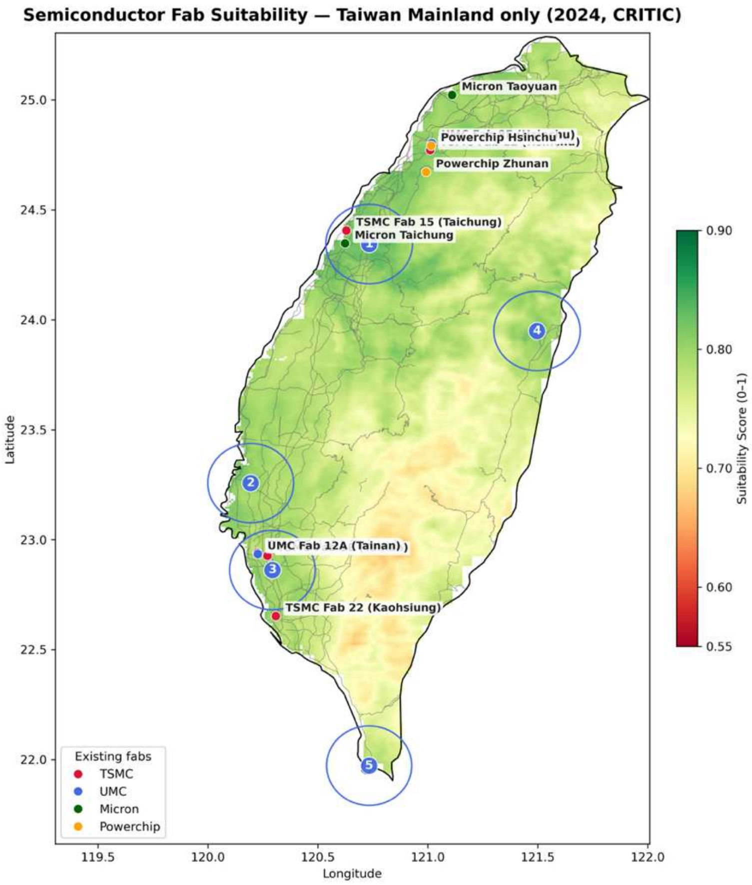


Figure 9: Taiwan baseline suitability (2024, mainland only)

5.3.2 Taiwan projection 2028 and 2038

By 2028, Taiwan's suitability patterns are expected to remain broadly similar under SSP2-4.5, with the highest-ranked zones concentrated where reservoir proximity and road access provide practical buffering. As Bevacqua et al. (2022) demonstrate, under SSP5-8.5, there is early score erosion in several southern and southeastern areas, which is consistent with increasing exposure to concurrent warm-dry conditions that tighten both water and cooling constraints.

By 2038, scenario divergence strengthens. In the context of SSP2-4.5, the majority of Top-5 zones maintain their competitive status, particularly within central-north interior regions where the presence of storage and accessibility serves to counterbalance the ongoing moderate drought conditions. As per the SSP5-8.5 scenario, there is an emergence of more pronounced declines in southern basins, coinciding with an increase in warm-dry persistence and a weakening of buffering margins. The projections demonstrate that Taiwan's resilience is dependent on its storage capacity. Regions that combine reservoirs and logistics connectivity exhibit comparatively robust resilience, while areas with limited buffering become increasingly vulnerable.

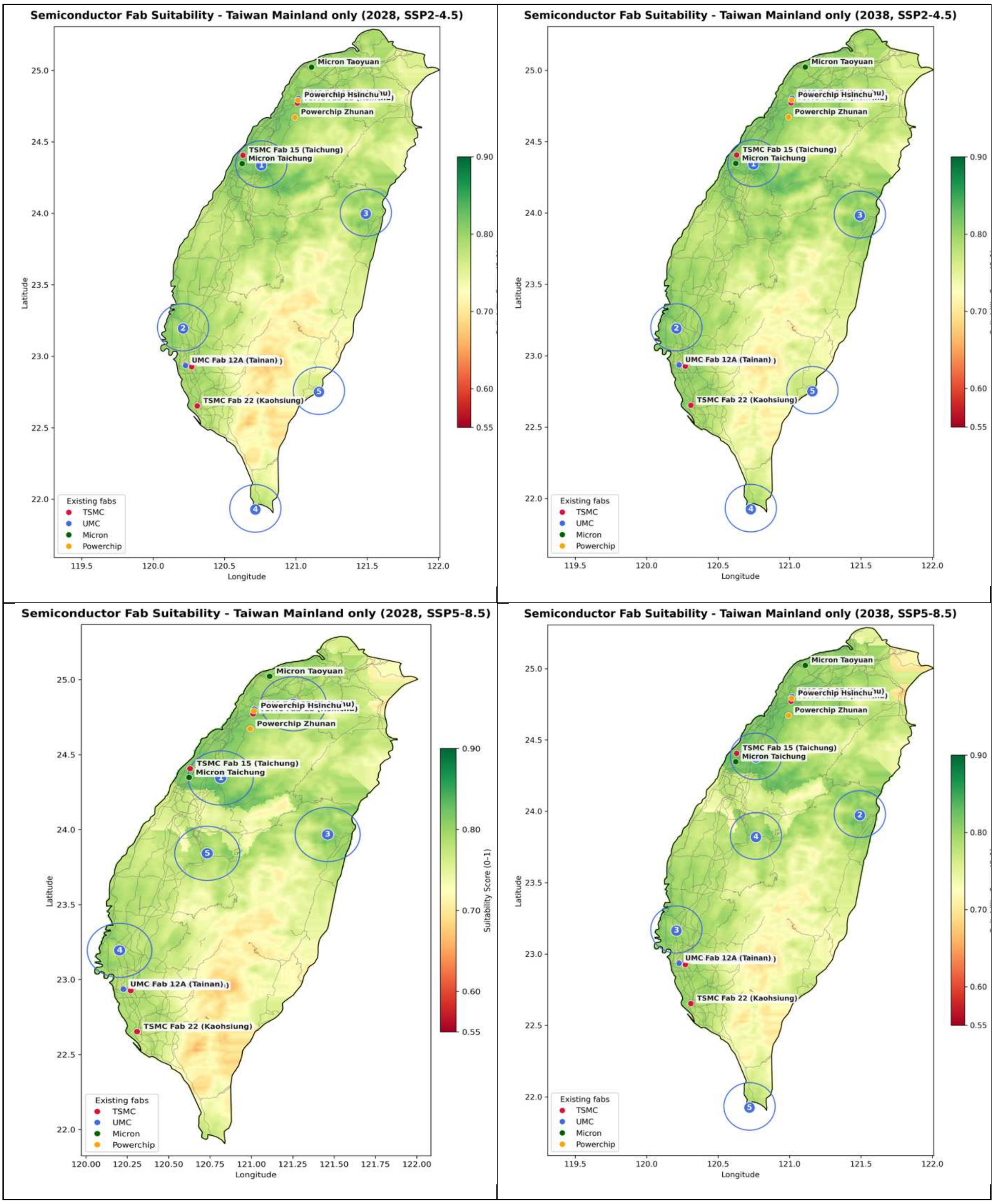
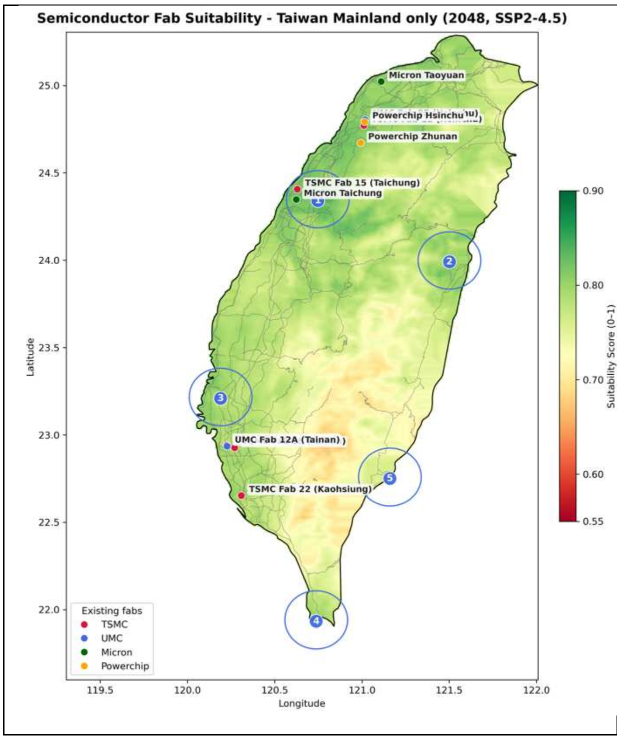


Figure 10: Taiwan mainland suitability, 2028 (SSP2-4.5)
Figure 11: Taiwan mainland suitability, 2028 (SSP2-4.5)
Figure 12: Taiwan mainland suitability, 2028 (SSP5-8.5)
Figure 13: Taiwan mainland suitability, 2038 (SSP5-8.5)

5.3.3 Taiwan projection 2048 (estimated water-risk layer)

Under the 2048 estimation approach, central north interior cells retain their relative advantage in both scenarios, with a narrower lead under SSP5-8.5 as the estimated water-risk layer becomes less favorable. Where reservoir proximity and grid/plant accessibility co-locate, these areas continue to appear among the Top-5 local maxima; by contrast, zones with weaker logistics access tend to drop in the relative ranking despite otherwise strong hydro-climate conditions (Hofste et al., 2019; Eyring et al., 2016; O'Neill et al., 2016).



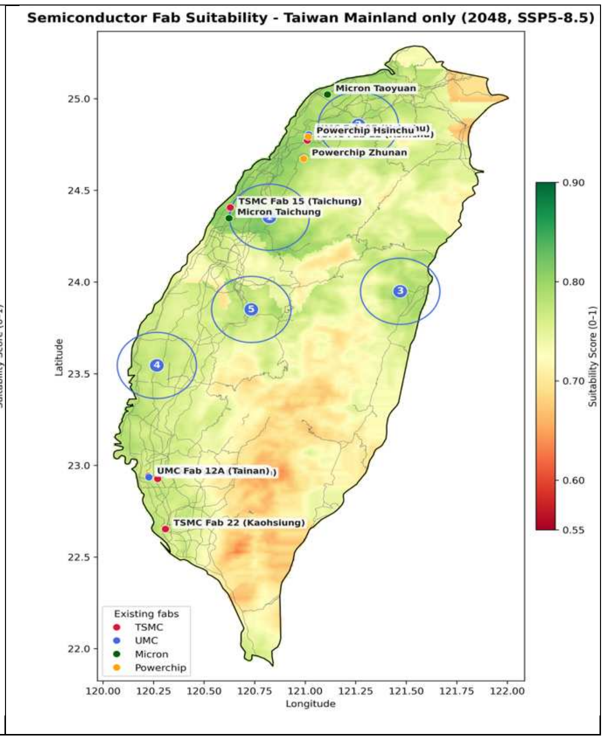


Figure 14: Taiwan mainland suitability, 2048 (SSP2-4.5; estimated water-risk layer)
Figure 15: Taiwan mainland suitability, 2048 (SSP5-8.5; estimated water-risk layer)

5.3.4 Taiwan: Top-5 and spatial narrative

Across years and scenarios, Taiwan's Top-5 zones consistently concentrate in:

1. Central north interior catchments that combine comparatively more favorable drought-persistence signals with access to reservoir storage;
2. areas within northern logistics reach (roads and ports) that sustain outbound service levels; and
3. systematic avoidance of southern and eastern basins where drought persistence and variability heighten curtailment risk.

Read through a reliability-aware lens, these zones minimize expected failure-cost proxies lower hot dry stress signals, the presence of storage buffers, and robust grid and logistics access and therefore tend to require smaller mitigation CAPEX/OPEX (e.g., ultrapure water (UPW) reuse and storage) to sustain operational uptime. This spatial pattern is consistent with the broader literature showing that precipitation trends and persistence dominate compound hot dry risk, as well as with evidence of an anthropogenically increased likelihood of concurrent warm dry months in East and Southeast Asia, both of which are directly relevant to fab continuity (Bevacqua et al., 2022; Ha et al., 2022).

5.4 Delta signals in climate inputs and implications for suitability

This section shows delta maps of the climate inputs near-surface temperature (tas) and precipitation (pr) between the baseline (2024) and future slices, for both SSP2-4.5 and SSP5-8.5 (Eyring et al., 2016; O'Neill et al., 2016). These deltas are not used directly in the MCDA scoring; rather, they provide physical context for the suitability patterns discussed in §§ 5.2-5.3. In the MCDA, suitability reacts to these inputs primarily through cooling load (tas) and water-availability and persistence proxies (pr), which interact with temperature to shape hot-dry exposure (Bevacqua et al., 2022).

Germany.

- SSP2-4.5: pr-deltas are broadly neutral to mildly positive across the north and northwest, while tas rises are moderate. This supports stable or slightly improving suitability in those corridors and localized declines in parts of the south and southeast.
- SSP5-8.5: stronger tas increases combine with more negative pr-deltas in the south and southeast, consistent with widening negative suitability deltas there, while northern logistics corridors remain comparatively resilient (§ 5.2).

Taiwan.

- SSP2-4.5: pr-deltas remain comparatively steady in central-north interior basins, aligning with stable to mildly positive suitability and neutral to negative shifts along parts of the south and east.
- SSP5-8.5: larger precipitation declines, combined with tas increases, appear in southern and eastern basins, matching broader erosion of suitability there and persistence of the central-north advantage highlighted in § 5.3.

Interpretation:

Across both countries, the tas/pr delta patterns reinforce the main findings. precipitation-driven persistence proxies explain a significant proportion of the spatial change relevant to continuous fab operations. While temperature increases amplify cooling-related power stress (Bevacqua et al., 2022; van Vliet et al., 2012). The spatial overlap between adverse pr-deltas and areas of declining suitability independently corroborates the shortlist logic, without the necessity for re weighting or post-hoc adjustment of the MCDA.

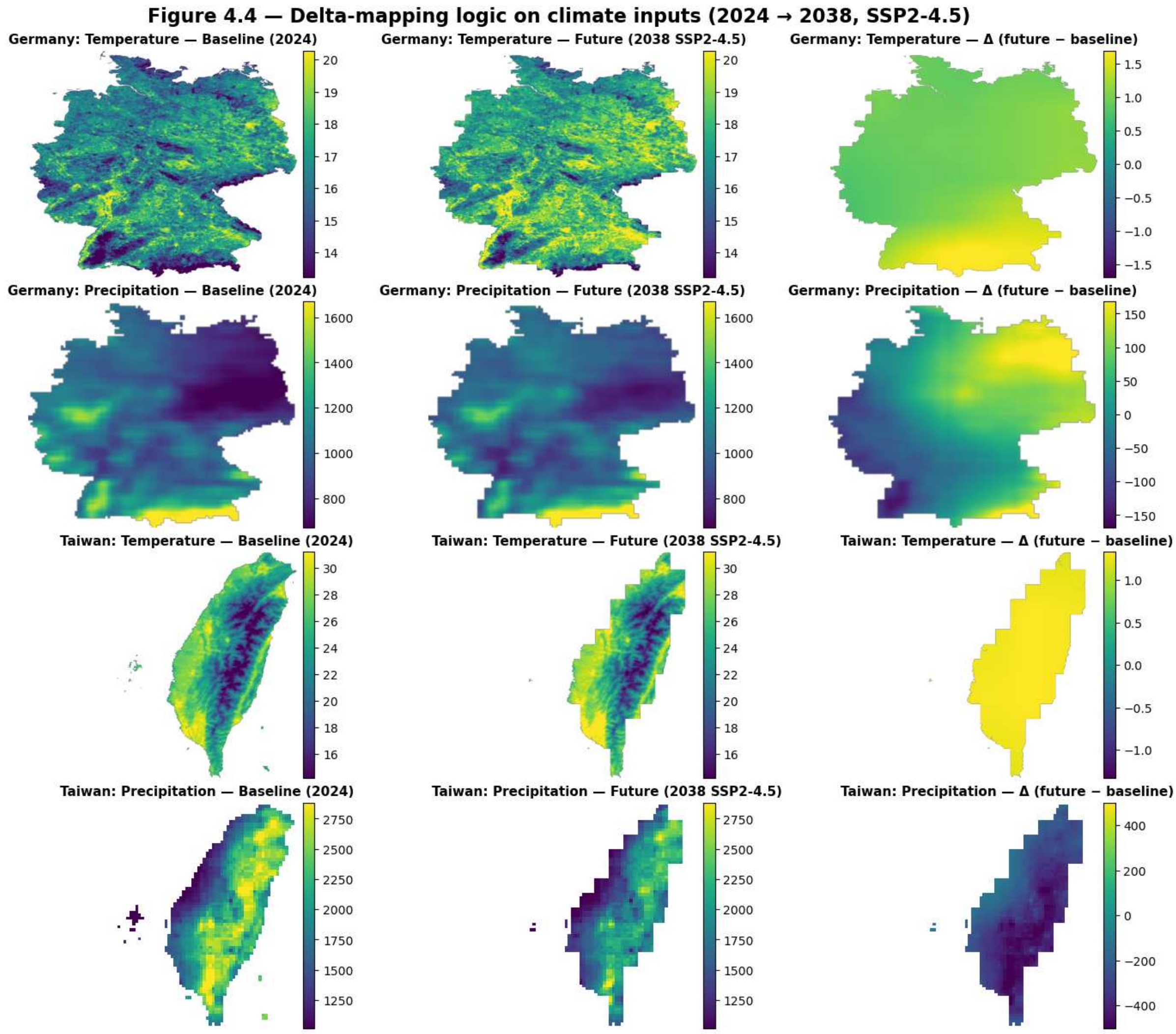


Figure 16: Delta mapping of near-surface temperature and precipitation inputs (2024 to 2038, SSP2-4.5)

5.5 Robustness: exceedance shares and intersections

To assess stability across years × scenarios, robustness is evaluated using rank-based diagnostics rather than a fixed global suitability threshold. Two measures are reported: (i) Top-5 recurrence the share of year × scenario runs in which a zone appears among the five highest local maxima and (ii) spatial overlap of Top-ranked areas across 2024/2028/2038/2048 via intersections of Top-K masks (with K aligned to the shortlist definition).

- **Germany.** High recurrence and large intersections concentrate along the north/north-west and selected central belts. Under SSP2-4.5, overlap across the four years is largest in the northern corridors; under SSP5-8.5, intersections contract but persist along the same axes, indicating scenario-robust anchor zones for portfolio siting.
- **Taiwan.** The central-north interior shows the highest Top-5 recurrence in both scenarios. Intersections remain even as SSP5-8.5 narrows margins, underscoring the role of reservoir adjacency and lower drought persistence.

The results are consistent with §§2-3 and RQ1-RQ2: precipitation driven persistence and co-occurrence dynamics are the main factors that affect compound hot dry risk. This is why areas with more stable precipitation signals and buffering capacity are more likely to be among the top candidates (Bevacqua et al., 2022; Ha et al., 2022).

5.6 Validation and sensitivity

5.6.1 Overlay with existing/planned fabs

Overlay analysis suggests that existing and planned fabrication facilities are not randomly located relative to the suitability surface, but alignment with the model's highest-ranked zones is heterogeneous.

In **Germany**, established clusters most notably Dresden do not consistently coincide with the model's Top-5 local maxima. This gap is economically interpretable: the MCDA prioritizes water availability and compound hot-dry exposure over historical cluster effects and agglomeration dynamics, so policy- and ecosystem-driven locations can rank lower under a climate-constrained operating perspective. In Taiwan, industrial activity aligns more often with the highest-ranked clusters, especially where reservoir proximity and logistics accessibility coincide.

Taiwan. Existing industrial corridors overlap more frequently with the model's highest-ranked clusters, particularly where reservoir proximity and road/port access coincide indicating stronger consistency between historical siting and hydro-logistics constraints than in Germany.

Overall, the results should be read as a forward-looking, climate-and-water screening lens rather than a reproduction of historical siting outcomes; important drivers not modeled here such as industrial policy, incentives, geopolitics, permitting speed, and strategic supply-chain considerations can still make a location attractive in practice (Snyder & Daskin, 2005).

5.6.2 Weight and preference sensitivity

Robustness within the additive MCDA framework is assessed qualitatively and comparatively rather than through exhaustive numerical sensitivity sweeps. Stability is evaluated by examining whether the identity of the Top-5 zones and the dominant spatial patterns persist across years and scenarios under the baseline CRITIC weighting and fixed group budgets.

Across both countries, the same clusters repeatedly appear among the highest-ranked local maxima, with only minor rank reshuffling within clusters across time slices and scenarios. No structural rank reversals are observed in the top tier. This indicates that the shortlist is robust to plausible managerial preference differences implicit in scenario choice and temporal horizon, even without re-estimating indicator weights.

5.6.3 Interpreting economic relevance

From a reliability-economics perspective, the results highlight a clear trade-off: accepting small steady-state cost premiums (e.g., marginally higher land or logistics costs) can reduce expected failure costs from downtime, yield loss, and mitigation during hot-dry periods.

Given the high disruption costs of semiconductor fabrication, prioritizing zones that are both highly ranked and robust across scenarios is therefore economically defensible. The robustness diagnostics translate directly into risk-adjusted decision value for site selection, consistent with reliability-aware facility location and robust optimization frameworks (Snyder & Daskin, 2005; Bertsimas & Sim, 2004).

5.7 Country takeaways

Germany: decision-ready insights

- Anchor the shortlist in the north/northwest. These corridors consistently appear among the Top-5 across years and scenarios, combining milder hot-dry exposure, lower basin stress, and strong logistics access (Hofste et al., 2019).

- Treat the south/southeast as exposure-managed. Under SSP5-8.5, suitability declines where warm-spell persistence coincides with tighter water balances and potential power-cooling constraints; projects here require stronger resilience add-ons (e.g., long-term water contracts, storage, diversified power sourcing) (Rousi et al., 2022; van Vliet et al., 2012).
- Prioritize reservoir-adjacent, grid-proximate cells in selected central belts. These retain high relative rankings under SSP2-4.5 and do not collapse under SSP5-8.5, offering optionality while preserving logistics reach.
- Portfolio logic. Combining two northern anchor sites with one central option hedges against scenario divergence while maintaining access to European demand centers, consistent with reliability-aware and robust decision frameworks (Snyder & Daskin, 2005; Bertsimas & Sim, 2004).

These insights align with evidence on increasing heat persistence in Western Europe and with work showing that precipitation dynamics shape compound hot dry risk relevant for fab uptime (Rousi et al., 2022; Vautard et al., 2023; Bevacqua et al., 2022).

Taiwan: decision-ready insights

- Focus on central-north interior. These zones recur most frequently among the Top-5, pairing lower drought persistence with reservoir buffers and manageable logistics access to northern conurbations (Narvaez et al., 2022) . Notably, the shortlist also includes an eastern candidate zone (visible in the maps) where no comparable fab cluster is currently present, suggesting a potentially underdeveloped option emerging under the climate-and-water screening lens.
- Avoid water-volatile south/east under aggressive forcing. Under SSP5-8.5, margins narrow substantially; where siting is unavoidable, budgeting for contingency water (buffer tanks, reuse upgrades) and grid optionality becomes essential (Narvaez et al., 2022).
- Reservoir and grid adjacency act as decisive tie-breakers. Where hydro-climatic signals are similar, proximity to storage and power infrastructure stabilizes Top-5 recurrence across scenarios and time horizons.

- Portfolio logic. Pairing one central-north interior site with a secondary site near northern logistics corridors balances water reliability, cooling security, and access to export routes (Snyder & Daskin, 2005; Bertsimas & Sim, 2004).

These insights are consistent with evidence that precipitation and persistence dynamics dominate compound warm dry exposure in East Asia, directly affecting process water and cooling reliability (Ha et al., 2022; Bevacqua et al., 2022).

5.8 What the shortlist means in practice

The Top-5 zones per country and year, together with their recurrence/overlap across scenarios, provide an actionable starting point for zone-level due diligence. For each shortlisted zone, the immediate next steps are:

- **Water:** basin-scale entitlements, ultrapure water (UPW) quality baseline, reuse potential, and drought curtailment rules affecting uptime.
- **Power:** grid-node capacity, summer derate exposure, and mitigation options via PPAs and/or on-site backup.
- **Land & permitting:** zoning, environmental setbacks, and critical-path permitting risks for time-to-build.
- **Logistics:** road/port redundancy and service-level reliability for downstream industries (e.g., automotive).

Overall, the maps translate climate- and water-aware risk into portfolio-consistent site choices, while the Top-5 recurrence/overlap view reduces the likelihood of capital lock-in to locations whose operational risk profile deteriorates under higher forcing.

6. Discussion

The present thesis was conceptualised with the intention of addressing three research questions:

- **RQ1:** guiding this study is as follows: "How do climate and water exposures alter fab suitability through 2048?"
- **RQ2:** concerns the identification of which zones demonstrate resilience across SSP2-4.5 and SSP5-8.5.
- **RQ3:** concerns the business-relevant implications of robust, climate-aware siting decisions for operational reliability and investment value.

The composite suitability maps, delta analyses, robustness diagnostics, and validation exercises provide coherent answers when considered collectively. The resulting models reveal spatial patterns that are physically plausible, stable across plausible futures, and interpretable in a managerial context.

6.1 Climate and hydro-climate exposures (RQ1)

The first research question examined how climate and water exposures shape fab suitability through 2048.In Germany, the higher relative suitability observed in north and northwest corridors is indicative of a combination of reduced heat persistence and more favourable basin-scale water stress conditions. There has been a marked increase in the intensity of heat extremes in Western Europe. Recent studies have indicated a correlation between amplified heatwave trends and the persistence of specific atmospheric circulation states, such as persistent double-jet configurations, which have been shown to favour prolonged warm spells over the region (Rousi et al., 2022; Vautard et al., 2023). While this study does not explicitly model atmospheric dynamics. The resulting suitability patterns are consistent with elevated operational stress on cooling and grid systems during extended heat events.

Conversely, parts of southern and southeastern Germany exhibit relative declines in suitability under higher forcing, consistent with increased concurrent hot dry exposure and tighter hydro-climate margins. In Taiwan, drought persistence and storage capacity dominate spatial differentiation. Central and northern interior basins that are adjacent to reservoirs demonstrate higher levels of suitability when compared to southern and eastern basins, which are more susceptible to prolonged periods of dryness. These patterns are indicative of the profound impact of precipitation trends, variability, and buffering capacity on compound hot dry risk, as evidenced in the hydro-climate literature (Bevacqua et al., 2022).

The analysis is capable of capturing joint climate water constraints that materially affect long-run uptime potential for water-intensive, cooling-dependent fabrication facilities, by integrating these exposures into composite suitability surfaces.

6.2 Robustness across futures (RQ2)

The second research question focused on identifying zones that remain attractive across SSP2-4.5 and SSP5-8.5 until 2048. Robustness is assessed using rank-based diagnostics aligned with the implemented decision logic, including repeated Top-5 occurrence across year × scenario realizations and stability of Top-ranked spatial clusters over time.

In **Germany**, north and northwest corridors and selected central belts repeatedly appear among the Top-5 ranked local maxima across years and scenarios; in **Taiwan**, central north interior catchments show consistent recurrence among the highest-ranked candidates. These patterns persist across time periods (2024, 2028, 2038, and 2048) and under both forcing pathways, indicating that the ranking structure is not an artifact of a single scenario or year.

This stability is important because it demonstrates that the identified shortlists are not overly sensitive to plausible structural uncertainties in the assessment (e.g., climate scenario divergence or moderate weight configuration differences). The resulting candidate zones therefore represent scenario-resilient options rather than single-snapshot optima.

6.3 Business relevance and operational implications (RQ3)

The third research question reframes siting choices in terms of business-relevant risk and investment logic. Rather than merely producing spatial rankings, this thesis interprets robust shortlists in terms of operational reliability, cost exposure, and mitigation effort dimensions that are central to investment governance.

6.3.1 Risk-adjusted siting and portfolio logic

Zones that repeatedly appear among the Top-5 ranked candidates across scenarios and years offer a form of downside protection. For capital-intensive projects with long operating horizons, such robustness translates into lower expected failure costs, including downtime, yield loss, and reactive mitigation during hot-dry periods (Snyder & Daskin, 2005). Framing site selection in terms of expected uptime and manageable operational risk aligns with reliability aware manufacturing location theory and provides an defensible quantitative foundation for executive decision making (Snyder & Daskin, 2005; Bertsimas & Sim, 2004). Instead of selecting a single "best" location, a combination of choosing a multiple robust candidates creates a hedged portfolio of sites (Bertsimas & Sim, 2004). For Germany, the strategic pairing of northern anchor locations with a central-belt alternative offers the potential for spatial diversification across hydro-climate and logistics conditions. For Taiwan, a central-north interior anchor, complemented by a secondary site with strong logistics access, balances water reliability with export connectivity. The portfolio logic underpinning this approach mirrors the risk management principles inherent in asset allocation, wherein diversification serves to mitigate scenario-contingent downside risk while preserving strategic reach.

6.3.2 Operational feasibility and due diligence implications

When climate and water exposures are similar across zones, constant accessibility proxies distance to reservoirs, grid nodes, and major transport corridors act as decisive operational tie-breakers. These criteria are auditable and directly translatable into contractual arrangements, such as power purchase agreements, storage expansion plans, and logistics service-level guarantees.

Consequently, the interpretation of suitability maps and robustness diagnostics as definitive siting decisions is misguided. Rather, they should be regarded as structured inputs into zone-level due diligence. For each zone that is shortlisted, the subsequent steps that are typically taken include basin-scale water rights analysis, grid resilience planning, zoning and permitting risk assessment, and scenario stress-testing of logistics timelines under heat and water constraints. This translation establishes a foundation for the integration of spatial results within operational risk registers and contractual frameworks, thereby rendering them actionable for boards and investment committees.

6.4 Limitations and future directions

Several limitations merit emphasis. First, the 2048 water-risk layer is estimated from earlier trends scaled by precipitation deltas; while explicit flagging and robustness checks mitigate misinterpretation, local hydrological studies remain essential prior to financial close. Second, climate inputs are coarser than infrastructure vectors; consistent grids and avoidance of smoothing reduce artificial precision at screening scale, but micro-site hazard assessments are required before detailed engineering design. Finally, while this discussion draws on peer-reviewed evidence on heat persistence and compound events, empirical results are strictly derived from the composite ranking and robustness framework; future work could incorporate ensemble spread and higher-resolution extremes as climate-model datasets evolve.

6.5 Bottom line

The scenario-robust shortlists identified for Germany (north/northwest corridors and selected central belts) and Taiwan (central/north interior zones) reflect documented physical risk mechanisms, basin scale water constraints, and accessibility conditions that directly influence operational uptime and long-run risk exposure. For boards evaluating capital allocation under deep uncertainty, these zones provide defensible, decision-ready starting points and a clear pathway from spatial screening to bankable due diligence.

7. Conclusion & Outlook

Conclusion

This thesis provides a climate- and water-aware siting assessment for semiconductor fabrication in Germany and Taiwan across four decision horizons (2024, 2028, 2038, 2048) and two forcing pathways (SSP2-4.5 and SSP5-8.5). Building on a reproducible geospatial pipeline, the analysis integrates (i) compound hot-dry signals derived from temperature and precipitation, (ii) basin-scale indicators of water stress, variability, and drought risk, and (iii) constant-accessibility proxies capturing proximity to power infrastructure, reservoirs, and major transport corridors. Objective within-group weights (CRITIC) are combined with a transparent managerial hierarchy (50% climate/water, 30% logistics accessibility, 20% remainder), yielding national suitability surfaces, change (delta) maps, and scenario-robustness diagnostics.

Three core conclusions emerge from the analysis:

First, climate and water constraints materially re-rank production locations even within advanced industrial economies. In Germany, north/northwest corridors consistently outperform southern and southeastern regions. Due to lower persistence of hot/dry conditions, more favorable basin-level water balances, and better access to resilient infrastructure. In Taiwan, central/north interior catchments with reservoir buffering repeatedly rank highest. While southern and eastern basins deteriorate under stronger forcing. These outcomes are consistent with established physical mechanisms and are reflected through the proxy-based indicators used in this assessment: circulation-driven heat persistence in Western Europe and precipitation-controlled compound hot/dry risk in East and Southeast Asia, both of which directly affect cooling demand, water availability, and fab uptime (Rousi et al., 2022; Vautard et al., 2023; Bevacqua et al., 2022).

Second, scenario robustness is an economically relevant property of production sites. Exceedance shares and Top-K intersections identify zones that remain above the decision threshold across years and scenarios rather than performing well in a single snapshot. In Germany, robust clusters persist in the north/northwest and selected central belts. In Taiwan, central/north interior zones maintain their advantage even as margins narrow under SSP5-8.5. From an investment perspective, these patterns support a preference for locations that are not only attractive today but also resilient to plausible future climate trajectories. Reducing the likelihood of costly re-optimization or retrofitting over the asset’s lifetime.

Third, reliability economics provides the bridge from spatial rankings to investment value. Semiconductor fabs are highly sensitive to coincident stresses on cooling water and electricity supply. Locations that reduce the probability of such coincident failures lower expected failure costs, including downtime, yield loss, and emergency mitigation expenditures. Proximity to resilient grid nodes and reservoir buffers thus functions as a hedge against operational disruptions, a mechanism explicitly reflected in the constant-accessibility module and the resulting Top-5 shortlists. Reliability-aware facility location theory formalizes why investors may rationally accept modest steady-state cost premiums (e.g., land or logistics) in exchange for lower downside risk over multi-decade operating horizons (Snyder & Daskin, 2005; Bertsimas & Sim, 2004).

Answers to the research questions

RQ1: Climate, water, and drought exposures shift fab suitability toward basins characterized by steadier precipitation, lower variability, and greater buffering capacity. In Germany, this favors north-northwest corridors; in Taiwan, central-north interior cells dominate, particularly where reservoir proximity enhances operational flexibility.

RQ2: Scenario-robust zones are those that repeatedly exceed the decision threshold across SSP2-4.5 and SSP5-8.5 and across the four-time horizons. These clusters persist in Germany's north/northwest and Taiwan's central-north interior, forming defensible anchors for long-horizon siting decisions.

RQ3: From a business perspective, robust, climate-aware siting improves the risk-adjusted economics of semiconductor production. By lowering the expected frequency and severity of water- and heat-related disruptions, robust locations reduce failure-related costs and stabilize long-run operating performance, strengthening the investment case for capital-intensive fabs.

Managerial implications

For boards and investment committees evaluating multi-billion-euro fab projects, the central implication is that water- and grid-aware siting reduces tail risk at manageable cost. The Top-5 shortlists generated here provide a structured starting point for due diligence, focusing attention on:

(i) basin-level water rights, allocation rules, and reuse potential for ultrapure water;

(ii) summer derate contingencies and node capacity in coordination with transmission system operators;
(iii) land-use constraints, environmental permitting, and critical-path timelines; and
(iv) the feasibility of infrastructure upgrades that enhance operational resilience.

Limitations

Two scope choices warrant emphasis. First, water risk for 2048 is transparently estimated from earlier-period tendencies scaled by CMIP6 precipitation deltas; while precipitation trends dominate compound hot-dry risk, site-specific hydrological studies remain necessary before financial close (Bevacqua et al., 2022). Second, constant-accessibility proxies reflect distance to infrastructure rather than contractual capacity, tariffs, or industrial water agreements. These simplifications are appropriate for national screening but must be refined during site-level engineering and negotiation. These limitations do not undermine the comparative logic of the rankings but delimit their appropriate use to early-stage screening.

Outlook

Several extensions could further strengthen decision quality.

Possible technical extensions include:

- embedding river-reach-scale hydro-energy models to sharpen assessments of power-derate risk in water-constrained basins;
- incorporating ensemble-explicit climate uncertainty (e.g., multi-model percentiles) to enable probability-weighted robustness metrics;
- extending the framework to a reliability-adjusted NPV that prices expected failure costs against resilience CAPEX and OPEX.

Governance steps include:

- decision-threshold governance, jointly calibrated across operations, risk, and finance functions;
- explicit portfolio policy, treating fab siting as a diversified investment rather than a point decision.

Closing statement

The central message of this thesis is economic and practical: where semiconductor production capacity is built has first-order implications for long-run operational reliability and investment value. Under increasing climate and water stress, siting decisions that explicitly account for robustness across plausible futures outperform ad hoc or single-year rankings. By combining objective weighting, transparent managerial priorities, and robustness diagnostics, this thesis delivers auditable, decision-ready shortlists that support economically resilient semiconductor capacity in Germany and Taiwan.

Use of AI Tools:

In preparing this thesis, I used a large language model (ChatGPT, OpenAI) as a writing and editing assistant. It was used to improve phrasing, grammar, structure, and readability, and to support the preparation of figure captions and methodological descriptions. All research questions, theoretical framing, methodological decisions, data collection, data processing, geospatial analysis, and interpretation of results were developed and carried out by me. Any suggestions generated by the AI tool were critically reviewed, adapted where appropriate, and independently verified against my own work and sources. I remain fully responsible for the final content of this thesis.

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Appendix

Infrastructure layers used in the suitability analysis (Germany):
The maps in this appendix illustrate the core infrastructure layers used to construct the accessibility component of the MCDA for Germany. They provide spatial context for distance-based indicators applied uniformly across the national analysis grid.

Specifically, the figures show:

(i) the national main road network overlaid with the country border, representing road accessibility and logistics connectivity;

(ii) the spatial distribution of reservoirs, capturing potential buffering capacity for industrial and cooling water supply;

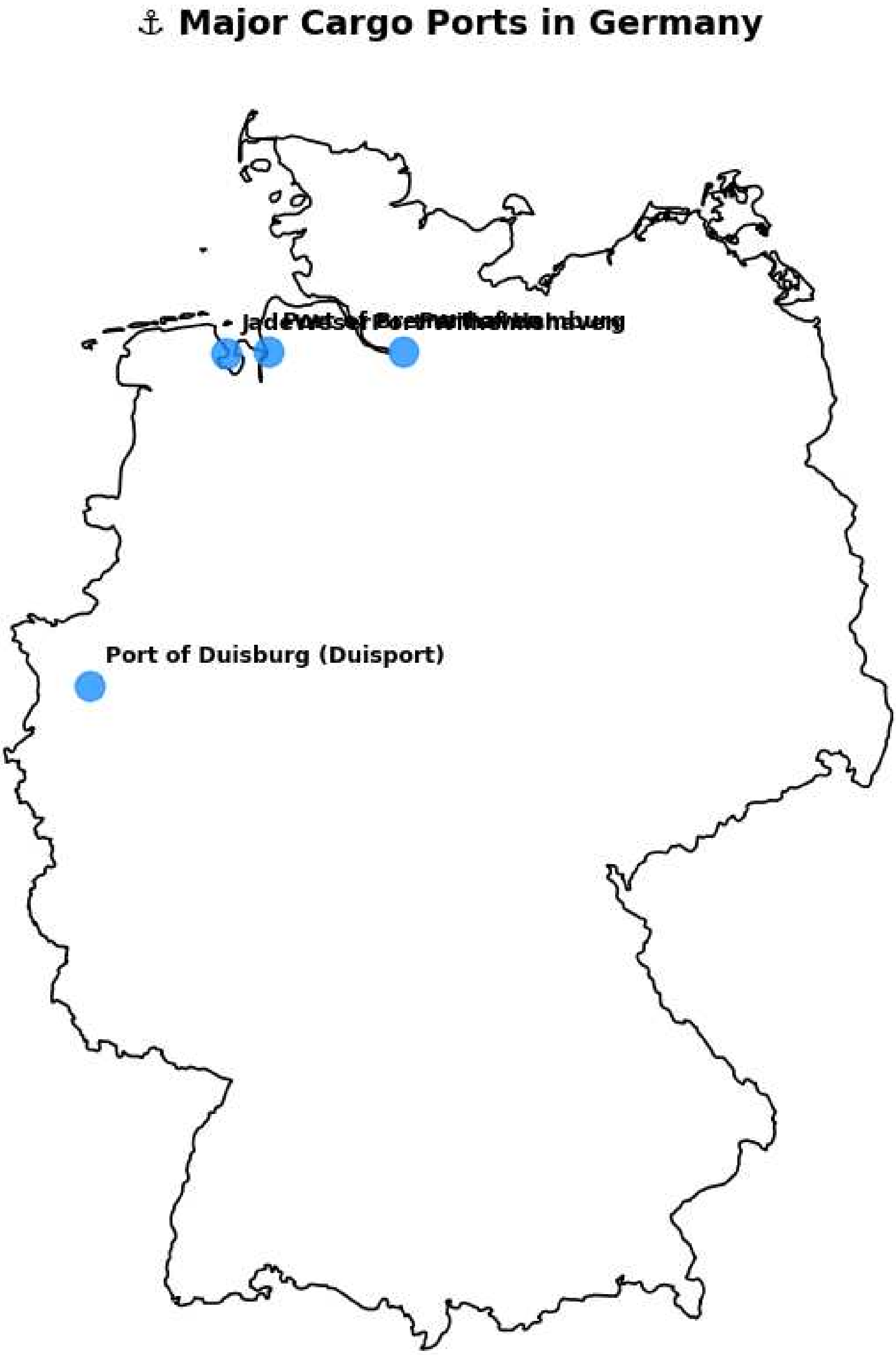
(iii) the locations of power plants, serving as proxies for proximity to electricity generation and grid robustness;

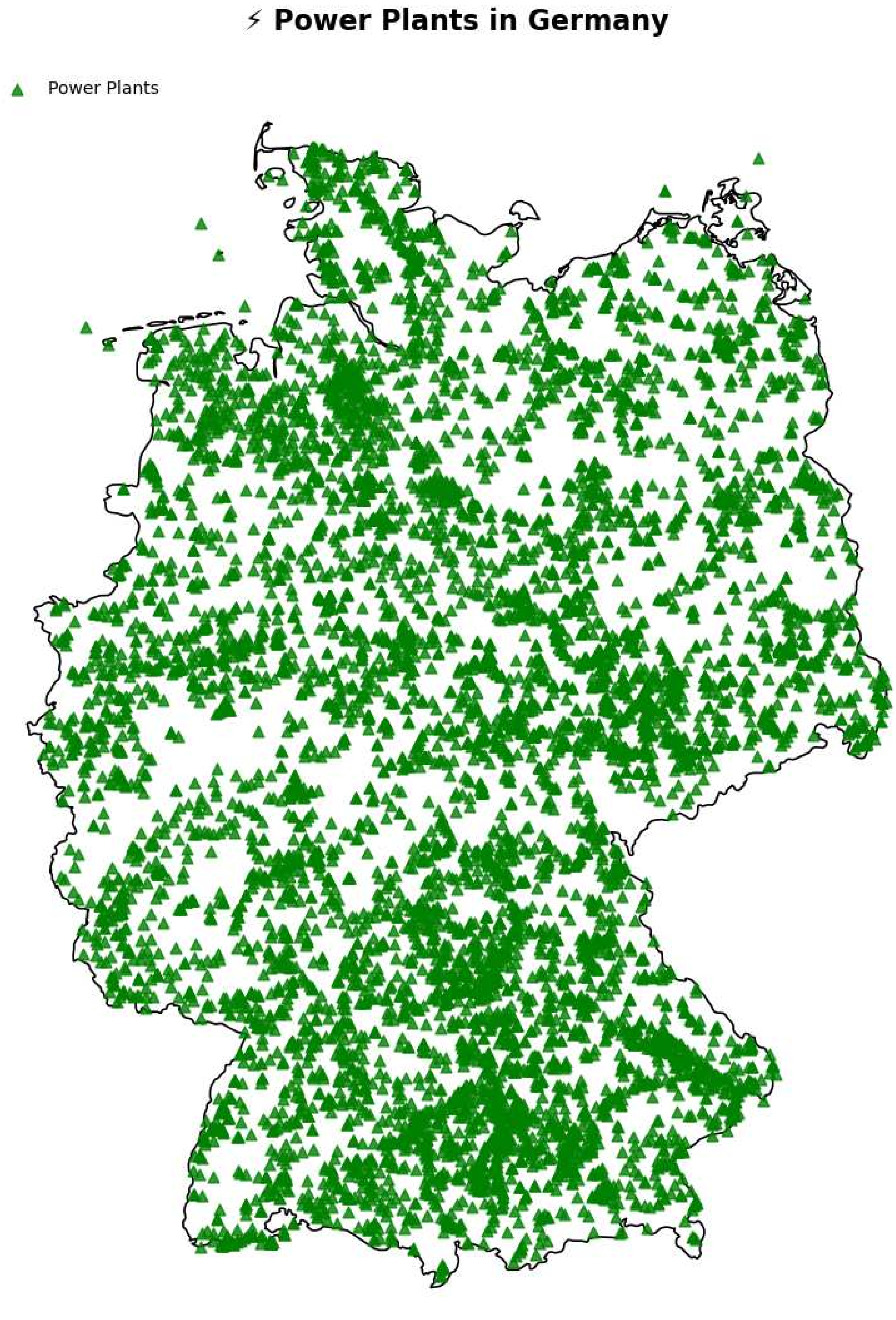
(iv) major cargo ports, indicating access to maritime freight corridors and international trade routes; and

(v) airports derived from OpenStreetMap, representing air-cargo and personnel accessibility.

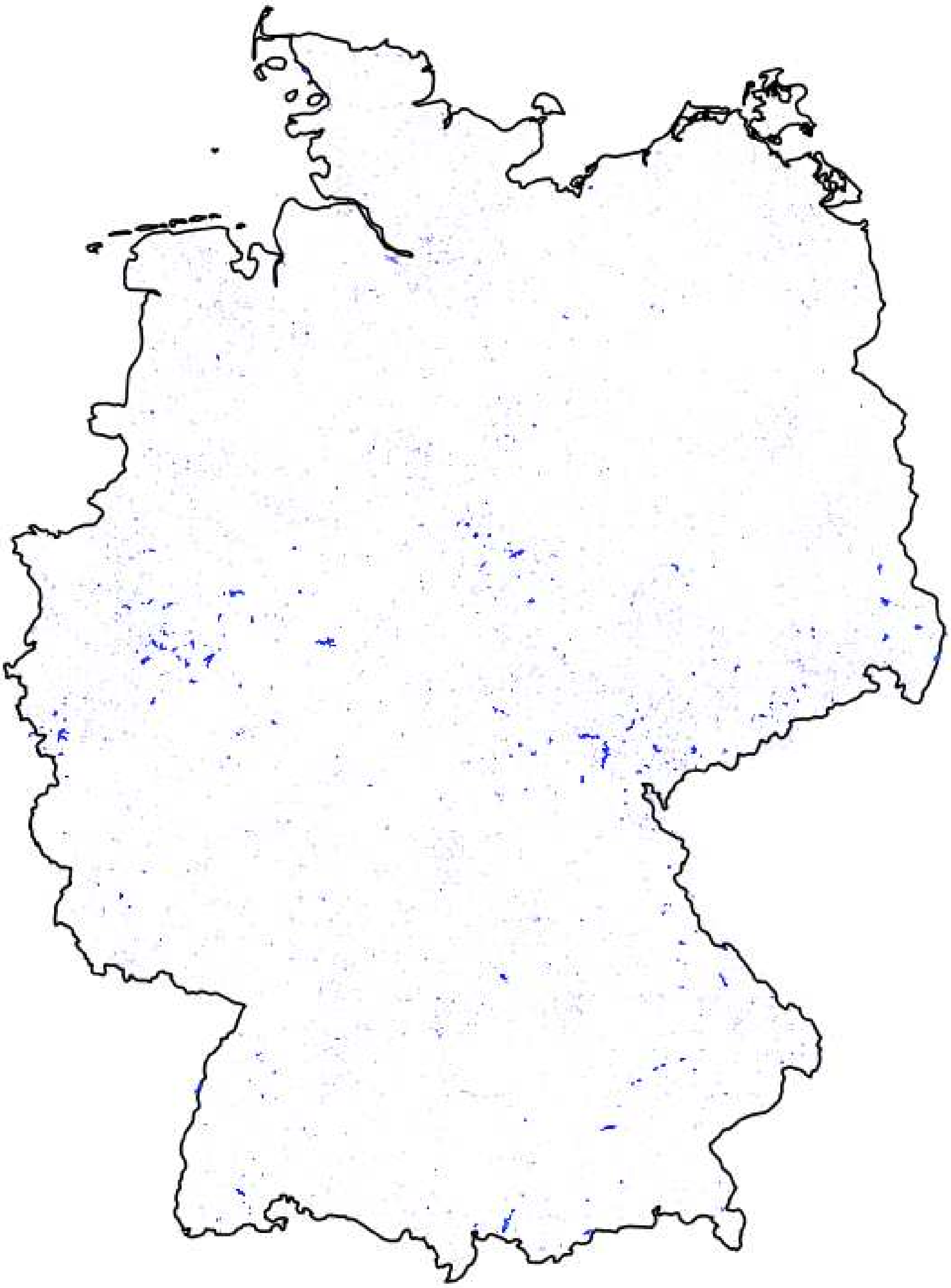
These layers are not interpreted individually, but are transformed into distance-to-nearest-feature rasters and integrated into the composite suitability index as constant-accessibility indicators. They support the identification of zones with structurally favorable infrastructure access relevant for long-term semiconductor fabrication operations.

Airports in Germany (OpenStreetMap)

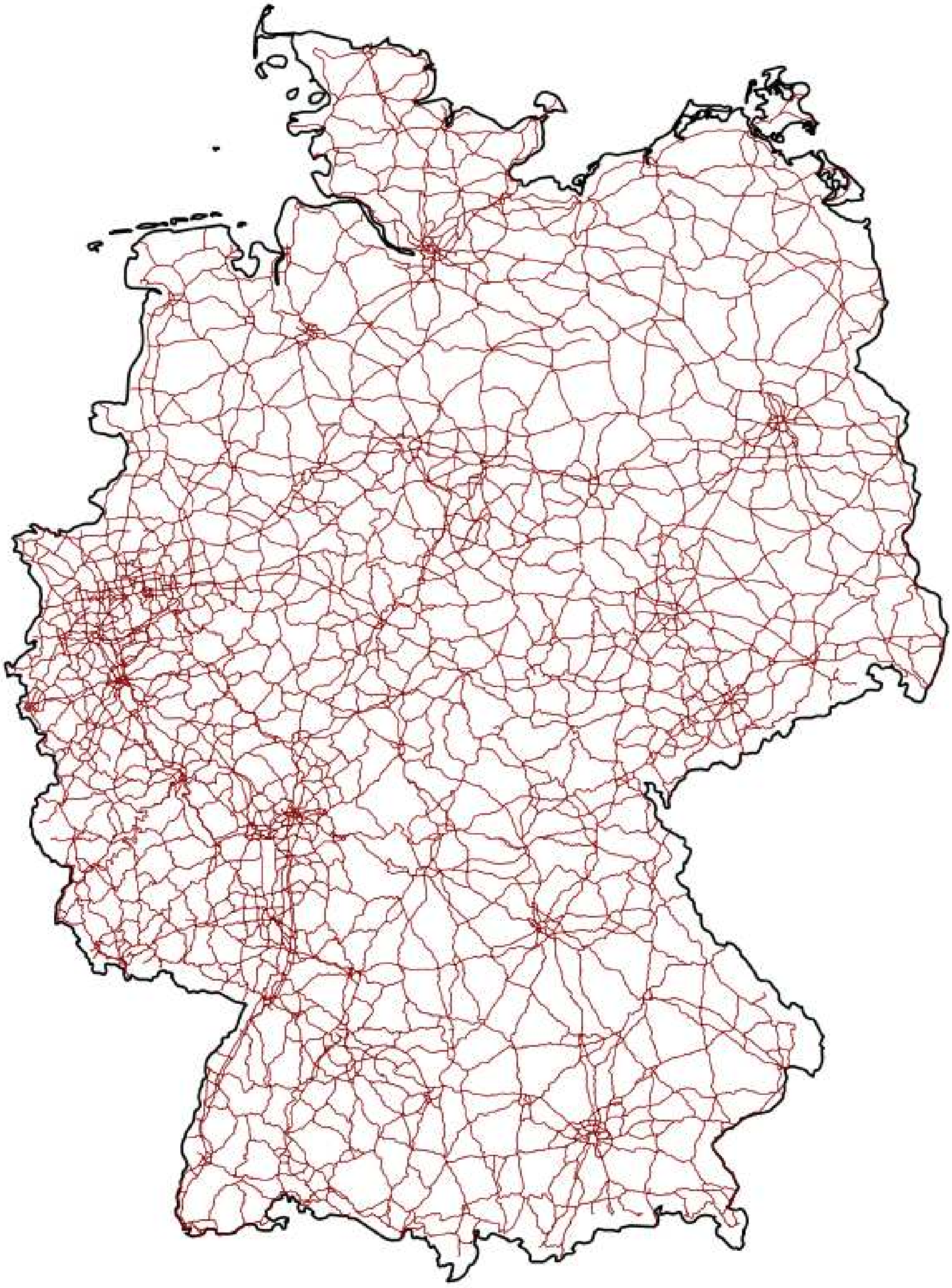

⚓ Major Cargo Ports in Germany
Port of Duisburg (Duisport)


⚡ Power Plants in Germany
Power Plants

Reservoirs in Germany



🗺 Germany – Main Road Network with National Border

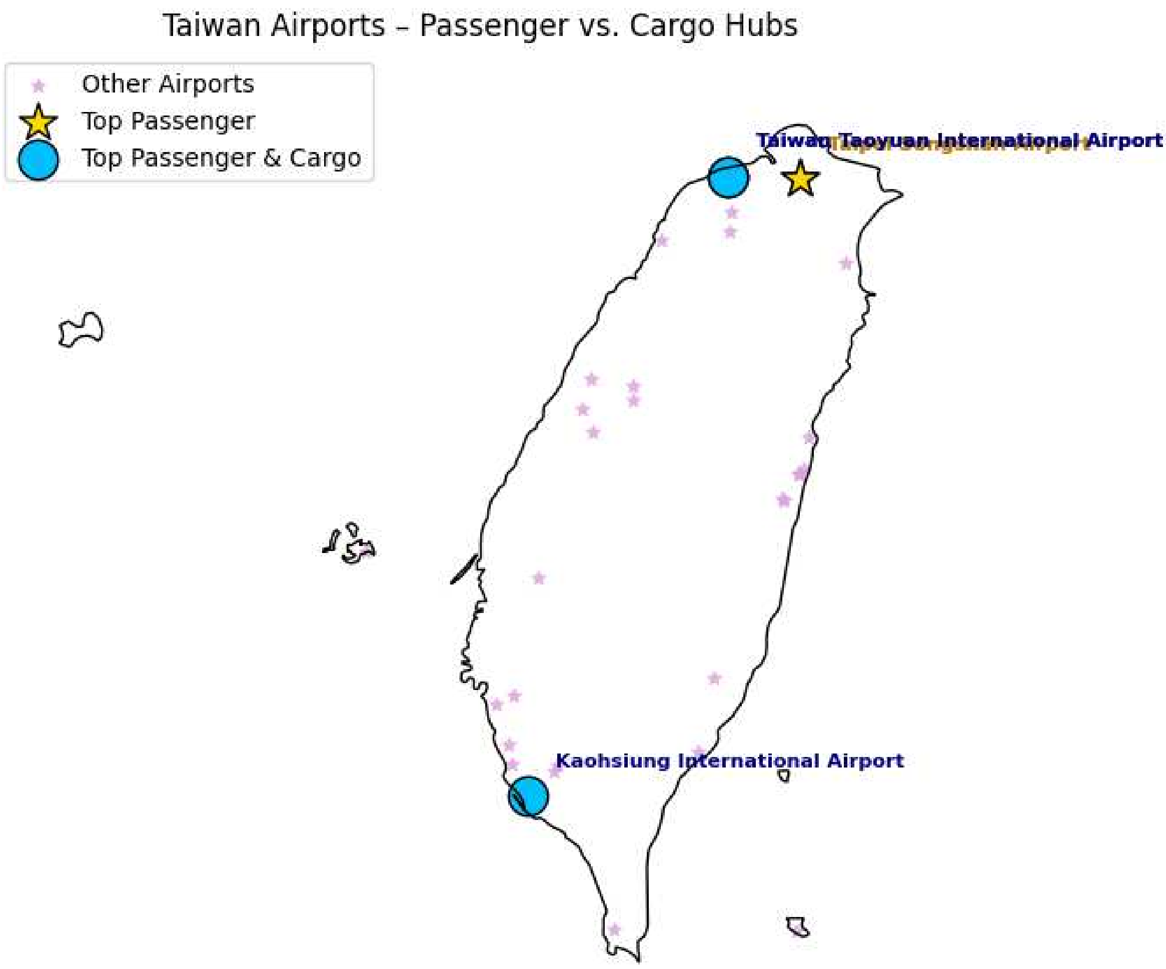


Infrastructure and industrial context - Taiwan:

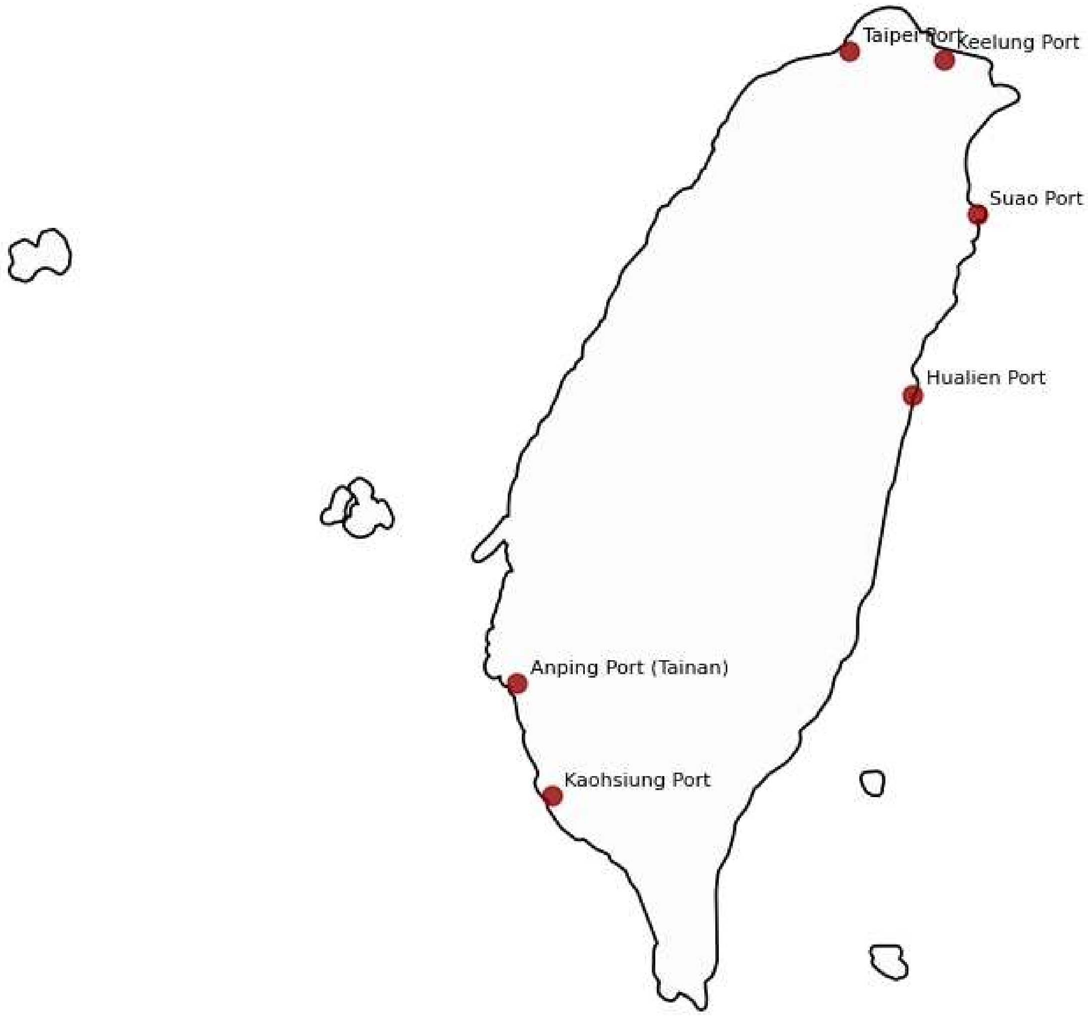
The appendix maps provide spatial context for the suitability analysis in Taiwan. The airport map distinguishes major passenger hubs from combined passenger-cargo airports, highlighting the dominance of Taoyuan International Airport in the north and Kaohsiung International Airport in the south as key air-freight gateways. The ports map shows the main maritime cargo hubs along the west and north coasts, with Kaohsiung, Taichung, Anping (Tainan), and the Taipei Keelung complex forming the backbone of Taiwan's export-oriented logistics system.

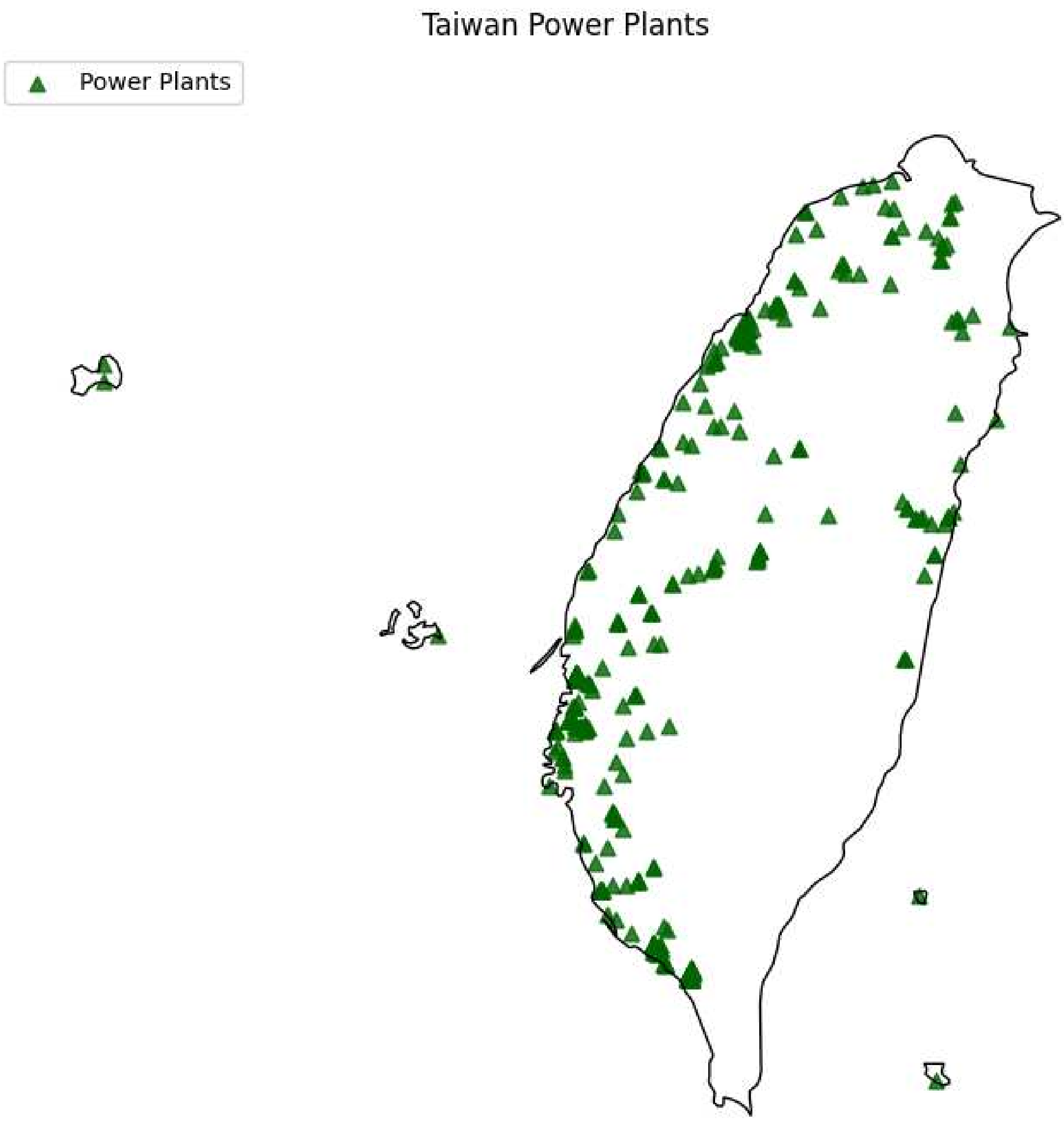
The power plant map illustrates the dense distribution of generation facilities, particularly along the western corridor, underscoring the close coupling between industrial activity and electricity infrastructure. The semiconductor fabrication sites map locates major fabs that together account for a large share of national production, concentrated primarily along the western plains. Finally, the reservoir map displays the spatial distribution and size of surface-water storage facilities, emphasizing the importance of reservoir buffering for industrial water security in a drought-sensitive island system.

Together, these maps contextualize the constant-accessibility indicators used in the MCDA and illustrate how logistics, power supply, industrial clustering, and water storage jointly shape the operational environment for semiconductor fabrication in Taiwan.

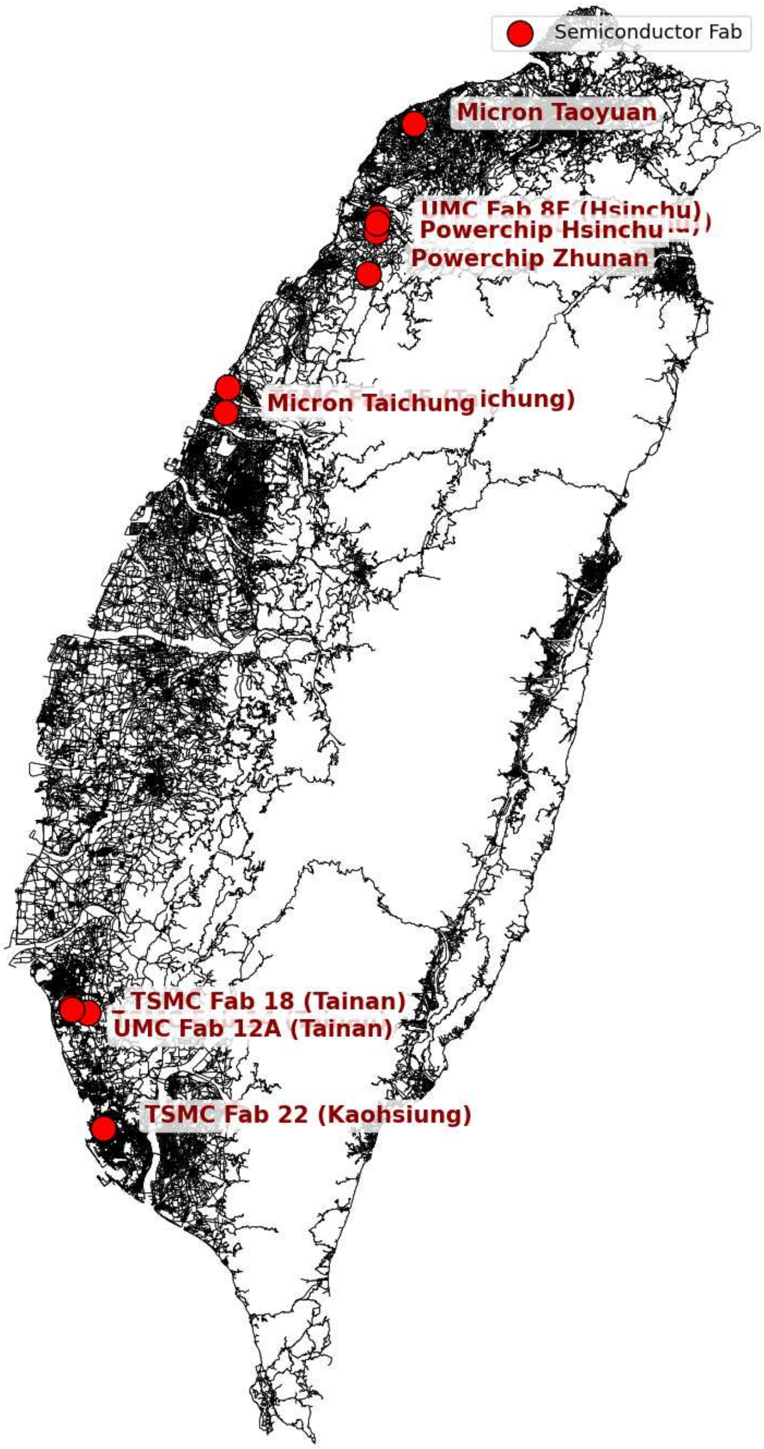

Taiwan Airports – Passenger vs. Cargo Hubs
Other Airports
Top Passenger
Top Passenger & Cargo
Taiwan Taoyuan International Airport
Kaohsiung International Airport

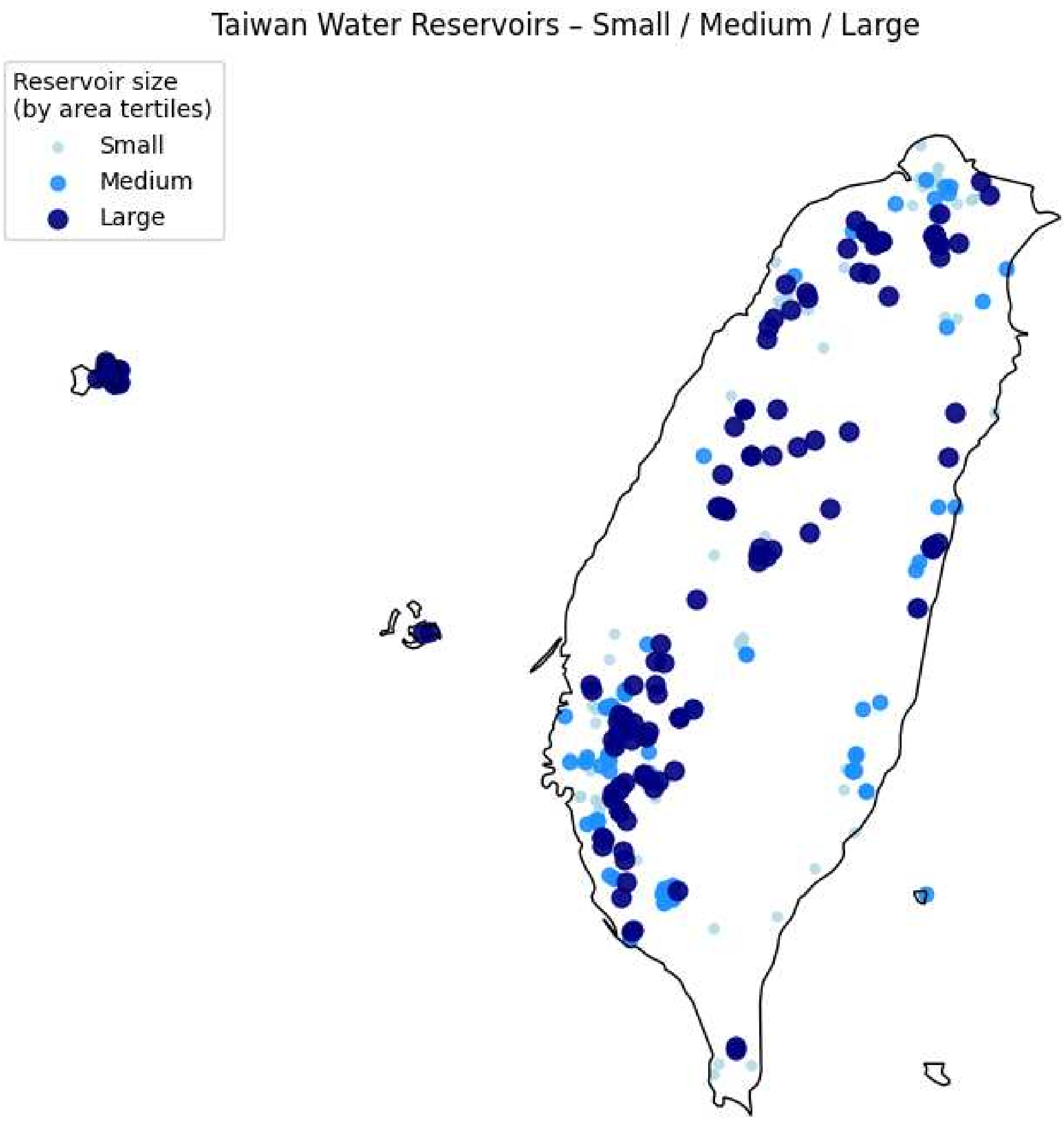
□ Major Taiwan Ports – Realistic Coastline




Taiwan Power Plants
Power Plants

Major Semiconductor Fabrication Sites in Taiwan (Market Share 75%)




Taiwan Water Reservoirs – Small / Medium / Large
Reservoir size
(by area tertiles)
Small
Medium
Large