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Exploring Inter-country Equity in Mekong River Basin Hydropower Generation

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Abstract

The Mekong River basin, one of the world's most complex transboundary water systems, is undergoing rapid infrastructural transformation. The massive expansion of the region's hydropower sector has altered natural flow regimes, creating a reality where the interests of upstream countries goes against those of downstream ones. Although the available literature extensively discusses the current situation and growing geopolitical tensions, there is still a need for quantitative studies that consider the inclusion of equity metrics within water resource management models.

This thesis aims to discuss this by exploring the trade-off between efficiency in hydroelectric production and equity in the distribution of benefits among the nations crossed by the Mekong River basin.

Using the epsilon-NSGA-II algorithm, the joint operation of the main reservoirs was optimized over a ten year historical horizon (2012-2022), pursuing the conflicting objectives of maximizing energy production and maximizing energy security.

The preliminary analysis of the historical scenario provided a critical view of current and historical management. The results show that the lack of international cooperation in dam operations has created a highly asymmetrical system: while upstream countries have maximized their national profits by ensuring stable production, downstream countries have suffered a transfer of hydrological risk, facing supply volatility and reduced energy security. This configuration proved not only inequitable but also technically inefficient, failing to exploit the temporal synergies between upstream releases and downstream demand.

Going beyond this logic, the results of the optimization scenarios reveal the existence of several possibilities for increasing the efficiency of basin management.

The first optimization scenario, in particular, refutes the hypothesis of a structural trade-off between efficiency and equity. Flexible coordination of releases makes it possible to increase the overall energy production of the basin and, at the same time, reduce the energy deficit without compromising the revenues of upstream producers.

The study also highlights the limitations of the approach based on rigid allocation con-

straints (constrained scenario), which prove to be sub-optimal compared to integrated management based on hydrological solidarity.

In conclusion, the study discusses that the transition from national water sovereignty to cooperative regional management is the only viable strategy. The results suggest that if the goal is to drastically reduce inequity within the basin, it is necessary to use the Atkinson index as the objective function to be optimized.

Another possibility is to use the energy surplus generated, by technical efficiency, as the basis for political benefit sharing mechanisms, ensuring sustainable and equitable development for the entire Mekong region.

Keywords: Energy production; Optimization; Equity

Abstract in lingua italiana

Il bacino del fiume Mekong, uno dei sistemi idrici transfrontalieri più complessi al mondo, è al centro di una rapida trasformazione infrastrutturale. La massiccia espansione del settore idroelettrico della regione ha fortemente alterato i regimi naturali di flusso, generando una realtà che vede contrapposti gli interessi dei paesi a monte rispetto a quelli dei paesi a valle. Sebbene la letteratura a disposizione discuta approfonditamente la situazione attuale e le crescenti tensioni geopolitiche, esiste ancora il bisogno di studi quantitativi che considerano l'inserimento di metriche di equità all'interno dei modelli di gestione delle risorse idriche.

Questa tesi mira ad approfondire questo argomento, esplorando il compromesso tra efficienza nella produzione idroelettrica ed equità nella distribuzione dei benefici tra le nazioni attraversate dal bacino del fiume Mekong.

Utilizzando l'algoritmo epsilon-NSGA-II, è stato ottimizzato il funzionamento congiunto dei principali invasi su un orizzonte storico decennale (2012-2022), perseguendo obiettivi contrastanti di massimizzazione della produzione energetica e massimizzazione della sicurezza energetica.

L'analisi preliminare dello scenario storico ha fornito una visione critica della gestione attuale e storica. I risultati dimostrano che l'operatività priva di cooperazione internazionale delle dighe ha generato un sistema fortemente asimmetrico: mentre i paesi a monte hanno massimizzato i propri profitti nazionali garantendosi una produzione stabile, i paesi a valle hanno subito un trasferimento di rischio idrologico, affrontando una volatilità delle forniture e una ridotta sicurezza energetica. Questa configurazione si è rivelata non solo iniqua, ma tecnicamente inefficiente, mancando di sfruttare le sinergie temporali tra i rilasci a monte e la domanda a valle.

Andando oltre questa logica, i risultati degli scenari di ottimizzazione rivelano l'esistenza di diverse possibilità per aumentare l'efficienza della gestione dei bacini.

Lo scenario della prima ottimizzazione, in particolare, smentisce l'ipotesi dell'esistenza di un trade-off strutturale tra efficienza ed equità. Il coordinamento flessibile dei rilasci permette infatti di incrementare la produzione energetica complessiva del bacino e, simul-

taneamente, di ridurre il deficit energetico, senza compromettere i ricavi dei produttori a monte.

Lo studio evidenzia inoltre i limiti dell'approccio basato su vincoli di ripartizione rigidi (scenario vincolato), il quale si dimostra sub-ottimale rispetto a una gestione integrata basata sulla solidarietà idrologica.

In conclusione, lo studio sostiene che la transizione dalla sovranità idrica nazionale a una gestione regionale cooperativa sia l'unica strategia praticabile. I risultati suggeriscono che, se l'obiettivo è ridurre drasticamente l'iniquità all'interno del bacino, è necessario utilizzare l'indice di Atkinson come funzione obiettivo da ottimizzare.

Un'altra possibilità è quella di utilizzare il surplus energetico generato dall'efficienza tecnica come base per meccanismi politici di condivisione dei benefici, garantendo uno sviluppo sostenibile ed equo per l'intera regione del Mekong.

Parole chiave: Produzione energetica; Ottimizzazione; Equità

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1 | Introduction

The Mekong River basin spans through six nations; China, Myanmar, Laos, Thailand, Cambodia and Vietnam. The case study is an example of the conflict between economic growth, energy security, and ecological sustainability (Schmitt et al., 2019).

In the 21st century, the push for renewable energy has led to a massive expansion of hydropower related infrastructure in the region. Development of large scale hydropower is proceeding rapidly in the Mekong basin, with little consideration given to the biological resources being lost (Campbell and Barlow, 2020).

This situation create problem related to environmental issues (Campbell and Barlow, 2020). The most important impacts, directly related to the construction of dams, arise from the reservoirs acting as a barrier to the movement of sediment and aquatic organisms (Campbell and Barlow, 2020).

In the Mekong river, that carries a very large amount of sediment load, the trapping of sediment has important consequences (Campbell and Barlow, 2020). For once, riparian and floodplain systems derive part of their nutrient supply from deposited silt, that can be severely reduced because of the blocking of sediment supply (Campbell and Barlow, 2020). Other important issues that comes with the reduction of sediment supply are the resulting sediment starvation, beyond coastal erosion and salinization; this also compounds other local threats, including groundwater extraction, sand mining, mangrove loss, and sea level rise (Kondolf et al., 2022). Together, these factors are causing the delta to sink (Kondolf et al., 2022).

Another pathway by which dams can impact the Mekong ecosystems is by alteration of downstream flow patterns (Campbell and Barlow, 2020).

For the main part, the problems in the case study come not from the construction of individual dams but from their cumulative effects, combined with a historical lack of basin wide planning (Schmitt. et al., 2021).

In fact, historically, dam construction in the Mekong followed an ad hoc, project by project approach driven by economic criteria. Without a system scale perspective, this uncoordinated development rarely produces optimal trade-offs between energy generation

and environmental health (Schmitt. et al., 2021).

In contrast to what has been done in the past, achieving environmental goals requires a multi-objective strategic approach to dam planning (Barbarossa and Schmitt, 2024).

Consequently, the basin is now facing a "lock in" effect: avoidable negative impacts are already established, limiting future opportunities for sustainable management (Barbarossa and Schmitt, 2024).

The long term outcomes are not encouraging for the lower Mekong countries. Over the next few decades there are a number of predictable consequences that will arise as a result of the development of hydropower in the Mekong, that will mostly affect them (Campbell and Barlow, 2020).

Historically, upstream development has been dominated by China's massive hydropower expansion. Operating primarily on national interests, China's unilateral water release and sediment retention strategies have forced the countries of the lower Mekong to passively adapt to suboptimal conditions, bearing the brunt of the negative ecological and economic impacts (Yu et al., 2024).

In fact, water resource infrastructure drives energy production and food security. But, expanding storage capacity threatens the Mekong's ecosystem services, as previously discussed. In international river basins, this conflict escalates (Yu et al., 2024). Riparian countries prioritize local gains over basin-wide ecological health. The Mekong is a prime example of these dynamics, making a transboundary perspective absolutely essential (Yu et al., 2024).

Maximizing aggregated benefits is not easy, it requires robust international cooperation. The cooperation can make a great difference, in fact, operating infrastructure collaboratively can generate substantial economic and environmental advantages across the Lancang Mekong region (Yu et al., 2024).

Compared to partial or non cooperative approaches, full cooperation increases total economic benefits by 3% to 21% (Yu et al., 2024). More importantly, it drastically reduces ecological damage.

For instance, cooperative management can cut fishery losses from 23% to 12% and reduce sediment transport deficits from 60% down to 22% (Yu et al., 2024), as shown in the figure 1.1.

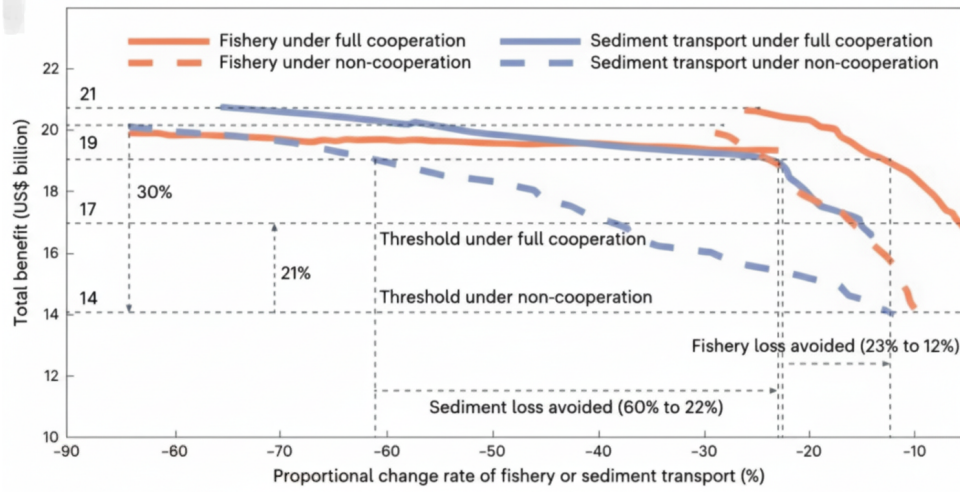


Figure 1.1: Fishery and sediment transport under non cooperation and full cooperation scenarios (Yu et al., 2024).

As infrastructure expands and climate change intensifies, this collaborative approach becomes even more necessary to obtain long term resilience (Yu et al., 2024).

Shifting from a fragmented system to a fully cooperative model is necessary, but not easy, it requires fair benefit sharing mechanisms (Barbarossa and Schmitt, 2024). Currently, upstream nations shoulder the financial burden of building and operating the dams, while also capturing the bulk of the economic gains. At the same time downstream nations absorb severe ecological hits (Barbarossa and Schmitt, 2024).

This disparity destabilizes any attempt of cooperation, with the distribution of impacts that is currently highly asymmetrical. Ultimately, this structural imbalance between localized profits and exported damages forms the core of the inter-country equity dilemma (Barbarossa and Schmitt, 2024).

The lack of cooperation, as explained above, leads to a worrying situation in terms of equity within the basin (Yu et al., 2024).

In this respect, there is a gap in the scientific landscape. In fact, optimization studies using multi-objective algorithms are usually conducted with the aim of analyzing the trade-off between different objectives, without taking into account equity between different countries (Barbarossa and Schmitt, 2024).

The limitation of these analyses is that few studies consider equity, despite the wide range of indices available in the literature (as we will see in the next chapter). This is an important limitation because equity is the basis for sustainable development.

In fact, a technical optimization alone cannot resolve these basin wide conflicts.

Infrastructure planning must explicitly incorporate ethical and distributional dimensions (Atkinson, 1970).

If spatial equity is not prioritized alongside emission reductions, also the transition to low carbon energy (like the increase of hydropower generation) risks to increase regional inequalities in access to essential services (Atkinson, 1970).

Defining and quantifying equity, requires careful consideration. Every metric relies on an underlying social welfare function, meaning its ethical assumptions must be completely transparent (Ashraf et al., 2025). Selecting an indicator, such as the Gini coefficient, the Atkinson Index, or another measure, is never a purely neutral or technical choice. Instead, it embeds specific value judgments regarding how strongly a society penalizes inequity (Atkinson, 2011).

The theoretical choice of how manage the search of equity have profound implications for transboundary rivers (Basheer et al., 2023).

For instance, negotiations surrounding the grand ethiopian renaissance dam (GERD) on the Nile demonstrate that cooperative adaptive management can boost basin wide resilience. Yet, realizing these benefits demands policy frameworks that balance economic efficiency with environmental justice (Basheer et al., 2023).

Sector coupling offers another promising pathway to achieve this balance. In the context of Lancang Mekong, the proposed dual water-electricity cooperation (DWECC) framework illustrates how the integration of the energy and water markets can generate mutual benefits (Zhang et al., 2023). By leveraging electricity trade revenues to compensate for compromises in water allocation, such mechanisms simultaneously improve overall economic performance and resource equity among riparian nations (Zhang et al., 2023).

In order to adopt equitable measures and analyze the possibilities for more equitable development and greater cooperation, it is necessary to have the tools needed to carry out the analyses (Dang et al., 2020b).

Successfully managing such a vast and highly regulated basin requires reliable simulations of its physical dynamics (Dang et al., 2020b).

Historically, hydrological modeling in the Mekong has struggled with severe data scarcity (Dang et al., 2020b). Researchers often had to rely on simplistic, rule based assumptions for reservoir operations, and the resulting models rarely adhered to FAIR (Findable, Accessible, Interoperable, Reusable) data principles (Dang et al., 2020b).

An important innovation is VIC-Res Mekong, an open source hydrological water management model designed for the basin (Eldardiry et al., 2025). This model simulates water and energy budgets using the Variable Infiltration Capacity (VIC) model and incorporates

a detailed streamflow routing scheme, VIC-Res, which accounts for reservoir storage and release dynamics (Eldardiry et al., 2025). The model overcomes traditional data scarcity by integrating a database of reservoir storage time series inferred from satellite images for 129 dams, allowing for a realistic and transparent representation of dam operations, together with a precise characterization of dam induced hydrological alterations (Eldardiry et al., 2025).

There are two fundamental aspects pertaining to the representation of water reservoirs in large scale hydrological models, the hypsometric curve and the mass balance, linking water storage, inflow, evaporation and release (Eldardiry et al., 2025). They both present challenges that can be overcome by using recent advances in spatial analysis and remote sensing (Eldardiry et al., 2025). This observation based approach grounds the simulation in reality. By capturing the distinct signature of dam operations on river discharge, the tool provides a transparent and reproducible method to quantify how human interventions are altering the Mekong's natural flow regime (Eldardiry et al., 2025).

Accurately representing reservoirs is not just a structural detail; it is fundamental to avoid flawed model calibration (Dang et al., 2020a). When infrastructure is omitted, model parameters compensate to match observed data (Dang et al., 2020a). This artificial compensation misrepresents actual processes, such as baseflow and surface runoff (Dang et al., 2020a). The possibility to overcome this compensation by the simulation of reservoir operations, as done in the VIC-Res Mekong model, is mandatory for reliable hydrological assessments (Dang et al., 2020a).

Moving beyond modeling, current research explores mitigation strategies, primarily through dam re-operation (Galelli et al., 2022). The fundamental issue lies in standard operational practices: dams typically hold water during the summer monsoon and release it during the dry season. This seasonal inversion is highly detrimental (Galelli et al., 2022). It pushes river flows outside their natural variability envelope for roughly 30% of the year (Galelli et al., 2022). By dampening vital peak flows and artificially inflating low flows, these operations erase the critical hydrological situation required for fish migration and spawning, once again having a greater impact on the countries of the Lower Mekong (Galelli et al., 2022).

With all this complication inside the basin, the success of any physical mitigation, such as dam re-operation, depends on political realities rather than hydrological modeling alone (Yu et al., 2024). True basin wide optimization requires strict international cooperation and inter-country equity (Yu et al., 2024). The obstacle to a basin wide optimal solution is the current paradigm of non cooperative planning (Yu et al., 2024).

Technical solutions alone cannot force policy changes. Cooperative frameworks from other international basins offer valuable precedents. Yet, Implementing these optimal portfolios requires addressing the political realities of burden sharing and benefit distribution.

Building on this context, the subsequent work aim to quantify the equity dimension. Analyzing how the asymmetrical distribution of hydropower revenues currently shapes regional geopolitics.

It also studies how the current management can be improved.

After reviewing the available literature, the workflow involves analyzing the historical situation in terms of energy production and energy security. This is followed by an analysis of the variations that can be achieved in the basin through multi-objective optimization. The thesis concludes with a critical analysis of the results obtained and the analyses carried out.

The study of historical hydroelectric energy production data for the period 1981-2022 confirms what has been described in the literature. Analysis of the results shows a profound inequity between the countries crossed by the Mekong river, both in terms of actual production and in terms of energy security.

The analyses also show that weighting countries by GDP per capita does not improve the Atkinson index values, demonstrating that the problems do not stem solely from the presence of the Chinese superpower.

A further concern arises from the study of monthly production rates, which shows that, when the problem is examined through a magnifying glass, equity between countries worsens further. Historically, studying production over several decades, it becomes clear that, in the long term, there have been variations in equity, dictated by differences in infrastructure development between countries.

Optimizations demonstrate the possibility of improving the efficiency of the system. At the same time, it is clear that it is very difficult to directly and significantly improve equity conditions within the basin without the presence of an equity measure within multi-objective optimization.

So, this work offers important insights into the possibilities for increasing the productive efficiency of the basin through optimization and cooperation between different states. At the same time, it also confirms the need to include an equity measure (such as the Atkinson index) in multi-objective optimization; if the goal is to maximize equity in the basin.

1.1. Objectives and Research Questions

To address these transboundary challenges, this thesis investigates the relationship between hydropower production and inter-country equity in the Mekong river basin. The research is structured around three progressive methodological phases.

Initially, the study defines the historical baseline to quantify past production dynamics and assess the existing distribution of resources among riparian stakeholders.

Building on this foundation, a multi-objective optimization model is applied to simulate alternative management scenarios. This step evaluates how optimized dam portfolios might alter energy generation compared to historical ones.

Finally, the research critically examines these optimized outcomes to determine whether technical re-operation alone can resolve structural equity issues, or if broader policy interventions and management frameworks are ultimately required.

Specifically, this work seeks to answer the following research questions:

1. What is the historical baseline regarding production dynamics and resource equity within the basin?
2. What variations and impacts emerge when applying the optimized scenario compared to the historical baseline?
3. Do the implemented optimizations effectively resolve the equity problem, or is the adoption of further procedures and policies necessary?

1.2. Outline of the thesis

This thesis is organized as follows. Chapter 2 describes the general background of hydrological models and, specifically, the VIC-Res Mekong model employed in this study. Furthermore, it introduces the concept of equity by presenting the applicable metrics, with a specific focus on the Atkinson index, which is subsequently used in the production and results discussion phases. Lastly, Chapter 2 describes the multi-objective optimization algorithm utilized, namely Epsilon-NSGA-II.

Chapter 3 presents the various analyses conducted on hydropower production within the basin. Specifically, it includes the following investigative sections: Equity analysis based on historical data - Production (Section 3.1), Equity analysis based on historical data - Firm hydropower (Section 3.2), and Equity analysis based on optimized variables (Section 3.3). Section 3.1 is divided into the following subsections: Unweighted analysis (3.1.1), Weighted production using GDP per capita (3.1.2), Atkinson index with monthly time

step (3.1.3), and Evolution of equity over the decades (3.1.4). Section 3.3 is further divided into the following subsections: Introduction to optimizations (3.3.1), First optimization: top 20 reservoirs (3.3.2), Second optimization: top 19 reservoirs (max 4 per country) (3.3.3).

Following the presentation of the results, there is chapter 4 presenting an in-depth discussion of the results observed with the two optimizations.

Finally, Chapter 5 (conclusions) summarizes the main findings and outlines potential directions for future research.

2 | State of the Art and Methods

To properly assess the trade-offs in the Mekong Basin, this chapter integrates physical modeling with ethical theory. The discussion begins in Section 2.1 by addressing the hydrological challenge: the need for transparent, open-source tools. This leads to a technical breakdown of VIC-Res Mekong, the computational engine used in this work to simulate hydropower generation.

Subsequently, Section 2.2 establishes the evaluative framework. It argues that trans-boundary water management cannot rely on efficiency alone but must prioritize spatial equity. Within this context, the selection of the Atkinson Index is justified, as the most robust metric for quantifying the disparities in benefit distribution among riparian nations.

Section 2.3 explain the main features of the model used during the optimization phase. In conclusion, Section 2.4 explain the methods of this work.

2.1. Model

The Mekong river basin is the ecological and economic backbone of Southeast Asia. Over the past two decades, the rapid proliferation of hydroelectric dams, has drawn intense scientific debate (Chowdhury et al., 2021). While these projects offer a massive source of clean electricity (Chowdhury et al., 2021), they alter the river’s natural hydrological regime (Ziv et al., 2012). These physical changes have immediate biological repercussions, disrupting delicate ecological balances and threatening species survival (Ziv et al., 2012). Specifically, the collapse of fish populations and biodiversity loss triggers a domino effect, leading to severe social and economic instability for communities relying on the river (Ziv et al., 2012).

Effective resource management in the Mekong is based on accurate hydrological modeling (Johnston and Kummu, 2011). For this reason, several large scale hydrological models have been developed and implemented at the basin scale to study the interaction between anthropogenic alterations (such as change in land use and dam construction), climate variability, and hydrological processes (Eldardiry et al., 2025).

However, a critical review of the current landscape reveals two major blind spots (Eldardiry et al., 2025). First, no existing model (before VIC-Res Mekong) fully adheres to FAIR principles (Findable, Accessible, Interoperable, and Reusable) (Wilkinson et al., 2016), which are necessary to enhance the transparency and applicability of models.

In addition, while strictly necessary, the incorporation of reservoir operations remains a challenge (Eldardiry et al., 2025). Most models rely on simplistic assumptions regarding bathymetry and release rules. This is not a failure of modeling logic, but a symptom of data scarcity (Eldardiry et al., 2025). Information on dam design and operational objectives is rarely shared between nations and, without precise data on reservoir releases, which directly dictate downstream flow regimes, it is nearly impossible to mitigate the resulting environmental and social crises (Eldardiry et al., 2025).

Remote sensing offers a powerful solution to these institutional barriers (Dong et al., 2023; Vu et al., 2023). Using scalable, near global satellite coverage, researchers can now derive detailed bathymetric data and infer operating rules without relying on limited government disclosures.

To address these gaps, for this work VIC-Res Mekong was used. Unlike its predecessors, this open-source hydrological water management tool is designed from the ground up to be fully FAIR compliant, ensuring accessibility and reproducibility for the scientific community (Eldardiry et al., 2025).

2.1.1. VIC-Res Mekong

The model is built on previous work (Dang et al., 2020b; Galelli et al., 2022), the framework integrates the Variable Infiltration Capacity (VIC) model for catchment scale water and energy balance simulation, together with the VIC-Res model to simulate stream flow routing and reservoir operations (Eldardiry et al., 2025). This work gives the user the opportunity to have features that advance previous modeling frameworks in two key directions. First, the bathymetry of each reservoir within the basin is represented by hypsometric curves, that relate area, storage, and elevation. Second, the reservoir operation module in VIC-Res is enriched by information retrieved from MSEA-Res, a 1985–2023 time series dataset, that provides absolute reservoir storage for Southeast Asia (Eldardiry et al., 2025). The user can choose to select the daily storage values (for each reservoir) retrieved from the MSEA-Res dataset, or to directly force the model with the observed storage (Eldardiry et al., 2025).

As already cited, the foundation of the model is the Variable Infiltration Capacity (VIC) model, a large scale, semi distributed land surface model (Liang et al., 1994). VIC orga-

nizes the spatial domain into computational cells, and, for each one of them, simulates the water and energy fluxes governing the terrestrial water cycle.

Each cell consists of one vegetation layer and two (or three) soil layers, for which important processes such as evapotranspiration, infiltration, runoff, and baseflow are calculated at a daily or sub-daily time step (Lohmann et al., 1996). Water inputs are strictly through the atmosphere, and the model considers that water reaching the channel network cannot flow back into the soil. The key outputs of interest, the gridded baseflow and the runoff, are routed through the river network using the routing model developed by Lohman (Lohmann et al., 1996). This routing process is based on a flow direction matrix, created from a Digital Elevation Model, and a linearized version of the Saint-Venant equations (Eldardiry et al., 2025).

The routing scheme in VIC-Res incorporates a clear representation of water reservoir operations (Dang et al., 2020a,b). Specifically, each reservoir within the spatial domain is represented by one or more computational cells to account for the location of the dam and the extent of the water surface (Dang et al., 2020b). The mass balance equation for each reservoir accounts for water storage, inflow, evaporation, and release. The release of the reservoir itself can be modeled with multiple approaches (Dang et al., 2020b), the chosen one depend on the specific modeling instances and simulation scenarios.

Two primary approaches are provided with VIC-Res Mekong (Eldardiry et al., 2025):

- The Predetermined Rule Vurves approach, which establishes daily release as a function of target storage values, simulated water availability, inflow, and dam design specifications (Eldardiry et al., 2025).
- The Observed Storage Forcing approach, which is critical for validation, uses the observed storage time series as a boundary condition to solve the mass balance equation for each reservoir. Observed storage, along with modeled inflow and evaporation, is used to invert the mass balance and calculate the historical release (Eldardiry et al., 2025).

VIC-Res is further complemented by python wrappers that support essential model calibration tasks and sensitivity analyses (Eldardiry et al., 2025).

The spatial domain spans approximately $630'000 \text{ km}^2$, extending from the Tibetan Plateau down to Stung Treng, Cambodia (Eldardiry et al., 2025).

For computational and analytical purposes, the spatial domain is divided into six sub-basins (labeled 1 to 6), which respectively contain 29, 15, 25, 17, 1, and 42 dams (as illustrated in Figure 2.1,) (Eldardiry et al., 2025).

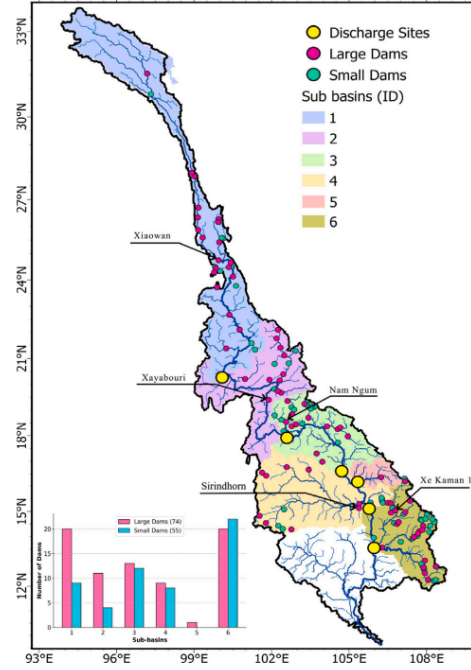


Figure 2.1: Spatial domain of the VIC-Res Mekong model (Eldardiry et al., 2025)

The Mekong floodplains were excluded from the domain since accurate modeling of the complex inundation processes would require a two dimensional (2D) hydrodynamic model, exceeding the scope of the VIC-Res one dimensional (1D) routing scheme (Triet et al., 2020). This domain choice ensures the model focuses on dam operation impacts within the most regulated portions of the basin. Within the defined model domain, a total of 129 dams (all operational in 2022) are included (Triet et al., 2020).

The adopted spatial resolution is 0.0625° . This very fine resolution is essential for two reasons (Eldardiry et al., 2025):

- To avoid the co-location of dams within one grid cells.
- To retain the spatial fidelity required for accurate catchment delineation and flow routing.

Both aspects are very important for representing reservoir operations in a regulated basin (Eldardiry et al., 2025). The included dams meet specific criteria, each having a storage capacity larger than 0.001 km^3 or an installed capacity exceeding 5 MW (Eldardiry et al., 2025).

The VIC and VIC-Res models require a wide array of input data. Climate forcings for VIC include precipitation (mm), minimum and maximum temperature ($^\circ\text{C}$) and wind speed (m/s) over the period 1981–2022 (Eldardiry et al., 2025). Precipitation data were

retrieved from the CHIRPS-2.0 dataset, while the remaining climate forcings were sourced from the ERA5 reanalysis dataset (Eldardiry et al., 2025). Data describing land use and cover and soil properties were obtained from the global land cover characterization dataset and the harmonized world soil database, respectively (Eldardiry et al., 2025). In addition, monthly leaf area index (LAI) and albedo values were derived from terra MODIS satellite images (Eldardiry et al., 2025).

It is known that these large scale datasets may not fully capture the diverse cropping systems, heterogeneous land management practices, and complex soil characteristics of the region (Eldardiry et al., 2025). This introduces a degree of uncertainty in the simulation of crucial hydrological processes such as infiltration/runoff, subsurface water drainage, and evapotranspiration (Eldardiry et al., 2025).

Together with climate and terrestrial inputs, VIC-Res uses information for each water reservoir. This data includes the name, dam location, year of commissioning, maximum and minimum reservoir levels, dead and active storage capacity, turbine capacity, design discharge, hypsometric curves (linking storage, level, and water surface area), and operational rules (Mahto et al., 2025). This reservoir information was retrieved from the existing literature and from the MSEA-Res database (which provides monthly to weekly and daily storage time series for all reservoirs in Southeast Asia over the period 1985-2023)(Mahto et al., 2025).

The representation of water reservoirs within large scale hydrological models is based on two critical aspects: the characterization of their hypsometric curves and the accurate solution of the mass balance equation that links water storage, inflow, evaporation, and managed release. Both aspects present significant challenges that can be overcome by the implementation of the recent advances in spatial analysis and remote sensing (Eldardiry et al., 2025).

The primary challenge concerning hypsometric curves comes from the fact that 29 large dams in the Mekong were constructed prior to the wide availability of digital elevation models (DEMs). This means that, traditionally, only the bathymetry of reservoirs built relatively recently could be studied accurately. In this modeling effort, the SRTM DEM V3 (acquired in 2000) was utilized, which allowed direct modeling of the bathymetry for 100 of the 129 dams. For the remaining 29 older dams, the GRDL dataset was used (Hao et al., 2024). This dataset was created using a deep learning model trained on observational data from hypsometric curves. Importantly, relying on the GRDL dataset allows the framework to avoid making simplifying assumptions about the bathymetry of a reservoir (Eldardiry et al., 2025).

The main challenge in the implementation of the mass balance equation is the lack of ob-

servations for key variables, including storage, inflow, evaporation, and release. A robust solution to data scarcity is the use of observed reservoir water level and/or water surface area, combined with hypsometric curves (Mahto et al., 2025). Doing that it is possible to reconstruct a storage time series spanning periods from a few years to several decades. The model relies on the MSEA-Res database (Mahto et al., 2025), which provides monthly to weekly and daily (by interpolation) storage time series for all reservoirs in Mainland Southeast Asia.

The data collection and processing procedure initially focused on the 74 largest reservoirs (with a capacity exceeding 0.1 km^3). For the remaining 55 smaller reservoirs, the methodology developed by Mahto was applied (Mahto et al., 2025). Within this smaller group, hypsometric curves for the 42 reservoirs (roughly 2% of the total storage) built after 2000 were derived from the SRTM DEM V3. For the last 13 reservoirs (which account for approximately 0.7% of the total storage), the GRDL dataset was used. Subsequently, the water surface area was estimated by processing the NDWI images provided by Landsat and Sentinel-2, and this time series was combined with the hypsometric curves to estimate the final storage time series (Eldardiry et al., 2025).

It is important to note that satellite derived storage data are subject to uncertainty. These inaccuracies can come from imprecision in water surface detection, cloud contamination, and sensor resolution (Eldardiry et al., 2025). Other inaccuracies may come from the bathymetric reconstruction, particularly for the 29 reservoirs whose derived accuracy depends on the size and quality of the GRDL training dataset (Eldardiry et al., 2025). These uncertainties may propagate to VIC-Res Mekong when estimating dam release, especially during periods of rapid drawdown or refill. Despite these limitations, the use of remotely detected data remains the best available solution to implement for hydrological models in transboundary regions (Eldardiry et al., 2025).

To calibrate the VIC-Res Mekong model, the spatial domain was organized into six sub-basins (or zones), as shown in figure 2.1. This division is based on their topographic, soil, and land use characteristics, as well as the availability of high quality discharge data from key monitoring stations provided by the Mekong River Commission (MRC) (Eldardiry et al., 2025).

For each sub-basin, seven parameters controlling the output of the land surface model (VIC) and two parameters controlling the routing model (VIC-Res) outputs were selected. In total, this resulted in 54 parameters that required tuning (Eldardiry et al., 2025).

Given the complexity of the calibration, a multi-objective optimization problem was formulated. This was solved by coupling VIC and VIC-Res with an evolutionary algorithm. Specifically, the ϵ -NSGA-II algorithm was utilized, linked to the two models using the

python wrappers introduced by Dang (Dang et al., 2020b).

The selection of objective functions can be complex due to the large number of performance metrics available in the literature. Drawing from previous studies in the region (Dang et al., 2020a; Galelli et al., 2022), four key metrics were adopted: Nash–Sutcliffe efficiency (NSE), Transformed root mean square error (TRMSE), Mean squared derivative error (MSDE), and Runoff coefficient error (ROCE) (Eldardiry et al., 2025).

The calibration period chosen was 1996–2005, preceded by a two year warm up period (1994 and 1995) (Eldardiry et al., 2025). This specific time frame represents a relatively stable phase in the Mekong’s dam development history, situated after the early construction wave (1981–1995) but before the rapid expansion, that began around 2005. For the use of the ϵ -NSGA-II algorithm is required to determinate the initial population size and the number of function evaluations, which were set to 10 and 100, respectively (Eldardiry et al., 2025). These values were chosen to obtain a reasonable balance between computational requirements and the quality of the solutions. The parameter ϵ , which controls the algorithm’s ability to identify Pareto efficient solutions, was set to 0.001, a common choice for this type of model calibration problem (Vu et al., 2023).

For model validation, the parameterization (solution) that produce the best compromise among the four objective functions was selected. VIC-Res Mekong was then run over the period 1981–2022 (Eldardiry et al., 2025). The releases from each dam during this period were calculated by taking the observed (satellite derived) storage as input and inverting the mass balance equation (Eldardiry et al., 2025).

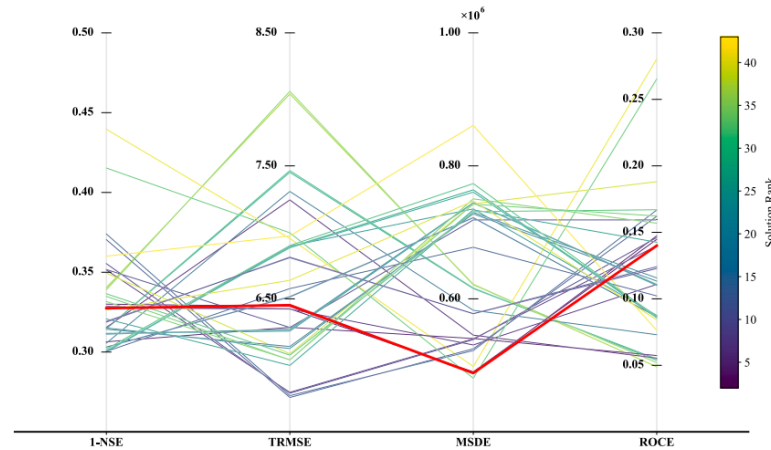


Figure 2.2: Parallel coordinate plot illustrating the values of the goodness of fit statistics obtained through the calibration exercise. Each line connecting the axes represents a parameterization, i.e., a Pareto-efficient solution (Eldardiry et al., 2025)

The calibration exercise resulted in a total of 43 solutions, or parameterizations, with their performance illustrated in figure 2.2. The objective values achieved by these solutions indicate that the model shows satisfactory performance (Moriassi et al., 2007). However, results also demonstrate the difficulty of calibrating a single model that achieves optimal performance across all selected objectives simultaneously.

For validation purposes, a specific parameterization was emphasized. This was selected using the Utopia point criterion, where the chosen parameterization is the closest one to the Utopia point (in terms of Euclidean distance) within the solution set (Eldardiry et al., 2025).

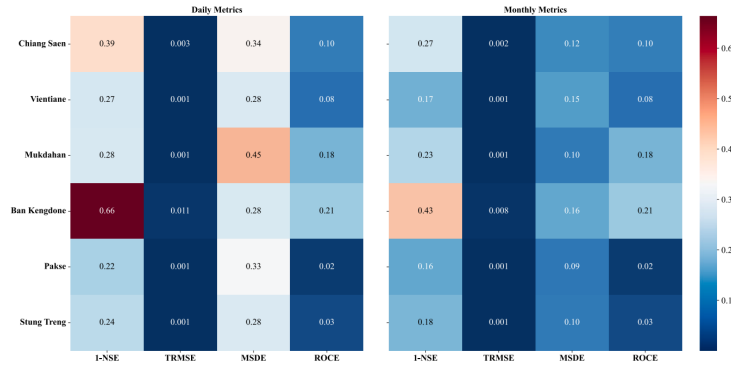


Figure 2.3: Value of the performance metrics (1-NSE, TRMSE, MSDE, ROCE) at the six gauging stations obtained when using daily and monthly data. The performance metrics are calculated on the calibration (1996–2005) and validation (1981–1995 and 2006–2022) periods combined (Eldardiry et al., 2025).

In figure 2.3 is possible to see the comparison between the observed and simulated discharges at the six gage stations. This comparison highlights important aspects of the model's performance. First, VIC-Res effectively captures the seasonal increase in river discharge driven by the summer monsoon (Eldardiry et al., 2025). Then, the cumulative discharge plot shows that the model reasonably captures the total river discharge. However, performance is lower at two stations: Mukdahan (located on the main stem) and Ban Keng Done (located on a tributary) in the central portion of the basin (Eldardiry et al., 2025).

The main inaccuracy of the model lies in its ability to reproduce peak flows. This feature is confirmed by the analysis of both the flow duration curves and the box plots illustrating the variability in daily flow across each calendar month (Eldardiry et al., 2025).

The model successfully captures the changes in the hydrograph caused by the construction of new dams. Note that this specific validation step is particularly challenging due to the large number of reservoirs built during the study period (Eldardiry et al., 2025).

The capability of VIC-Res to account for the timing of dam construction and their operational rules allows it to capture the unique signature these infrastructures impose on river discharge (Poff et al., 2009). To quantify this impact, the model was run to generate two daily discharge time series over a common climatic reference period (1981–2022): historical (regulated) dam development and operations, and baseline (natural) conditions (Poff et al., 2009).

This comparative approach helps separate human influences on flow regimes from climatic variability (Poff et al., 2009). The difference between these two scenarios is quantified using the monthly percentage deviation from natural flow conditions, defined as:

$$\frac{q_t^{HIST} - q_t^{NAT}}{q_t^{NAT}} * 100$$

, where

$$q_t^{HIST} \text{ and } q_t^{NAT}$$

are the simulated discharge in month t under historical (regulated) and natural conditions, respectively.

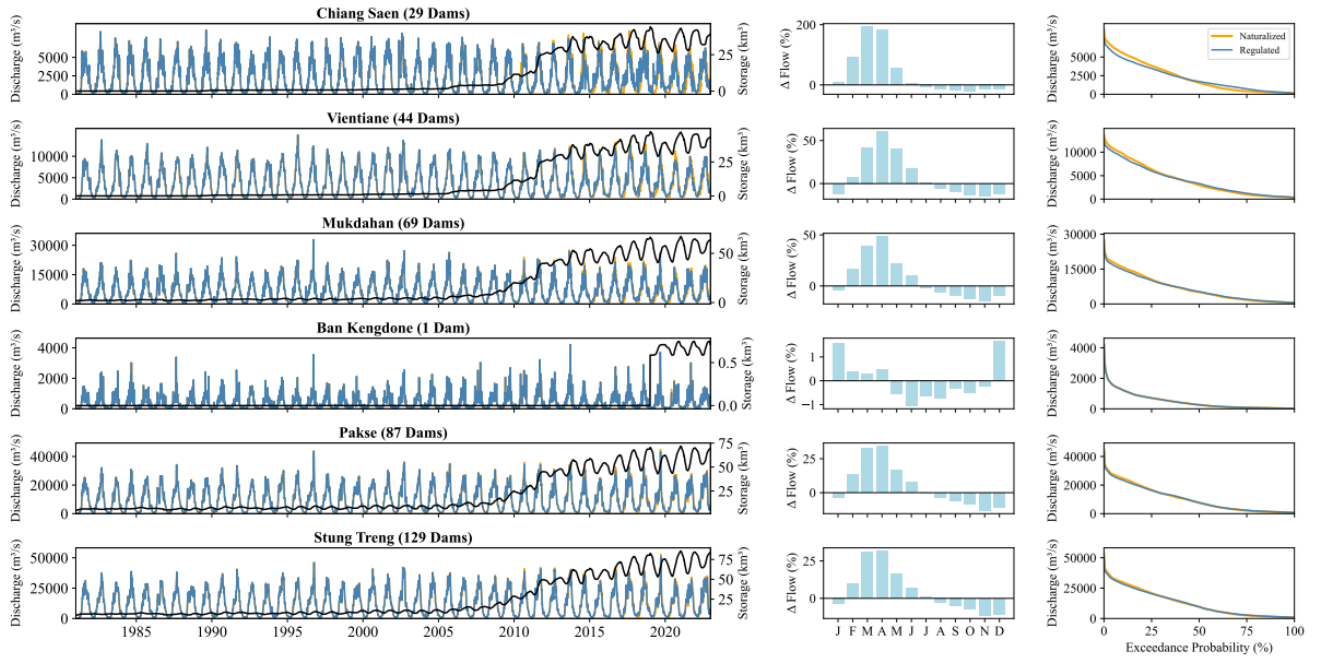


Figure 2.4: For each gauging station, the signature of dams on river discharge through three panels is represented. The left one illustrates the total (daily) upstream storage and the simulated historical and natural flow. The central and right panels illustrate the percentage deviation from natural flow conditions and flow duration curves (historical and natural flow), respectively (Eldardiry et al., 2025).

Figure 2.4 illustrates the discharge time series, the value of this indicator over the last decade (2011–2022), and the flow duration curves for both historical and natural conditions (2011–2022). The primary observation is the steady increase in hydrological alterations caused by dam construction (Eldardiry et al., 2025).

To ensure a steady production of energy, dams release stored water during the dry season and refill their depleted storage by retaining part of the inflow during the wet season (Chowdhury et al., 2021). These operational rules lead to discharge conditions significantly higher than natural ones during the dry season. These findings are further confirmed by the flow duration curves, which show that, under regulated conditions, the exceedance probability of high flows decreases (Chowdhury et al., 2021). A difference in the magnitude of alteration can be seen throughout the basin. The lower reaches are characterized by substantial alterations, yet these are smaller than those characterizing the upper reaches of the Mekong.

This spatial pattern reflects two key factors (Eldardiry et al., 2025):

- The concentration of large upstream reservoirs in the Lancang region, where flow regulation is strongest.
- The higher rainfall and consequently greater natural runoff in the lower basin, which partially offsets the downstream impact of the upstream dam operations.

Overall, these results demonstrate that a model like VIC-Res Mekong provides a reliable modeling platform for studying how human interventions modify hydrological processes in large river basins (Eldardiry et al., 2025). By isolating the effects of dam operations from climatic variability, the results offer a clear view of how and why flow regimes have changed over time, highlighting where flow regulation is most intense. This information is relevant for transboundary water negotiations, hydropower planning, and regional coordination efforts to manage water resources (Eldardiry et al., 2025).

In conclusion, the VIC-Res Mekong model addresses a critical need for an open-source hydrological water management tool designed specifically to describe hydrological processes and reservoir operations in the Mekong River Basin.

Developed and shared following the FAIR principles, the model’s primary intent is to provide a platform that ensures future studies in this region are going to be transparent and reproducible (Eldardiry et al., 2025).

The model incorporates several additional features designed to facilitate future research (Eldardiry et al., 2025).

- Independent reservoir parameters: the design and operating parameters for each

reservoir are modeled independently (and stored in a file system), allowing users to easily adapt the model to specific case studies.

- Optimization linkage: the platform is linked with python wrappers of the VIC-ResOpt library (Dang et al., 2020b), which facilitates solving a variety of sensitivity analysis and optimization problems.
- The availability of such open-source modeling tools makes the deployment of more accurate hydrological models straightforward and transparent, ultimately supporting water resource management in transboundary basins.

In this context, VIC-Res Mekong is very useful to provide critical input to policy processes, by informing flow regulation strategies and negotiations over water sharing among neighboring countries (Eldardiry et al., 2025). It can also help identify the regions most hydrologically affected by dam operations. So, this model is perfect in an area of growing importance for regional monitoring initiatives, such as the Mekong (Eldardiry et al., 2025).

Its open-source nature lowers the barrier to adoption and encourages wider use by technical agencies, researchers, and planners, ensuring that its findings can support sustainable water management across the basin (Eldardiry et al., 2025).

2.2. Equity

Many countries around the world are transitioning from fossil fuel dependent economies toward carbon neutrality, driven by global imperatives, such as the 2030 Agenda for Sustainable Development and the Paris Agreement (Ashraf et al., 2025).

This transition comes with a risk: it could maintain or increase existing inequities, thereby threatening sustainable development (Ashraf et al., 2025). For this reason the planning of low carbon energy transitions must explicitly consider the spatial equity of benefits, especially in developing countries characterized by multi-sector interdependencies and high service disparities between regions (Ashraf et al., 2025).

A core problem related to equity in the Mekong River Basin is the difficulty in managing transboundary waters. Transboundary waters extend hydrological interdependence across national frontiers, connecting users in different countries within a shared system (watkins, 2006). Managing this interdependence is one of the most significant challenges in human development facing the international community. The competition for water creates conflicting demands, forcing policymakers to make choices that have a profound implication for equity, human development, and poverty reduction (watkins, 2006).

Cooperative approaches to transboundary water management can yield substantial gains for human development. Is possible to improve water security for vulnerable populations on both sides of a border by improving the quality, quantity, and predictability of flows across countries (watkins, 2006). This holds true not only in the economic sphere but also across wider political, social, and environmental policy.

In the other end, when cooperation fails or breaks down, all countries stand to lose, with the poor standing to lose the most (watkins, 2006). A lack of cooperation also exposes smaller, vulnerable countries to the threat of unilateral actions by larger, more powerful neighbors. Any one country's use of water transmits effects to others, typically through one of three mechanisms: competition for a finite supply of water, impacts on water quality and timing of water flows (watkins, 2006).

This situation strongly affects livelihoods across borders (figure 2.5).

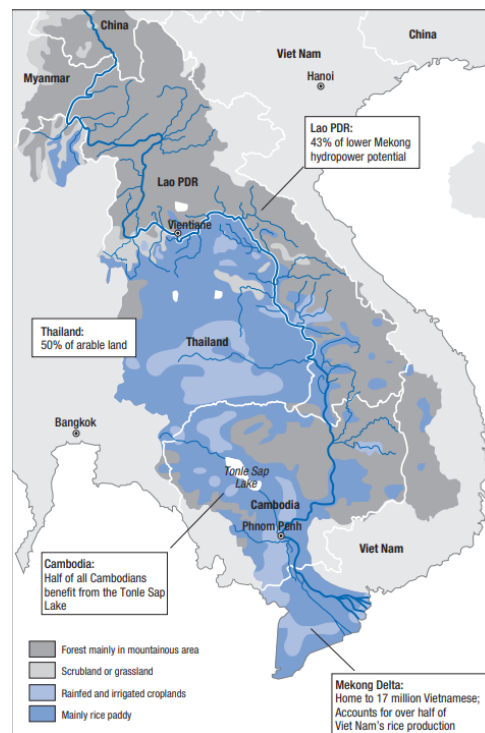


Figure 2.5: The Mekong binds livelihoods across borders (watkins, 2006)

More than a third of the population of Cambodia, Laos, Thailand, and Vietnam live in the Lower Mekong Basin, relying on the river for drinking water, food, irrigation, hydropower, transportation, and commerce (watkins, 2006). Millions more in China and Myanmar, and beyond the basin's boundaries, also benefit from the river. How a country navigates competing interests in the management of scarce water resources has profound implications for the distribution of opportunities and human development within its borders.

Also, these domestic implications influence equity in nearby countries (watkins, 2006). This problem is at center of the case study, and is not a single case, in fact shared water is an increasing important part of human geography and the political landscape (watkins, 2006). Shared water support the hydrological interdependence of millions of people, in fact international water basin cover almost half of earth's land surface, 60% of people of the world life depend upon this kind of basin (watkins, 2006).

Shared water has the potential for competition. Given the importance of water to national development, each country will pursue its own national agenda for using an international water basin. Although water use within countries is governed by established institutions, laws, and norms, the mechanisms for governing cross-border water are often less defined (watkins, 2006).

The general consensus is that the governance of international watercourses should be developed by taking into account the effects of use on other countries, the availability of alternative water sources, the size of the population affected, the social and economic needs of the watercourse states concerned, and the conservation, protection and development of the watercourse itself (watkins, 2006).

Without this type of policy framework, it is impossible to effectively fight inequity in both water use and, consequently, hydroelectric production (watkins, 2006).

The use of the water is critical is the thesis, in fact from the use of the upstream countries depend the amount and the timing of the water arriving in the downstream one's (as explained in previous paragraphs). This inevitability impact the possibility for hydroelectric production of each country, and from this hostile environment comes the theme of equity of energy production across the Mekong basin.

Up to this point, the issue of equity in the use of the common resource, the water of the Mekong Basin, has been defined. The following section will discuss how equity can be incorporated into optimization within mathematical models and explore the different equity indices that can be employed.

Traditionally, water system operations are formulated as multi-objective decision making problems. The conflicts among objectives, which capture the diverse interests of different stakeholders, typically produce a set of Pareto-optimal (or efficient) solutions rather than a single optimal one. However, Pareto optimality focuses on system wise efficiency and ignores the distributional effects of the optimal solutions among various stakeholders. This can potentially result in highly inequitable outcomes. The potential inconsistency between efficiency and equity risks inadvertently drives the analysis toward efficient, but ultimately unfair, solutions that stakeholders will find difficult to accept.

To better understand the importance of integrating fairness into model optimization, the following rows will discuss the results obtained in a specific study conducted on Lake Como (Yang et al., 2023). In this study, the equity index considered was formulated as the ratio between the standard deviation (σ) and the mean (μ) of the performance across four objectives: flood control, irrigation water supply, recreation services and river ecosystem (Yang et al., 2023).

Formulation	Name	Objectives	Including equity (Yes/No)
F1	Traditional	J^F, J^I	No
F2	Traditional and fair	J^F, J^I, ζ	Yes
F3	Inclusive	J^F, J^I, J^R, J^E	No
F4	Inclusive and fair	$J^F, J^I, J^R, J^E, \zeta$	Yes

Figure 2.6: Summary of the alternative problem formulations (Yang et al., 2023).

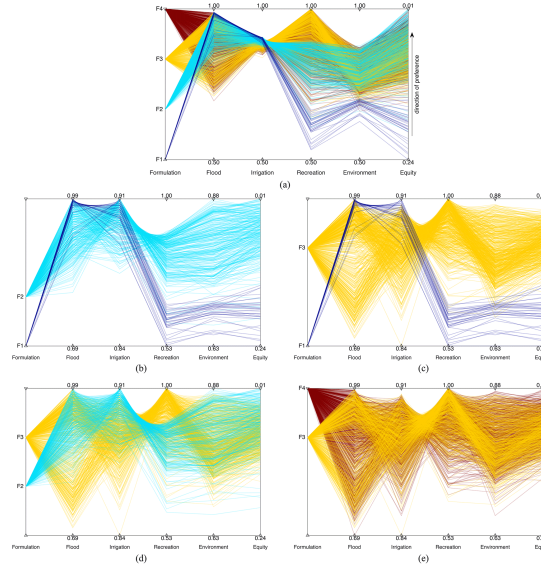


Figure 2.7: Parallel coordinates plot of comparisons between (a) all formulations, (b) traditional vs. traditional and fair, (c) traditional vs. inclusive, (d) traditional and fair vs. inclusive, and (e) inclusive vs. inclusive and fair. Each line connecting multiple axes represents one optimized solution, the horizontal dash line represents the mean line, and each type of line color represents one problem formulation. The axes with the labels “Flood”, “Irrigation”, “Recreation”, “Environment”, and “Equity” refer to the corresponding performance of J^F , J^I , J^R , J^E , and ζ , respectively, and the direction of solution preference is upward. It should be noted that panel (a) uses the same lower and upper axis bounds for each objective to better compare their best and worst performance and discover compromise solutions (shown with approximately horizontal lines), whereas panels (b), (c), (d), and (e) use the minimum and maximum performance values of formulations F1, F2, F3, and F4 as the lower and upper axis bounds, respectively (Yang et al., 2023).

The study analyzed four different optimization formulations (figure 2.6) ($F1$ to $F4$): $F1$ vs. $F2$ and $F3$ vs. $F4$ focus on assessing the value of including an equity related objective function in either the traditional multi-objective optimization (for $F1/F2$) or the inclusive optimization problems (for $F3/F4$) (Yang et al., 2023). $F2$ vs $F3$ investigates the differences between using the equity index as a means to indirectly include traditionally marginalized objectives (as in $F2$) versus formulating an inclusive optimization that directly includes all stakeholders' interests as separated objectives (as in $F3$) (Yang et al., 2023). Results shows that the solutions for $F3$ achieved lower equity values than the solutions for $F2$. Lastly, moving from $F3$ to $F4$ produced only a small improvement in terms of equity, with minor differences in the performance across the four objectives (Yang et al., 2023).

The performance across the four objectives can be seen in figure 2.7

The comparison between operating policies designed with and without considering equity amongst the operating objectives demonstrates that including equity in the operation design can indirectly improve marginalized objectives that are not explicitly considered in the optimization problem (Yang et al., 2023). Also, when marginalized objectives are also explicitly included, the addition of an equity indicator still generates more compromise solutions, effectively mitigating conflicts between the operating objectives (Yang et al., 2023).

This work also emphasizes that the search for equitable solutions across multi-sectoral interests depends heavily on how the multiple objectives are combined to formulate the equity index (Yang et al., 2023). Results show that using an equity index based on the original reliabilities can favor or negatively impact some objectives in a way that is difficult to control. Thus, the adoption of participatory approaches for eliciting the preference structure of stakeholders and policymakers becomes paramount for operationalizing equity principles, as it helps to rescale the objectives and represent a fair balance across competing interests (Yang et al., 2023).

The definition of equity is not unique in the literature. It remains challenging to design an objective value function and, consequently, to choose an equitable policy agreed by all stakeholders. Furthermore, the necessary level of equity could dynamically change over time according to the potential evolution of stakeholders' and decision makers' preferences (Yang et al., 2023).

Therefore, the choice of the equity coefficient (or index) to be used is critically important.

THE CONVENTIONAL SUMMARY MEASURES

The measures most commonly use include the following (Atkinson, 1970):

- Variance, V^2 .
- Coefficient of variation, V/μ .
- Relative mean deviation, $\int_0^{\bar{y}} |y/\mu - 1| f(y) dy$.
- Gini coefficient, $1/2\mu \int_0^{\bar{y}} [yF(y) - \mu\phi(y)] f(y) dy$.
- Standard deviation of logarithms, $\int_0^{\bar{y}} [\log(y/\mu)]^2 f(y) dy$.

The first issue, with this coefficients is the dependence of the measures on the mean income. With the exception of the variance, all the measures listed above are defined relative to the mean, so that they are unaffected by equal proportion increases in all incomes (Atkinson, 1970).

The second point (made by Dalton), argued that if we make a strictly positive transfer from a richer person to a poorer person, this need to lead to a strictly positive reduction in the index of inequity. If we accept this requirement, it provides grounds for rejecting measures which are not strictly concave, as the mean deviation (Atkinson, 1970).

2.2.1. Atkinson Index

The idea of Atkinson is to obtain a measure of inequity that is invariant with respect to linear transformation by introducing the concept of the equally distributed equivalent level of income (y_{EDE}), or the level of income per head which if equally distributed would give the same level of social welfare as the present distribution, that is, (Atkinson, 1970)

$$U(y_{EDE}) \int_0^{\bar{y}} f(y) dy = \int_0^{\bar{y}} U(y) f(y) dy.$$

starting from this idea, Atkinson define a new measure of inequality,

$$I = 1 - \frac{y_{EDE}}{\mu} \quad (2.1)$$

namely, 1 minus the ratio of the equally distributed equivalent level of income to the mean of the actual distribution (Atkinson, 1970).

If I falls, then the distribution has become more equal, in fact, it would be necessary to have a higher level of equally distributed income to achieve the same kevel of social welfare as the actual distribution. I has the convenient property of lying between 0 (complete equity) and 1 (complete inequity), this make this measures easy to understand (Atkinson, 1970).

Is therefore considered an index of intuitive appeal (if $I=0.3$, for example, this means that

if the income were equally distributed, then we should need 70% of the present income to achieve the same level of social welfare) (Atkinson, 1970).

All the index cited in the previous chapter are defined relative to the mean of the distribution, so that they are invariant with respect to proportional shifts. If we want the equally distributed equivalent measure to have this property, this restrict the index to be in the class of homothetic function, which in the case of discrete distributions imply a measure (Atkinson, 1970)

$$I = 1 - \left[\sum_i \left(\frac{y_i}{\mu} \right)^{1-\epsilon} f(y_i) \right]^{1/(1-\epsilon)}. \quad (2.2)$$

In this case the uncertainty becomes the choosing of ϵ , which is a measure of the degree of inequality aversion (or the relative sensitivity to transfers at different income levels). As ϵ rises, is increased the weight to transfers at the lower end of the distribution and less weight to the transfers at the top. The limiting case at one extreme is $\epsilon \rightarrow \infty$, giving the function $\min_i \{y_i\}$ which only takes account of transfers to the very lowest income group; at the other extreme $\epsilon = 0$, giving the linear utility function which ranks distributions solely according to total income (Atkinson, 1970).

The change in the value of the parameter ϵ brings a change in the formula of the index (Atkinson and Brandolini, 2015),

$$I = \begin{cases} 1 - \left[\frac{1}{n} \sum_i \left(\frac{y_i}{\mu} \right)^{(1-\epsilon)} \right]^{\frac{1}{1-\epsilon}} & \text{if } \epsilon > 0, \epsilon \neq 1 \\ 1 - \left[\prod_i \left(\frac{y_i}{\mu} \right) \right]^{\frac{1}{n}} & \text{if } \epsilon = 1 \end{cases} \quad (2.3)$$

The choice of the Atkinson index allows not only to measure inequity, but also to explicitly model risk aversion and inequity between countries. This provides the work with a much more solid theoretical basis than the use of conventional indices, whose relationship with social well being is implicit or weak (Blackorbyn and Donaldson, 1978).

Furthermore, the Atkinson index ensures that the measure is consistent with economic logic: if you transfer income from a richer person to a poorer one (without reversing their positions), inequity always decreases (Blackorbyn and Donaldson, 1978).

When choosing the index, it should be considered that Atkinson proposes a measure based on the level of equally distributed equivalent income (y_{EDE}), which, by virtue of its derivation from a homothetic social welfare function, is positioned within the family of equality measures based on the symmetric mean of order r (where $r = 1 - \epsilon$). This functional structure (the use of a generalized mean) guaranties greater analytical tractability in op-

timization models compared to non-parametric measures (such as the Gini coefficient), since the associated social welfare function is continuous and differentiable, simplifying the calculation of derivatives and stability analysis (Blackorbyn and Donaldson, 1978).

2.3. Epsilon-NSGA-II Algorithm

The multi-objective optimization process described in this thesis was performed using the ϵ -NSGA-II (ϵ -Nondominated Sorting Genetic Algorithm II). This algorithm is an evolution of the classical NSGA-II proposed by Deb (Deb et al., 2002) and was developed to address some limitations regarding convergence speed and the uniform distribution of solutions across the Pareto front (Kollat and Reed, 2005).

The primary limitation of NSGA-II is its reliance on crowding distance as the sole mechanism for maintaining population diversity. ϵ -NSGA-II solve this limit integrating the concept of ϵ -dominance (Laumanns et al., 2002), which introduces an adaptive discretization of the objective space. Given an objective vector $f(\mathbf{x}) = (f_1, f_2, \dots, f_n)$, a solution $\mathbf{a}$ is said to ϵ -dominate a solution $\mathbf{b}$ if and only if:

$$f_i(\mathbf{a}) - \epsilon_i \leq f_i(\mathbf{b}) \quad \forall i \in 1, 2, \dots, n \quad (2.4)$$

The objective space is divided into a grid of hyper rectangles (referred to as ϵ -boxes), whose dimensions are defined by the parameter ϵ . This is a resolution filter: each individual box can contain only one non-dominated solution (Hadka and Reed, 2012). The implementation of this grid addresses two critical challenges in Multi-Objective Evolutionary Algorithms (MOEAs):

- **Efficiency and redundancy:** the mechanism prevents the proliferation of solutions that are too close in the objective space, thereby limiting the expenditure of computational resources on regions of the Pareto front that have already been explored (Hadka and Reed, 2012).
- **Convergence and spread:** the algorithm ensures a highly homogeneous distribution of points. Since the solutions maintained in the archive preserve a minimum distance proportional to ϵ , the phenomenon of clustering, where points accumulate in restricted areas, is avoided, ensuring a good coverage of the entire Pareto front (Laumanns et al., 2002).

Unlike single population approaches, ϵ -NSGA-II adopts a bipartite structure designed to balance the exploration and exploitation phases:

- **Main population (P):** an active evolutionary population that explores the decision variable space through stochastic crossover and mutation operators (Deb et al., 2005).
- **External archive (E):** a dynamic elite archive that preserves the ϵ -non-dominated solutions identified during the process. The archive update using a logic: if a new individual is not ϵ -dominated by existing members, it is inserted, and any pre-existing solutions that become redundant are removed. If a new solution fall into an already occupied ϵ -box, the algorithm performs a comparison based on the distance from the box origin, preserving the analytically superior solution (Deb et al., 2005).

To maximize search efficiency, the algorithm implements two key procedural innovations (Kollat and Reed, 2005):

- **Archive-oriented selection:** during offspring generation, the selection process draws individuals from the external archive (E). This strategy ensures that the selective pressure is always directed toward the most promising regions of the objective space discovered up to that point (Kollat and Reed, 2005).
- **Steady-state evolution:** unlike generational approaches that update the entire population at fixed intervals, ϵ -NSGA-II employs a steady-state modality. Both the population and the archive are updated whenever a new valid solution is generated. This approach allows for immediate system responsiveness to new discoveries, significantly accelerating convergence compared to traditional methods (Kollat and Reed, 2005).

2.4. Methods

This section outlines the methodological framework conducted in this study. The workflow begins with an evaluation of the historical energy production (1981–2022) to establish a comprehensive baseline of the Mekong Basin’s hydropower dynamics.

To fully assess spatial equity, historical production was analyzed both in absolute terms (actual production) and by weighting the generation by the GDP per capita of the riparian nations. Furthermore, the historical trend of equity within the basin was examined across both long-term and short-term horizons. This multi-temporal analysis is essential to verify the actual magnitude and variability of inequalities experienced by the countries sharing the Mekong River.

The historical analysis also evaluates equity in terms of energy security, laying the ground-

work for the optimization phase. This step is fundamental because the subsequent multi-objective optimization relies on two distinct objective functions: total daily energy production and firm hydropower. It is crucial to distinguish between these two targets: while total energy production aims to maximize the absolute volume of electricity generated across the basin, firm hydropower focuses strictly on system reliability. Firm hydropower is defined as the maximization of the lowest monthly hydroelectric generation during the simulation period, representing the guaranteed minimum energy security.

Finally, the optimization phase explores the basin's productive potential and the inherent trade-offs through two distinct experimental setups:

- **Optimization 1:** this formulation optimizes the operations of the 20 dams with the largest active reservoirs in the basin, driven purely by traditional efficiency metrics.
- **Optimization 2:** this second formulation also optimizes the dams with the largest active reservoirs, but introduces a strict spatial constraint: a maximum limit of four managed reservoirs per country.

The core motive behind optimization 2 is to test whether artificially constraining the optimized infrastructure portfolio to be spatially distributed can induce a more equitable division of benefits among the riparian nations, comparing the results against the strictly efficiency driven outcomes of optimization 1.

3 | Results

This chapter presents the results of the thesis. The structure of the chapter aims to answer the key questions of the research, evaluating historical production and its effect on inter-country equity.

The analysis begins by assessing the unweighted historical production baseline, followed by a weighted analysis where the production is normalized using GDP per capita. Subsequently, the temporal dynamics of equity are examined using the Atkinson index, first with a monthly time step and then analyzing its evolution over the decades. The historical evaluation concludes with a focus on the Atkinson index applied to firm hydropower (firm hydropower is defined as the maximization of the lowest monthly hydroelectric generation during the simulation period, representing the guaranteed minimum energy security).

The historical analysis is followed by an examination of hydroelectric production observed in the two optimization scenarios, compared with the historical scenario in terms of energy efficiency, energy security, and equity.

3.1. Equity analysis based on historical data - Production

The sections below present the results obtained from the analysis of historical hydroelectric production data (1981-2022) simulated through VICRes-Mekong.

3.1.1. Unweighted analysis

In line with the development of the work, as a preliminary analysis of equity, the Atkinson index calculation was performed without considering any weights; each country counts as a single entity. Based on these initial graphs, it is possible to venture some first comments. In fact, the graph (Figure 3.1), which shows the hydroelectric production share by country from 1981 to 2022, clearly indicates a stark productive difference between China and the other stakeholders. This initial hypothesis of significant inequity in production is also confirmed by the Lorenz Curve (Figure 3.2). The Lorenz curve is a graphical repre-

sensation used to illustrate the distribution of a specific variable across a given population or group of entities. It provides a clear visual measure of inequity or concentration within a system. In this case is clearly visible an important deviation of the data curve from the 45 degree line (representing perfect equity). A deeply bowed Lorenz curve implies that a vast majority of the production is heavily concentrated in the hands of a few top actors.

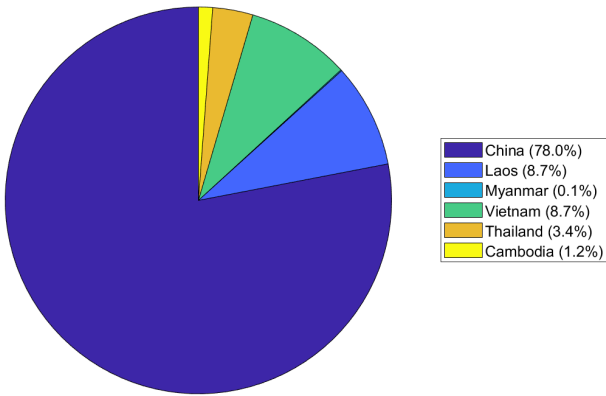


Figure 3.1: Hydroelectric production share by country

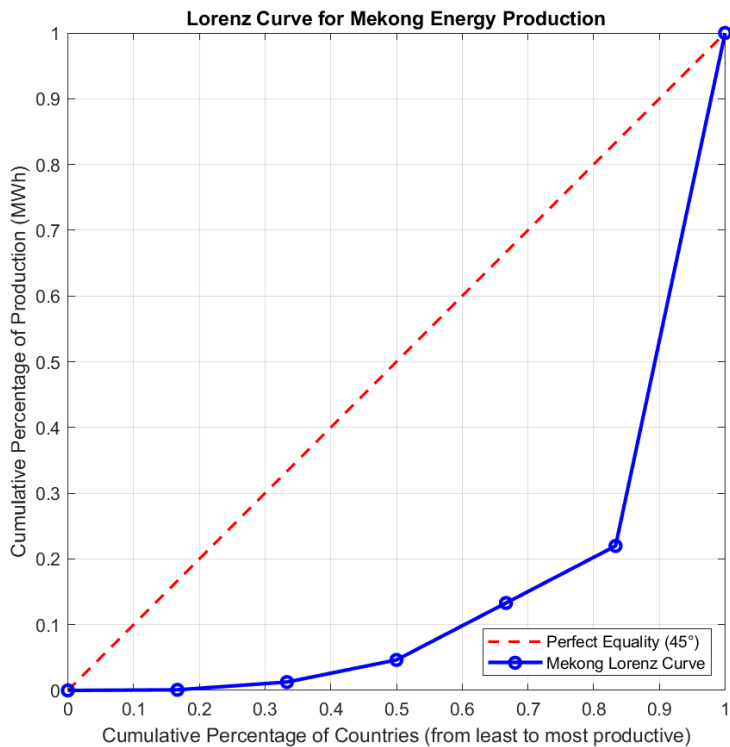


Figure 3.2: Lorenz curve for Mekong energy production

For the equity analysis, different values of ϵ (inequality aversion parameter) were considered, for which the calculation was repeated. Seeing the results in very clear that the

choice of ϵ is a key feature of the work (higher ϵ , higher the importance of equity in the society). The results are reported in table 3.1.

ϵ	$A\epsilon$	$A\epsilon(\%)$
0.1	0.0993	9.93%
0.25	0.2437	24.37%
0.5	0.4636	46.36%
0.75	0.6469	64.69%
1	0.7863	78.63%
1.5	0.9320	93.20%
2	0.9719	97.19%

Table 3.1: Equity index for different ϵ , different aversion to inequality

The parameter ϵ is the key to interpreting these results:

- Low aversion ($\epsilon = 0.1$ to 0.5): the index increases from 9.93% to 46.36%. At low levels of aversion, the inequity is already significant. A value of $A\epsilon = 0.4636$ for $\epsilon = 0.5$ is substantial and indicates that approximately 46% of the potential total equitable outcome is wasted or unrealized due to the unequal distribution.
- Moderate aversion ($\epsilon = 1$): the value of $A\epsilon$ is 0.7863 (78.63%). The $\epsilon = 1$ case is often used for its logarithmic properties, where the concern for inequity is proportional to the level of the outcome (income, equity, etc.). A result of almost 80% suggests an overwhelming inequity. It means that the Equally Distributed Equivalent (EDE), the level of uniform equity that, if given to everyone, would generate the same social welfare as the current distribution, is only about $(1 - 0.7863) \simeq 21.37\%$ of the actual average equity level.
- High aversion ($\epsilon = 1.5$ to 2): the index reaches peaks of 93.20% and 97.19%. These values reflect a deep concern for the well being of the populations with the lowest opportunity. An $\epsilon = 2$ significantly amplifies the impact of the disadvantaged. The near unity value (close to 1) is a warning sign, indicating that, from the perspective of a policymaker highly adverse to inequity, the distribution is almost completely unequal.

The rapid growth of the index (as shown in figure 3.3), with the growth of ϵ highlights that the largest disparities are concentrated in the lowest segments of the equity distribution. This implies that the most vulnerable countries along the Mekong basin are receiving a disproportionately small share or are disproportionately bearing the negative impacts.

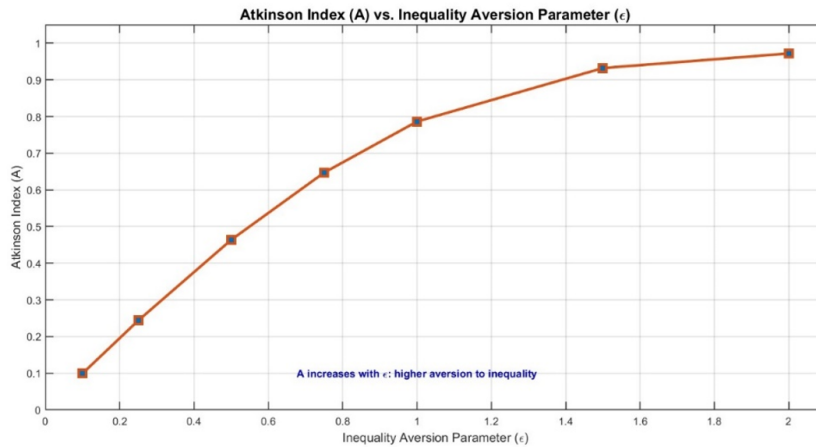


Figure 3.3: Atkinson Index vs Inequality Aversion Parameter

3.1.2. Weighted production using GDP per capita

The work continued by analyzing equity, weighting each country by its GDP per capita, in order to give more importance to the less wealthy countries within the analysis. The GDP per capita values considered for the different countries are visible in Figure 3.4 (ones again China has clearly the higher values among the six countries). The weights are applied with the idea of giving more importance to the poorest countries in the analysis. The total production is divided by the GDP per capita of the country, therefore, the richer the country, the greater the dampening of its hydroelectric energy production.

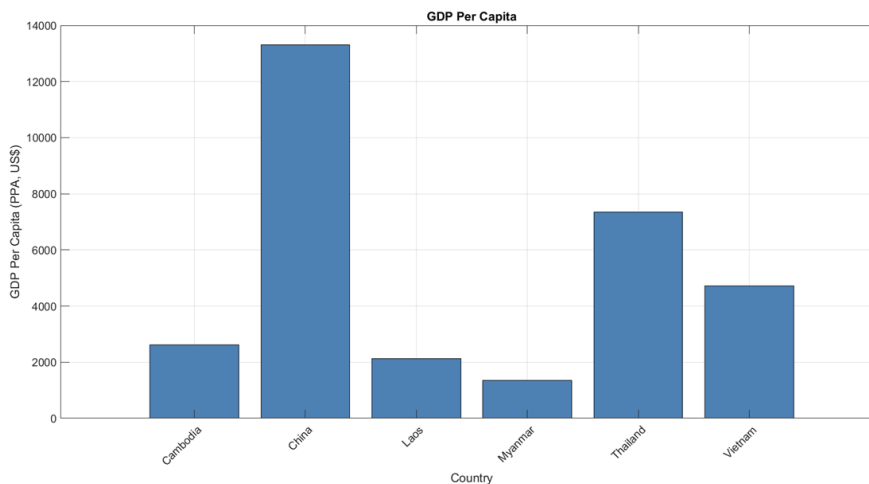


Figure 3.4: GDP per capita

For the analysis, different epsilon values were considered, for which the calculation was repeated. The results are reported in the table below (table 3.2).

ϵ	$A\epsilon$	$A\epsilon(\%)$
0.1	0.1157	11.57%
0.25	0.2756	27.56%
0.5	0.5070	50.70%
0.75	0.6923	69.23%
1.5	0.9359	93.59%
2	0.9642	96.42%

Table 3.2: Equity index for different ϵ

The increase in the Atkinson Index (analyzing the case $\epsilon = 0.5$) from 0.46 to 0.50 when applying the inverse weighting demonstrates that inequity is more severe than initially appears and is acutely felt by the most economically vulnerable nations. The fact that the index increased when there is more weight for poor countries (Cambodia, Laos, Myanmar, Vietnam) proves the following point: the greatest source of welfare loss due to production inequity is concentrated among the least affluent nations, thereby confirming that international inequity in energy capacity disproportionately harms the welfare of the poor. This analysis shows that the high absolute production of countries like China was not the main driver of the welfare loss in the weighted calculation. Instead, the index focuses on the distribution among low GDP per capita nations and finds that the disparities in electricity production within that group are acute, making the overall inequity more severe when viewed through a different lens.

Considering $\epsilon = 0.5$ was an example; in fact, the same decreasing trend in equity is confirmed with all ϵ values analyzed.

As noted previously, in this analysis also, the result of the Atkinson index varies strongly as ϵ changes, as shown in Figure 3.5, and figure 3.6.

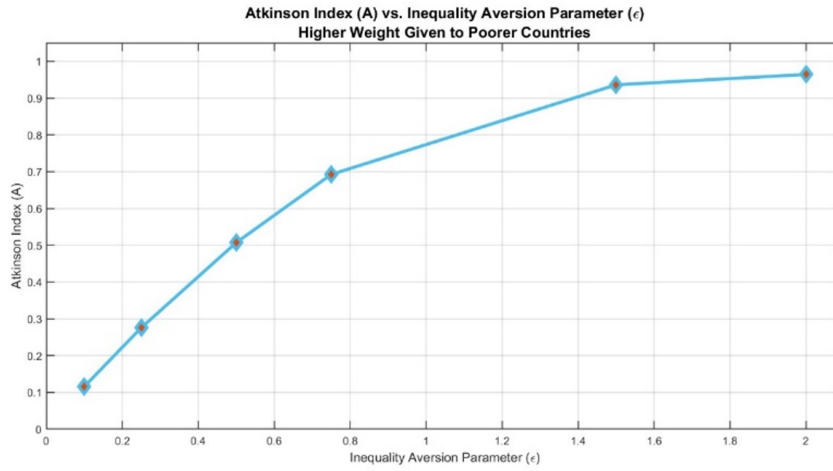


Figure 3.5: Atkinson index vs Inequality Aversion Parameter. Higher Weight Given to Poorer Countries

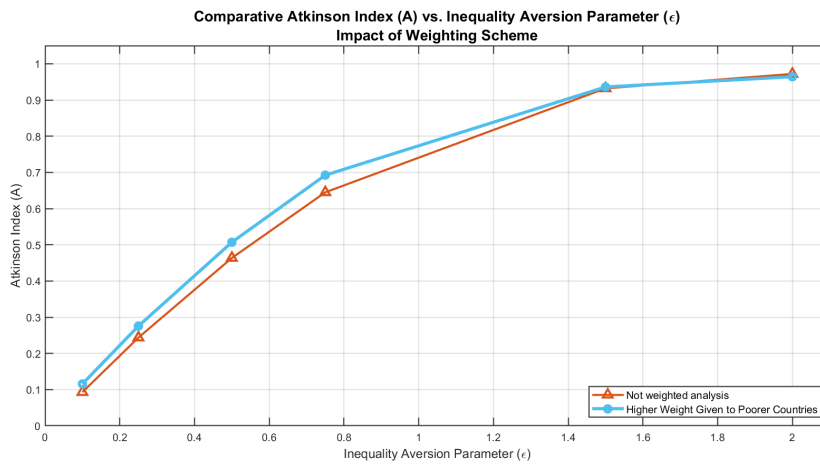


Figure 3.6: Atkinson index vs Inequality Aversion Parameter. Confront between weighted and not weighted analysis

3.1.3. Atkinson index with monthly time step

Subsequently, an analysis was performed to compare the Atkinson index calculated using total production (the analysis of which has already been carried out) with the average of the Atkinson Indexes calculated on a monthly basis. This analysis allows to take into consideration the disparities in terms of production risks.

The results of these analyses show (for $\epsilon = 0.5$):

- Atkinson index (long term average) $\rightarrow 0.4636$, 46.36%.

- Atkinson index (monthly / short term average) $\rightarrow$ 0.7121, 71.21%.

The long term average calculation, based on aggregate total production, tends to smooth out differences that occur in the short run. It represents the equity of each country's overall production share in the total.

Instead, calculating the index monthly and then averaging it captures the inequity occurring in each individual month. A higher value in this second analysis implies that in many months, equity is low, and this happens when production is heavily skewed in favor of one or a few countries in a given month.

The analysis reveals that equity is strongly influenced by the seasonality and volatility of the water resource. There are periods of the year (individual months) in which production is highly concentrated in just a few countries, and the effect of this temporary inequity is smoothed out only when looking at total aggregated production.

The analysis was performed for $\epsilon = 0.5$, but what was stated holds true for all ϵ values examined. The values for the Atkinson Index, long term average, and monthly figures for different epsilon values are reported below in Table 3.3.

ϵ	$A\epsilon(\%)(\text{long-term average})$	$A\epsilon(\%)(\text{monthly})$
0.1	9.937%	17.817%
0.25	24.379%	41.169%
0.5	46.369%	71.208%
0.75	64.697%	91.123%
1.5	93.201%	99.998%
2	97.189%	99.999%

Table 3.3: Equity decrease from long-term average to monthly for different ϵ

To validate the above mentioned findings, the analysis was replicated using the natural flow of the Mekong River, representing the hydrological regime in the absence of reservoir induced alterations. This analysis was conducted by re-employing the VICRes-Mekong model to simulate discharge under unregulated conditions.

The results are detailed in Table 3.4, while a comparative analysis of the Atkinson Index between the natural flow and the altered flow regimes is presented in Table 3.5.

ϵ	$A\epsilon(\%)(\text{long-term average})$	$A\epsilon(\%)(\text{monthly})$
0.1	11.386%	18.335%
0.25	28.053%	42.708%
0.5	55.618%	73.745%
0.75	77.416%	92.429%
1.5	98.026%	99.999%
2	99.162%	99.999%

Table 3.4: Equity decrease from long-term average to monthly for different ϵ , with natural flow

ϵ	$A\epsilon(\%)(\text{lt, Af})$	$A\epsilon(\%)(\text{lt, Nf})$	$A\epsilon(\%)(\text{mon, Af}),$	$A\epsilon(\%)(\text{mon, Nf})$
0.1	9.937%	11.386%	17.817%	18.335%
0.25	24.379%	28.053%	41.169%	42.708%
0.5	46.369%	55.618%	71.208%	73.745%
0.75	64.697%	77.416%	91.123%	92.429%

Table 3.5: Atkinson index. Altered flow vs Natural flow

As detailed in Table 3.5, the magnitude of the shift from long-term to monthly equity scales shows critical insights. The natural flow (Nf) already exhibits an important decrease in equity, when moving to a monthly resolution. This confirm that seasonality and water volatility are inherent drivers of disparity, this phenomenon is more visible under altered flow (Af) conditions.

The data indicates that the gap between the long-term average and monthly Atkinson Index values is wider in the modified regime (Af) compared to the natural one (Nf). This suggests that while reservoir regulation might lower the overall inequality index on an aggregate scale, it disproportionately amplifies short-term distributional imbalances.

So, the transition from annual to seasonal scales reveals that human induced alterations introduce a new layer of temporal instability, further destabilizing the month to month distribution of production benefits among riparian countries compared to the baseline hydrological cycle.

3.1.4. Evolution of equity over the decades

This further analysis was conducted with the objective of observing the temporal evolution of inter-country equity. The index was studied first by dividing the production data into

ten year blocks and then by calculating the Atkinson index for each year from 1981 to 2022.

The analysis was conducted using the ϵ values also used in previous section (0.1, 0.25, 0.5, 1, 1.5, 2). The annual and decennial trends were confirmed to be consistent across all parameter values, and consequently, only the case of $\epsilon = 0.5$ will be analyzed in this document.

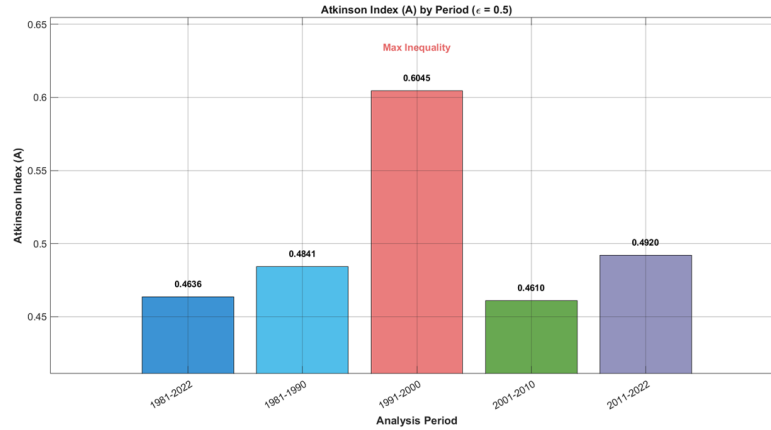


Figure 3.7: Atkinson index by period

The evolution of the non-weighted index (figure 3.7) tracks the overall equity of hydro-electric energy production within the Mekong region:

- **1981–1990 (initial status of the analysis):** the index starts already high (0.4841), indicating that nearly half of the potential equitable output was lost.
- **1991–2000 (peak inequity), historical maximum:** the index reach its historical maximum of 0.6045 (a 24.8% increase compared to the previous decade). This period coincided with increased investment and rapid, but uneven, economic development in Southeast Asia. This situation disproportionately amplified the production gap in the basin's nations. During this period, there have been significant investments by the Chinese government, which have led to the creation of these imbalances and a consequent decrease in equity.
- **2001-2010 (the correction phase) historical minimum:** the index dropped by 23.8% to its lowest point of 0.4610. This correction suggests an important step toward regional equity.
- **2011-2022 (recent trends):** the index rose by 6.7% to 0.492, settling at a level higher than the previous decade's minimum. This suggests that while production

has grown, recent projects have failed to sustain the equity improvements of the 2000s.

The data reveal that equity in energy production in the Mekong basin is highly volatile, reaching its worst point in the 1990s before correcting itself substantially in the 2000s. However, the fundamental driver of regional inequity is the divergence in production capacity between the economically stronger and weaker basin states.

To confirm the decadal results, the Atkinson index was calculated for every year from 1981 to 2022. The results obtained are visible in Figure 3.8.

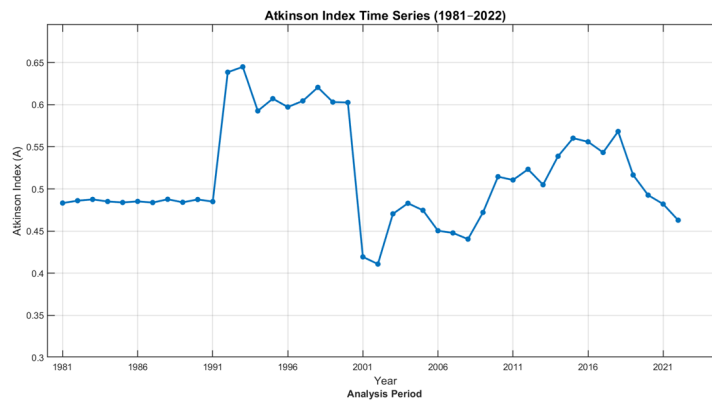


Figure 3.8: Atkinson Index Time series (1981-2022)

The analysis of the Atkinson index over decades and years appears to match, in fact, the uneven development of hydroelectric energy production in different countries has led to continuous variations in equity, with the worst decade being 1991-2000.

It now becomes interesting to try and understand the reasons why this occurs. For this purpose, the production evolutions for the six countries in the Mekong river basin are shown in Figures 3.9, 3.10, 3.11, 3.12, 3.13 and 3.14.

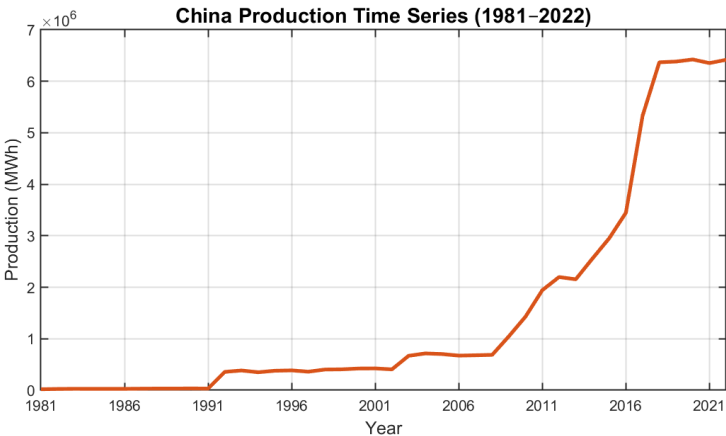


Figure 3.9: China production time series (1981-2022)

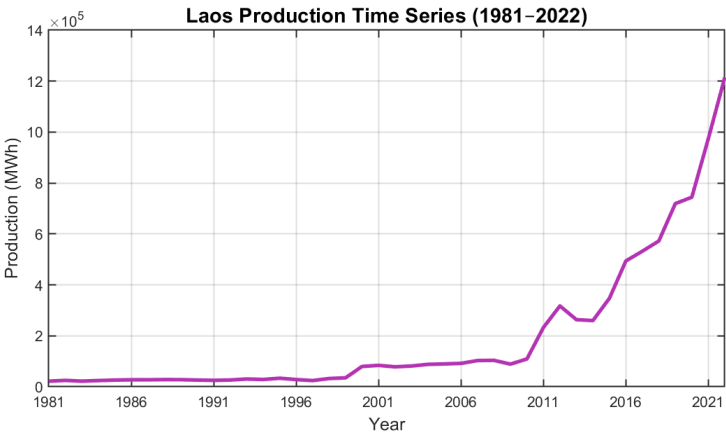


Figure 3.10: Laos production time series (1981-2022)

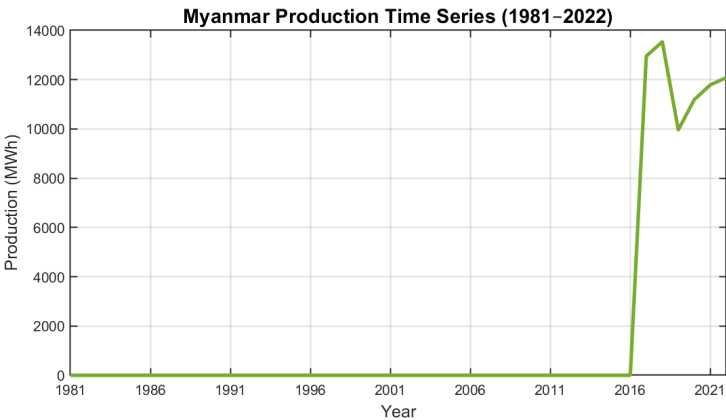


Figure 3.11: Myanmar production time series (1981-2022)

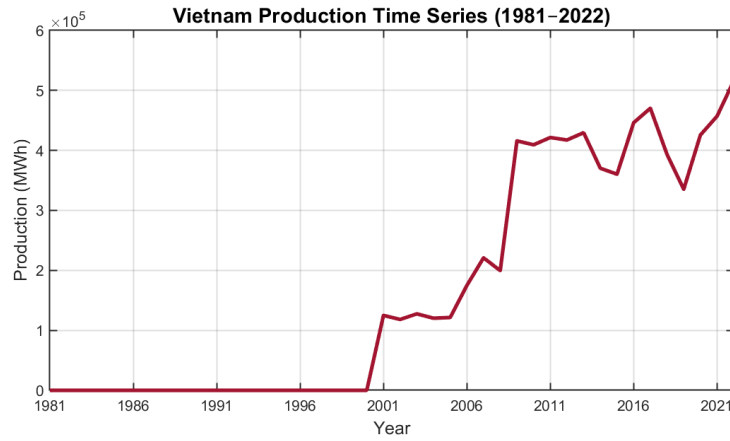


Figure 3.12: Vietnam production time series (1981-2022)

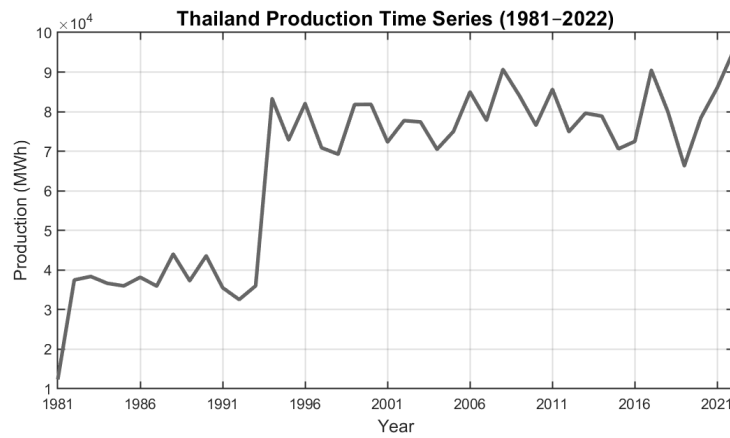


Figure 3.13: Thailand production time series (1981-2022)

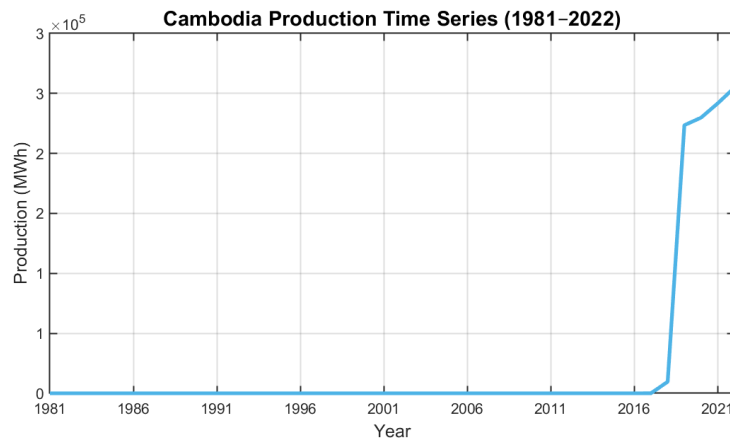


Figure 3.14: Cambodia production time series (1981-2022)

The graphs show that only China and Thailand developed reservoirs that ensured an increase in hydroelectric production beginning in the early 1990s. This (especially due to

the increase in production in China) led to the occurrence of poor equity conditions that characterized those years in the analysis previously discussed.

3.2. Equity analysis based on historical data - Firm hydropower

In order to evaluate the historical management of the system and establish a benchmark for the optimization results, the Atkinson index was calculated and applied to firm hydropower. While the index, discussed in the previous chapters, reflects the distribution of overall energy wealth for total production, in the case of firm hydropower, it serves as an indicator of equity in energy security. Firm hydropower is defined as the maximization of the lowest monthly hydroelectric generation during the simulation period, representing the guaranteed minimum energy security.

The procedure for determining the historical index was structured into the following phases:

- **Spatial and temporal aggregation:** for each country within the basin, the aggregate monthly energy production was calculated by summing the contributions from all hydroelectric infrastructure located within the national territory.
- **Identification of the reliability constraint:** for each year of the reference period, the minimum monthly production value recorded for each country was identified. This value represents the annual firm hydropower, defined as the minimum power guaranteed during the driest month or the period of lowest system performance for that year.
- **Temporal averaging of guaranteed production:** for each country i , the long-term average of these annual minimum (y_i) was calculated, finding an expected value for the firm or constant generation capacity of the country.
- **Calculation of the Atkinson index:** once the average values for the n countries were obtained, the Atkinson social welfare function was applied to measure the degree of inequity in the distribution of this energy security among the nations of the basin.

The mathematical formulation adopted is as follows:

$$A = 1 - \frac{1}{\mu} \left(\frac{1}{n} \sum_{i=1}^n y_i^{1-\epsilon} \right)^{\frac{1}{1-\epsilon}} \quad (3.1)$$

Where:

- y_i represents the average of the minimum monthly productions for the i -th country.
- μ is the global arithmetic mean of the minimum productions across all countries in the basin.
- n is the number of countries considered (in this study, $n = 6$).
- ϵ is the inequality aversion parameter. This coefficient reflects the decision-maker's sensitivity toward disparities: a value of $\epsilon > 0$ implies that a more equitable distribution of firm hydropower among countries is preferred, even at the expense of a slightly lower global average production.

The index allows to quantify how efficient historical management has been, not only in terms of energy production but also in ensuring its balanced distribution across the various nations (energy security). An A value close to 0 would indicate that all countries enjoy a similar level of minimum energy security; in contrast, high values signal that energy stability is concentrated within only a few areas of the basin, leaving other nations in a state of greater vulnerability during periods of water scarcity.

In Table 3.6, the results obtained for the 1981-2022 period as the ϵ index varies are presented:

ϵ	$A\epsilon$	$A\epsilon(\%)$
0.1	0.1346	13.46%
0.25	0.3265	32.65%
0.5	0.5973	59.73%
0.75	0.7855	78.55%
1.25	0.9549	95.49%
1.5	0.9798	97.98%
2	0.9933	99.33%

Table 3.6: Equity index for different ϵ

The analysis of the results obtained through the calculation of the Atkinson index for historical firm hydropower reveals a dynamic of great disparity in the distribution of energy security among the countries of the Mekong river basin. The observed values, as the inequality aversion parameter (ϵ) varies, provide a quantitative measure of the structural imbalance inherent in the traditional management of the system.

The Atkinson index was calculated by testing different levels of social sensitivity (varying ϵ parameters), obtaining the following key results:

- **Low aversion** ($\epsilon = 0.1$): even with minimal sensitivity to disparities, the index stands at 13.46%. This value indicates that, even from an utilitarian perspective, the historical distribution of firm hydropower is suboptimal (in equity terms).
- **Moderate aversion** ($\epsilon = 0.5$): at this level, the index rises to 59.73%. This suggests that over half of the social welfare potential linked to energy stability is lost due to unequal distribution among nations.
- **High aversion** ($\epsilon = 1.25$): for values of ϵ greater than unity, the index exceeds 95%, tending asymptotically toward near total disparity (surpassing 99% for $\epsilon = 2$). This mathematical behavior highlights how minimum energy security is concentrated within a small number of countries, leaving the majority of actors in a state of critical vulnerability.

The progression of the index highlights that the historical management of the basin is characterized by a polarization of resources. The analysis of firm hydropower, specifically the supply guarantee during lean periods, reveals that the system has operated by prioritizing the stability of specific nodes at the expense of transboundary equity.

In conclusion, the results confirm that historical management is characterized by a systemic fragility. These findings demonstrate a more severe lack of equity than that observed when studying the total hydroelectric production of the basin. This evidence supports the necessity of a transition toward transboundary coordination strategies capable of balancing production efficiency with a more democratic and resilient supply guarantee for all stakeholders involved.

3.3. Equity analysis based on optimized variables

3.3.1. Introduction to optimizations

The analytical focus of this study now transitions towards the derivation of optimized operational outcomes. The optimization protocols, comprehensively defined in the sections that follow, were conducted by utilizing the VICRes-Mekong modeling framework. This procedure consists of optimizing the specific decision variables located within the reservoir datasets. The objective is to secure a set of optimized parameters, which are subsequently employed to execute a re-simulation of daily production metrics throughout the hydrological expanse of the Mekong river basin.

The implementation of the ϵ -NSGA-II evolutionary algorithm enables a multi-objective optimization framework. The underlying model supports a wide array of potential objective functions, ranging from environmental metrics like sediment loads, peak flow attenuation, and flood threshold exceedance, to operational constraints such as daily water deficit and water level deviations. This study deliberately focuses on two primary objectives: daily hydropower and firm hydropower. This selection is strategically designed to capture the fundamental dichotomy in reservoir management: the maximization of aggregate production, versus the assurance of energy security. Daily hydropower serves as a proxy for the total economic efficiency of the system, quantifying the gross energy yield available to the basin. In contrast, firm hydropower measures the reliability of the supply. By isolating these two conflicting goals, the analysis addresses the core tension between opportunistic seasonal generation and stable base load provision. This specific trade-off provides the most relevant quantitative foundation for the subsequent equity analysis, as the capacity to guarantee firm energy is often where the deepest disparities among riparian nations emerge.

Ideally, the optimization framework would encompass the entire network of 125 reservoirs and the entire study period. However, due to the prohibitive computational cost imposed by such a high dimensional decision space, a strategic subset selection was necessary.

Consequently, two distinct optimization scenarios were developed. While both prioritize reservoirs with the largest storage volumes observed over the 1981–2022 period, they differ in their distributional constraints. The first scenario is purely capacity-driven, selecting the top 20 reservoirs irrespective of their geographic location. The second scenario, conversely, introduces a geopolitical constraint by capping the selection at four facilities per nation (19 reservoirs), thereby ensuring a more spatially and politically homogeneous representation across the basin. Both scenarios were optimized from 2012 to 2022.

The selection of the 20 and 19 target reservoirs was predicated on identifying facilities that managed the largest storage volumes over the 42-year observation window (1981–2022). Crucially, the definition of the storage capacity for each asset was established using a criterion of maximum empirical robustness.

Specifically, the reference capacity for the optimization model was not derived from the theoretical design value (full supply volume or design capacity), but rather from the maximum historical storage recorded within the analyzed time series. This approach aligns with recent advancements in reservoir representation that prioritize observational data over static registries to account for discrepancies in global datasets (Gao et al., 2012). In fact, nominal design data (full supply volume) represents the maximum geometric

capacity of the reservoir at the time of construction. However, robust system optimization must rely on the actually mobilizable water resource rather than virtual storage space. If a reservoir has failed to reach its theoretical maximum level over a 40-year period, it indicates that the relevant catchment area is hydrologically incapable of saturating that capacity. By utilizing the maximum historical peak, the model optimizes based on the effective hydrological capacity, the volume of water the local climate realistically provides. This prevents the introduction of fictitious storage buffers that would never be utilized in practice, thereby ensuring that the resulting energy production estimates are realistic and not artificially inflated. In engineering data science, direct measurements hold a higher reliability hierarchy than static metadata. This approach prioritizes observational evidence.

This conservative approach ensures that the efficiency gains identified by the algorithm are genuinely achievable and not the result of an overestimation of the available regulation capacity.

The optimization framework implemented in this study relies on the ϵ -NSGA-II algorithm, deployed within a complex system that integrates both hydrological and energy variables. The framework leverages the coupling of two core models: VIC (Variable Infiltration Capacity) for hydrological modeling and VIC-Res for reservoir operation. The optimization targets a network of 20 and 19 reservoirs, whose release policies drive the overall performance of the entire basin. This selection stems from a preliminary screening study that ranked all 125 analyzed reservoirs based on their realized storage capacity. This approach ensures that the optimization focuses on the most influential facilities within the system.

The problem is formulated as a bi-objective optimization task, aimed at identifying the optimal trade-off between two fundamental energy criteria.

Both objectives are treated as minimization problems by transforming their original metrics:

- **Minimization of the daily hydropower production deficit (J_1):** The primary objective is to maximize the total energy generated by the system of the optimized reservoirs over the entire 3653-day simulation horizon.
- **Minimization of the firm hydropower deficit (J_2):** This criterion aims to ensure a constant base load energy output, which is essential for grid stability and meeting minimum demand requirements. It reflects the reservoirs' capacity to transfer water availability from wet to dry seasons.

To ensure balanced algorithm performance and prevent bias arising from differing or-

ders of magnitude, a normalization procedure within the $[0, 1]$ range was implemented. This dimensionless approach not only equalizes objective priority but also enhances the computational efficiency of the dominance sorting mechanisms.

The objective functions are mathematically formalized within the optimization algorithm as follows:

- **Total installed capacity (C_{tot}):** this represents the system's theoretical upper generation limit (MW). It is calculated as the sum of the nominal nameplate capacities of all the optimized reservoirs:

$$C_{tot} = \sum_{i=1}^{19/20} 0.9 \cdot g \cdot H_i \cdot Q_{design,i}$$

where 0.9 represents the turbine efficiency coefficient, g is the gravitational acceleration (m/s^2), H_i is the nominal hydraulic head (m), and $Q_{design,i}$ is the design flow rate (m^3/s). This value serves as a fundamental scaling factor, rendering the results independent of the physical dimensions of the basin.

- **Total production (P_{tot}):** a direct output of the VIC-Res model representing the total energy produced, typically measured in Megawatt-hours (MWh). It is calculated by integrating inflow rates, the variable hydraulic head (a function of the storage level), and mechanical efficiency on a daily basis.

- **Objective function J_1 :**

$$J_1 = 1 - \frac{P_{tot} \cdot 1000}{C_{tot} \cdot N_{days}}$$

- **Objective function J_2 :**

$$J_2 = 1 - \frac{H_{firm} \cdot 1000}{30 \cdot C_{tot}}$$

Firm hydropower (H_{firm}): calculated by identifying the minimum guaranteed monthly production across the historical time series (MWh).

Although the framework includes indicators for water deficit and sediment load, these metrics were disabled in the current configuration to isolate the energy trade-off.

The optimizer operates on a heterogeneous set of decision variables that define the reservoir release policies. The system manages various operational strategies (OP1, OP2, OP3, OP5), encompassing:

- **Target water levels:** optimization of storage thresholds (h_{min} , h_{max}) and operational volumes (dead volume v_{dead} and maximum capacity v_{cap}).

- **Temporal parameters:** determination of activation timings and seasonal windows.

To ensure convergence towards an accurate and well distributed Pareto front, the following computational parameters were adopted:

- **Function evaluations:** 50,000 total iterations to extensively explore the solution space.
- **Population size:** 150 individuals, ensuring a balance between genetic diversity and computational speed.
- **Epsilon (ε):** set to 0.0001 for both energy objectives. This value defines the resolution of the Pareto grid, ensuring the preservation of a diversified solution archive where each point represents a significant improvement over others.
- **Parallelization:** execution was distributed across 10 cores, enabling the simultaneous management of multiple VIC-Res model simulations.
- **Optimization period:** January 1, 2012 – December 31, 2022.

3.3.2. First optimization: top 20 reservoirs

The performance evaluation of the ε -NSGA-II algorithm begins with the identification of the historical benchmark point within the objective space. This point represents the system's behavior under the traditional management strategies documented over the 1981–2022 period.

The comparative analysis between historical management and the Pareto front resulting from the optimization highlights a significant performance gap. As observed in the comparison graph (Figure 3.15), the historical point is located in a region of strong sub-optimality, being effectively dominated by the entire set of solutions identified by the algorithm. The Euclidean distance between the historical benchmark and the non-dominated front serves as an indicator of untapped operational efficiency. The results suggest that coordinated and optimized management of the 20 reservoirs would have allowed for a drastic reduction in energy deficits, while simultaneously improving both gross yield (J_1) and the reliability of base production (J_2). The distribution of solutions along the front delineates the system's physical limit, thus defining a new decision making horizon for the optimal management of the basin.

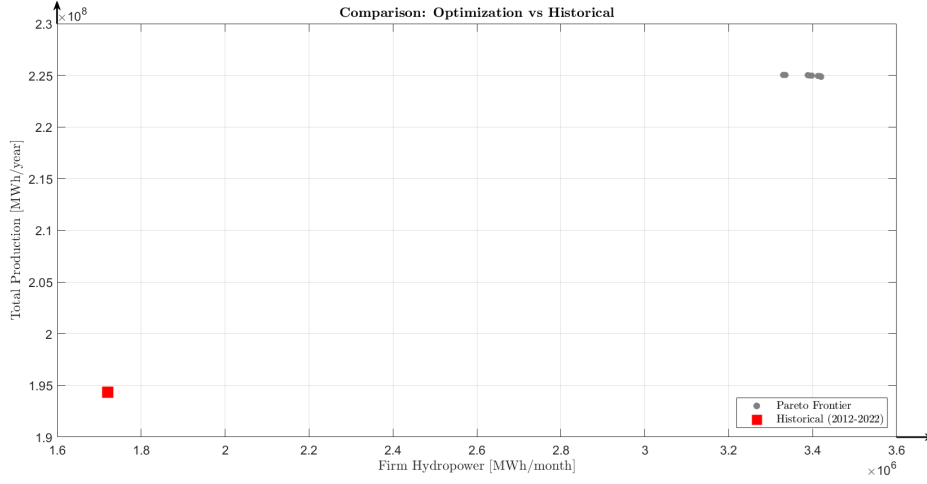


Figure 3.15: Comparison: Frontier vs. Historical

To gain deeper insights into the nature of the trade-off between maximizing hydropower production and service stability, the analysis proceeds with a detailed study of three strategically significant solutions selected from the Pareto front. The investigation of these characteristic points: the individual optimum for total production (J_1), the individual optimum for firm hydropower (J_2), and the best compromise solution (minimum distance from the utopia point), enables the exploration of diverse operational system configurations.

This approach facilitates an understanding of how reservoir release policies evolve when shifting from a strategy oriented towards total energy volume to one focused on resilience and supply consistency. This section analyzes the three representative configurations identified on the Pareto front. Each point reflects a distinct management priority, allowing for the quantification of the opportunity cost associated with prioritizing one objective over the other.

Best compromise point (utopia criterion)

This configuration was identified as the closest solution, in terms of normalized euclidean distance, to the utopia point (the ideal, unattainable target). It represents the most balanced solution within the entire Pareto set. This point simultaneously minimizes the deficits of both objectives, offering a system management strategy that does not penalize either the gross energy yield or supply stability.

The Pareto front is shown in figure 3.16.

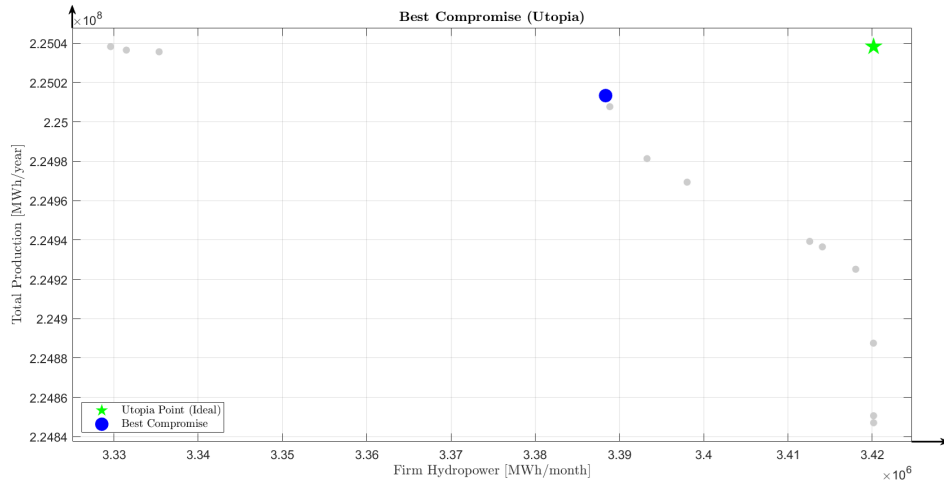


Figure 3.16: Best compromise point

Optimum for total production (J_1 minimum)

This solution is located at the extreme end of the Pareto front dedicated to maximizing the overall energy volume. This represents the energy oriented configuration. Although it guarantees the lowest total production deficit, it exhibits the highest deficit value for firm hydropower. Physically, this implies that the system maximizes overall energy release but compromises its capacity to guarantee a constant minimum power output during critical periods.

The Pareto front is shown in figure 3.17.

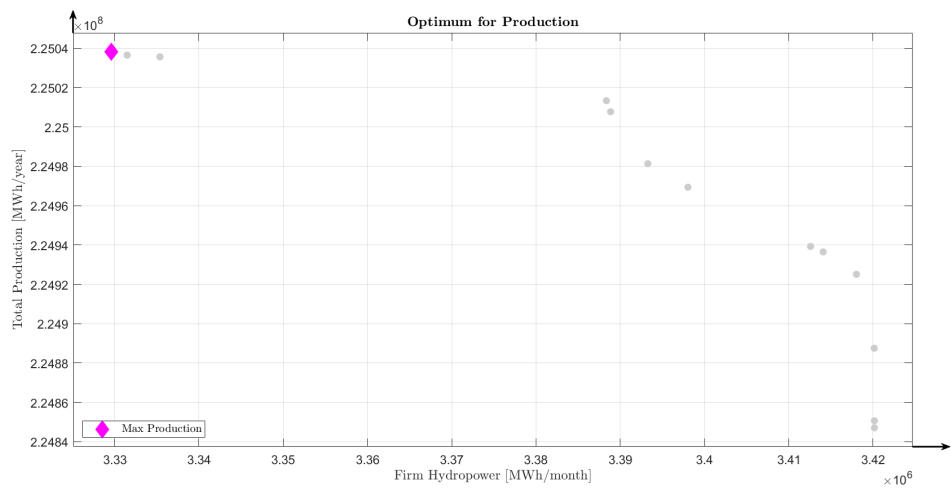


Figure 3.17: Optimum for total production

Optimum for firm hydropower (J_2 minimum)

This configuration stands in direct contrast to the previous one, focusing specifically on system resilience. This represents the reliability oriented strategy. Here, the system sacrifices a portion of total production to guarantee the maximum possible stability of the base load supply. It is the optimal choice in scenarios of severe hydrological stress or where the priority is the security of minimum energy supply for the grid.

The Pareto front is shown in figure 3.18.

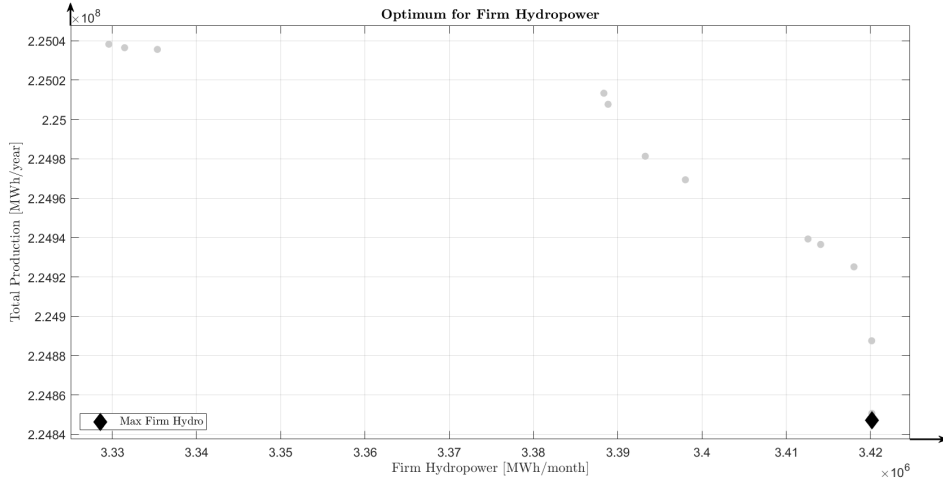


Figure 3.18: Optimum for firm hydropower

Among the candidate solutions identified on the Pareto frontier, the selection process prioritized the Best Compromise solution, determined through the application of the utopia point criterion.

This methodological approach is substantiated by the criterion's ability to identify the solution that minimizes the euclidean distance from the ideal utopia point, a theoretical coordinate where all objective functions are simultaneously maximized. In a multi-objective context characterized by conflicting goals (such as maximizing hydroelectric production vs. maximizing firm hydropower), selecting the point geometrically closest to the ideal ensures the identification of the most balanced trade-off. Unlike extreme solutions, which maximize a single parameter to the detriment of the other one, the utopia selection guarantees a robust equilibrium, mitigating the risk of disproportionate performance losses in any single dimension and offering a least regret scenario for the basin management.

The validity of this selection was further corroborated during the comprehensive analysis of the results for both optimization scenarios. Specifically, a cross-examination of total production and firm hydropower metrics against the equity indicators revealed a trajectory of diminishing returns towards the extremities of the Pareto frontier.

Deviating from the identified best compromise point yields only marginal gains in terms of production and energy security, while incurring a disproportionate cost in terms of distributive equity. Consequently, given the substantial efficiency improvements already secured through the optimization process, the utopia point is confirmed as the superior configuration within the Pareto set, offering the most robust and balanced overall performance.

First Optimization: results

Table 3.7 presents a comparative analysis of hydroelectric production performance, contrasting the historical baseline against the results yielded by optimization scenario 1 over the 2012–2022 assessment period.

All dams in the model (125) were taken into account in producing the results shown below, not just the optimized ones.

All production figures reported (3.19 and 3.20) are expressed in megawatt-hours per year (MWh/year).

Country	Optimized production	Historical production	Difference (%)
China	182242877.40	154401288.60	+18.03%
Laos	27493977.73	21092104.27	+30.35%
Myanmar	286315.4618	286315.46	+0.00%
Vietnam	11400154.29	10971382.09	+3.91%
Thailand	1915747.222	1905476.47	+0.54%
Cambodia	7447136.802	5681577.131	+31.08%
TOTAL	230786208.9	194338144	+18.75%

Table 3.7: Comparison of production: historical vs. optimized

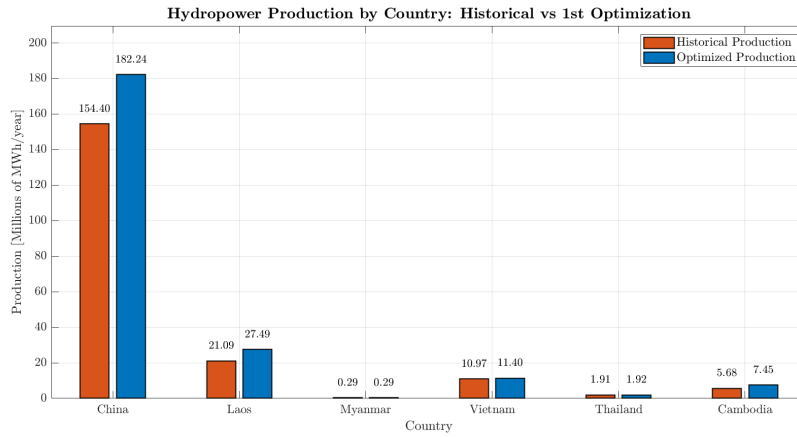


Figure 3.19: Absolute production: historical and optimized for every Country

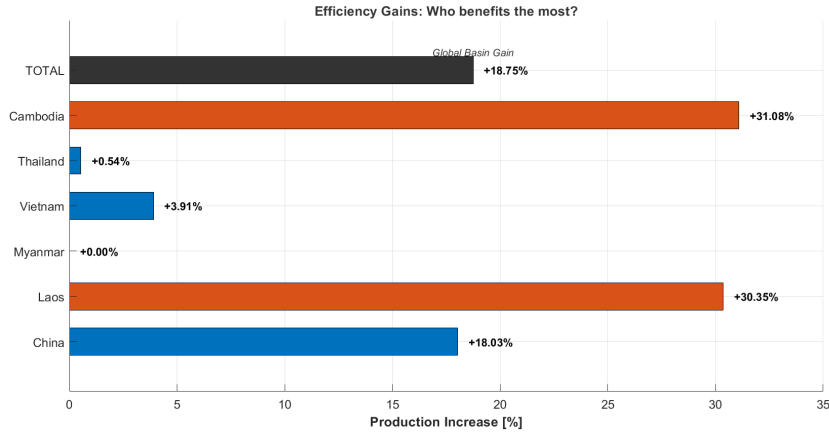


Figure 3.20: Production increase for every Country and for the whole basin

Table 3.8 and figure 3.21 presents the calculated values of the Atkinson Index, facilitating a quantitative analysis of equity performance. The data illustrates the sensitivity of distributional outcomes to variations in the inequality aversion parameter (ϵ) and across the distinct production series under review.

ϵ	Atkinson (%) [Optimized]	Atkinson (%) [Historical]	Difference (%)
0.1	10.37	10.38	-0.01%
0.25	25.46	25.43	+0.03%
0.5	48.26	48.98	-0.72%
0.75	66.57	65.90	+0.67%
1.0	79.60	78.60	+1.00%
1.5	92.44	91.49	+0.95%

Table 3.8: Atkinson index for production

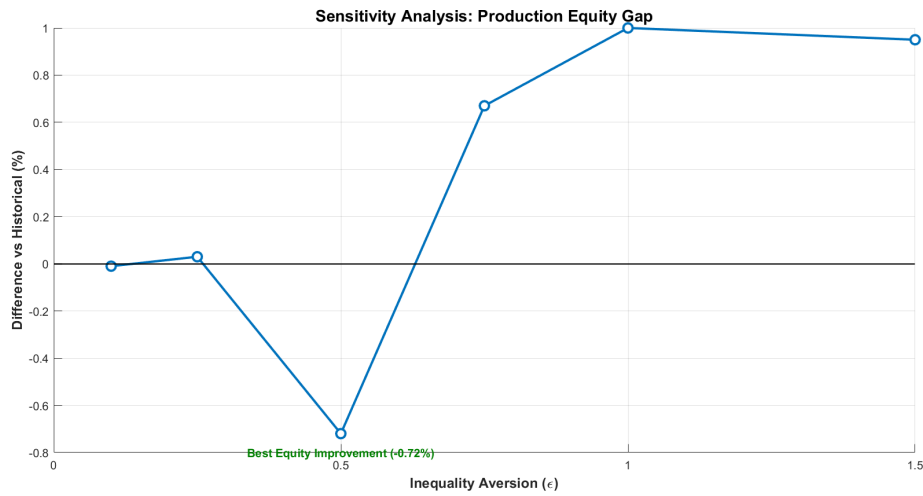


Figure 3.21: Atkinson index for production

The analysis subsequently extends to the examination of firm hydropower values. As detailed in Table 3.9, these metrics are derived from both the historical baseline and the optimized production datasets, providing a comparative assessment of system reliability. The data shown in the table are in MWh. In Table 3.9, the TOTAL row represents the average of the averages of the individual countries.

Country	Optimized mean	Historical mean	Difference (%)
China	14001686.73	9381076.80	+49.25%
Laos	1399472.88	569383.92	+145.79%
Myanmar	2579.60	2579.60	+0.00%
Vietnam	146632.04	186877.18	-21.66%
Thailand	48672.82	55588.32	-12.44%
Cambodia	503410.81	126966.07	+296.49%
TOTAL	2683742.48	1720411.92	+55.99%

Table 3.9: Comparison of firm hydropower: historical vs. optimized

Figure 3.22 and figure 3.23 show respectively the absolute value of firm hydropower and its increase/decrease compared to historical values.

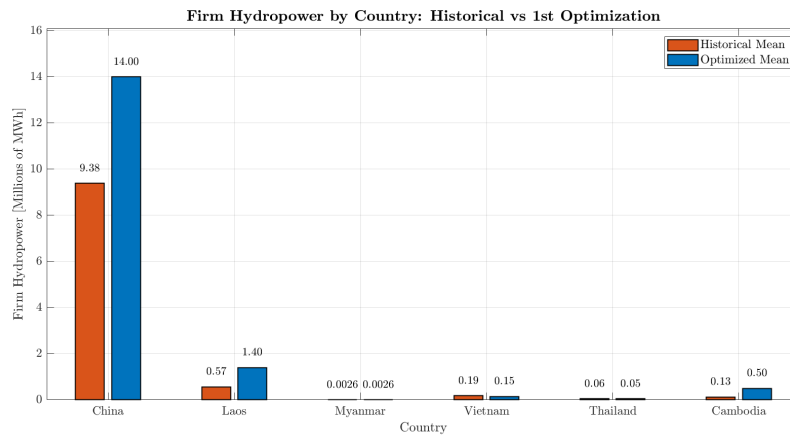


Figure 3.22: Absolute firm hydropower: historical and optimized for every Country

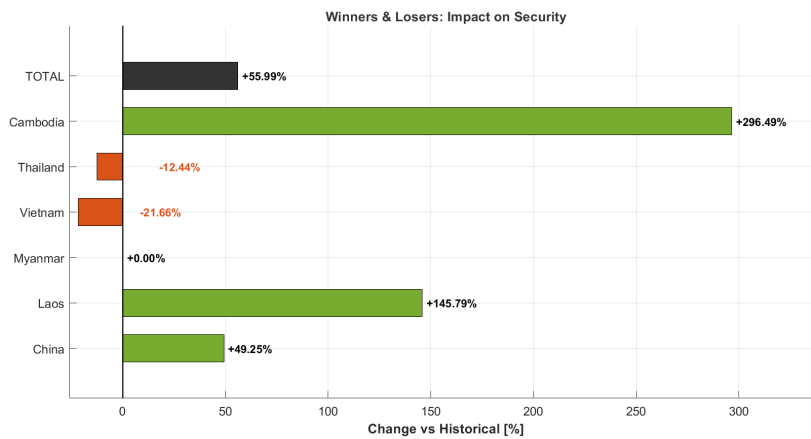


Figure 3.23: Firm hydropower increase for every country and for the whole basin

Table 3.10 and figure 3.24 presents the calculated values of the Atkinson Index, facilitating a quantitative analysis of equity performance. The data illustrates the sensitivity of distributional outcomes to variations in the inequality aversion parameter (ϵ) and across the distinct firm hydropower series under review.

ϵ	Atkinson (%) [Optimized]	Atkinson (%) [Historical]	Difference (%)
0.1	12.82	13.76	-0.94%
0.25	31.48	33.48	-2.00%
0.5	59.07	61.35	-2.28%
0.75	79.33	80.19	-0.87%
1.25	96.46	95.56	+0.89%
1.5	98.45	97.78	+0.66%

Table 3.10: Atkinson index for firm hydropower

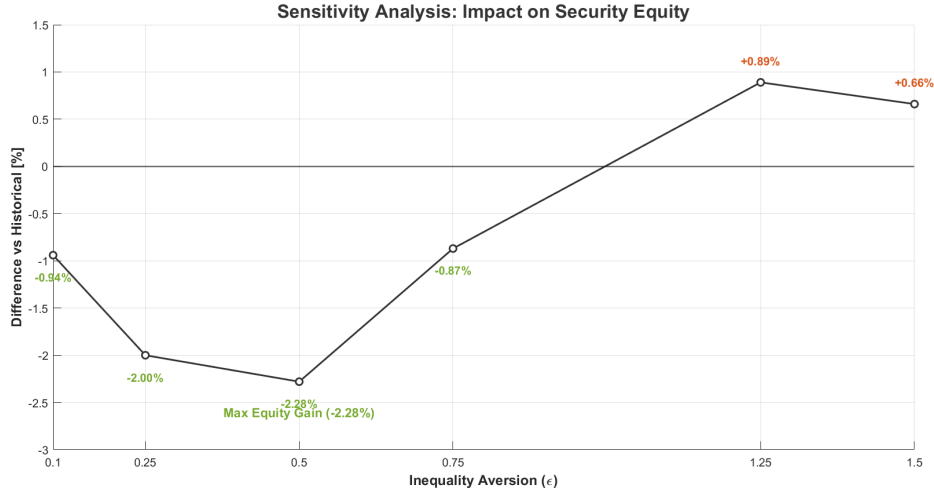


Figure 3.24: Atkinson index for firm hydropower

3.3.3. Second optimization: top 19 reservoirs (max 4 per country)

The performance evaluation of the ε -NSGA-II algorithm begins with the identification of the historical benchmark point within the objective space. This point represents the system's behavior under the traditional management strategies documented over the 1981–2022 period.

The comparative analysis between historical management and the Pareto front resulting from the optimization highlights a significant performance gap. As observed in the comparison graph (Figure 3.25), the historical point is located in a region of strong sub-optimality, being effectively dominated by the entire set of solutions identified by the algorithm. The Euclidean distance between the historical benchmark and the non-dominated front serves as an indicator of untapped operational efficiency. The results suggest that a coordinated and optimized management of the 19 reservoirs would have allowed for a drastic reduction in energy deficits, simultaneously improving both the gross quantitative yield (J_1) and the reliability of base load production (J_2). The distribution of solutions along the front clearly delineates the system's physical limit, thus defining a new decision making horizon for the optimal management of the basin.

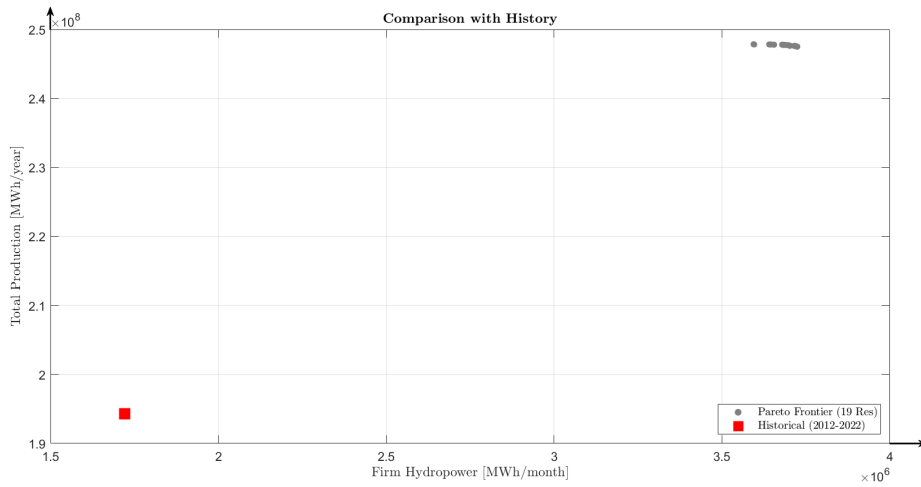


Figure 3.25: Comparison: frontier vs. historical

To gain deeper insights into the nature of the trade-off between maximizing hydropower production and service stability, the analysis proceeds with a detailed study of three strategically significant solutions selected from the Pareto front. The investigation of these characteristic points proceed as explained above.

Best compromise point (utopia criterion)

This configuration was identified as the closest solution, in terms of normalized Euclidean distance, to the utopia point (the ideal, unattainable target). It represents the most balanced solution within the entire Pareto set. This point simultaneously minimizes the deficits of both objectives, offering a system management strategy that does not penalize either the gross energy yield or supply stability.

The Pareto front is shown in figure 3.26.

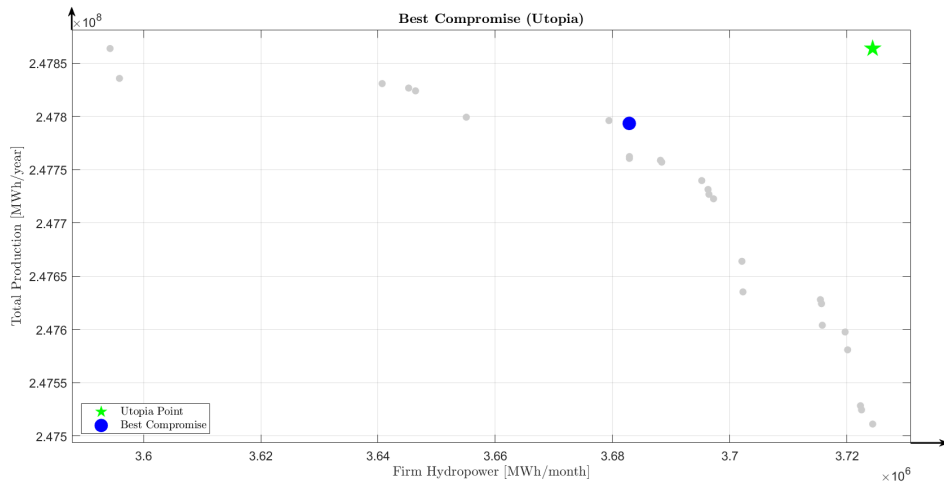


Figure 3.26: Best compromise point

Optimum for total production (J_1 minimum)

This solution is located at the extreme end of the Pareto front dedicated to maximizing the overall energy volume. This represents the energy oriented configuration. Although it guarantees the lowest total production deficit, it exhibits the highest deficit value for firm hydropower. This implies that the system maximizes overall energy release but compromises its capacity to guarantee a constant minimum power output.

The Pareto front is shown in figure 3.27.

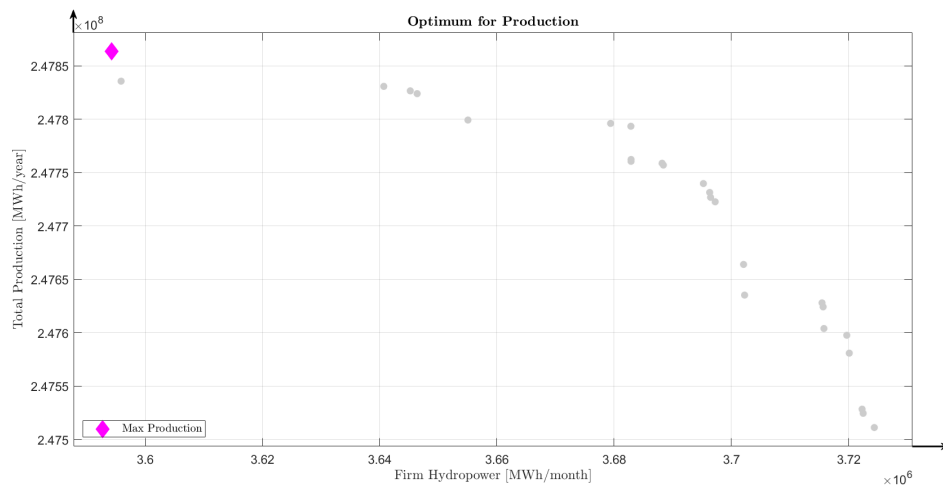
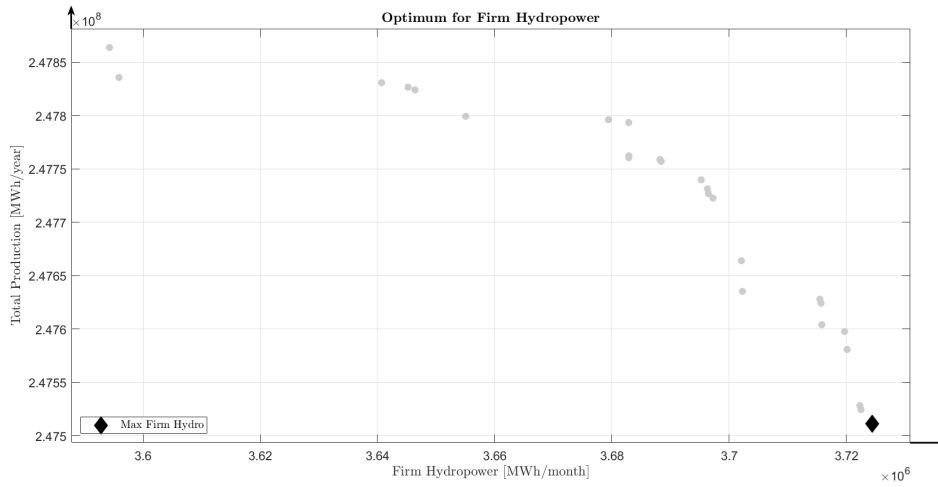


Figure 3.27: Optimum for total production

Optimum for firm hydropower (J_2 minimum)

This configuration stands in direct contrast to the previous one, focusing specifically on system resilience. This represents the reliability oriented strategy. Here, the system sacrifices a portion of total production to guarantee the maximum possible stability of the base load supply. It is the optimal choice in scenarios of severe hydrological stress or where the priority is the security of minimum energy supply for the grid.

The Pareto front is shown in figure 3.28.



Country	Optimized production	Historical production	Difference (%)
China	182205516.50	154401288.60	+18.01%
Laos	22984097.67	21092104.27	+8.97%
Myanmar	280708.04	286315.46	-1.96%
Vietnam	11471187.38	10971382.09	+4.56%
Thailand	1917250.08	1905476.47	+0.62%
Cambodia	7569709.06	5681577.13	+33.23%
TOTAL	226428468.70	194338144.00	+16.51%

Table 3.11: Comparison of production: historical vs. optimized

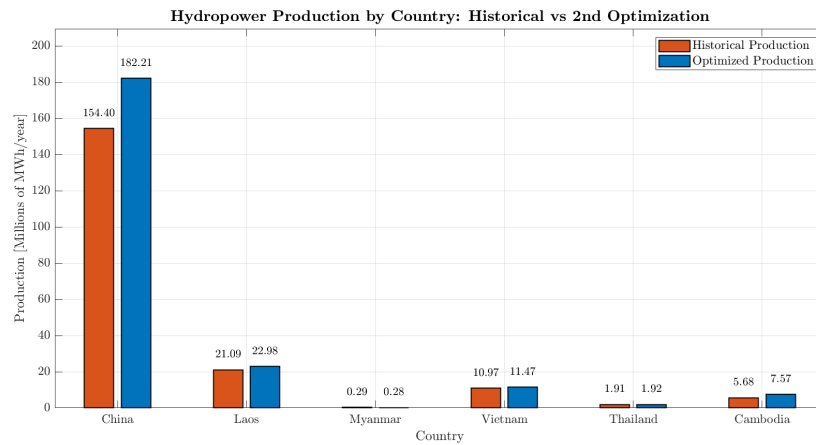


Figure 3.29: Absolute production: historical and optimized for every country

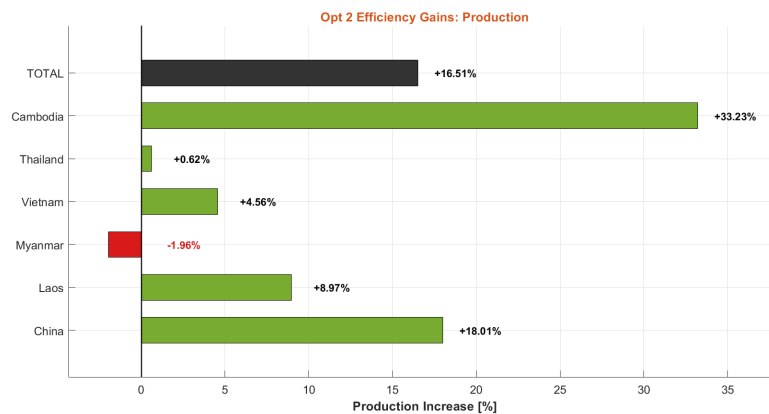


Figure 3.30: Production increase for every country and for the whole basin

Table 3.12 and figure 3.31 presents the calculated values of the Atkinson index, facilitating a quantitative analysis of equity performance. The data illustrates the sensitivity of

distributional outcomes to variations in the inequality aversion parameter (ϵ) and across the distinct production series under review.

ϵ	Atkinson (%) [Optimized]	Atkinson (%) [Historical]	Difference (%)
0.1	10.62	10.38	+0.23%
0.25	25.98	25.43	+0.55%
0.5	48.91	47.98	+0.93%
0.75	67.05	65.90	+1.15%
1.0	79.81	78.60	+1.20%
1.5	92.43	91.49	+0.94%

Table 3.12: Atkinson index for production

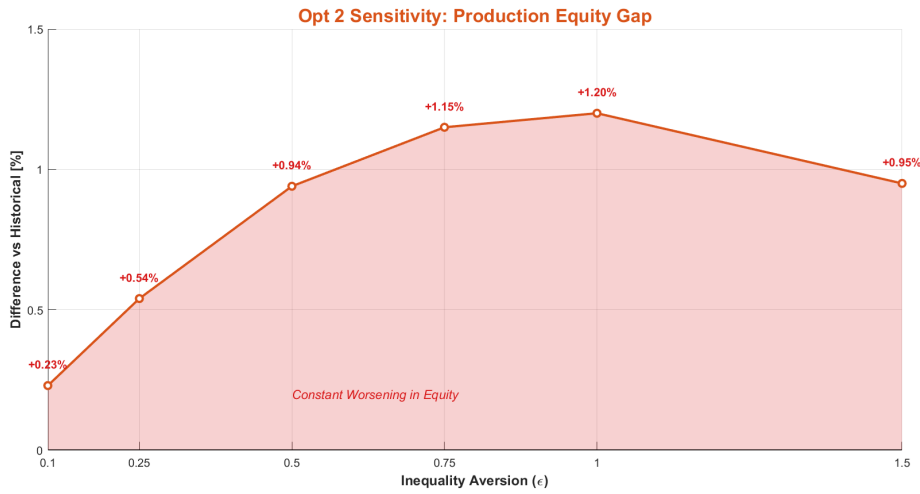


Figure 3.31: Atkinson index for production

The analysis subsequently extends to the examination of firm hydropower values. As detailed in Table 3.13, these metrics are derived from both the historical baseline and the optimized production datasets, providing a comparative assessment of system reliability. The data shown in the table are in MWh. In Table 3.13, the TOTAL row represents the average of the averages of the individual countries.

Country	Optimized mean	Historical mean	Difference (%)
China	14001686.73	9381076.80	+49.25%
Laos	909794.49	569383.92	+59.79%
Myanmar	1596.21	2579.52	-38.12%
Vietnam	170924.16	187165.2	-8.68%
Thailand	64980.02	55588.32	+16.90%
Cambodia	575811.59	126966.00	+353.52%
TOTAL	2620798.87	1720459.96	+52.34%

Table 3.13: Comparison of firm hydropower: historical vs. optimized

Figure 3.32 and figure 3.33 show respectively the absolute value of firm hydropower and its increase/decrease compared to historical values

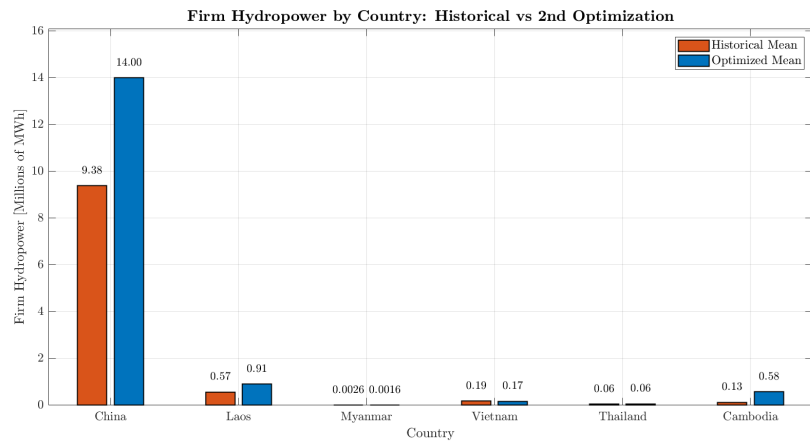


Figure 3.32: Absolute firm hydropower: historical and optimized for every Country

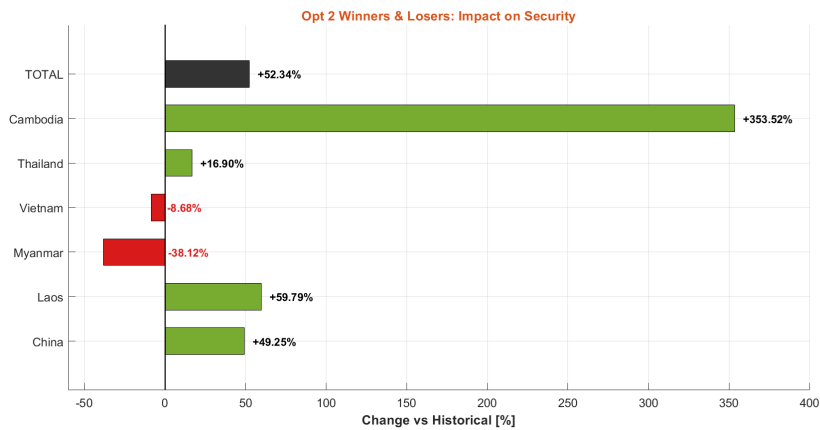


Figure 3.33: Firm hydropower increase for every country and for the whole basin

Table 3.14 and figure 3.34 presents the calculated values of the Atkinson Index, facilitating a quantitative analysis of equity performance. The data illustrates the sensitivity of distributional outcomes to variations in the inequality aversion parameter (ϵ) and across the distinct firm hydropower series under review.

ϵ	Atkinson (%) [Optimized]	Atkinson (%) [Historical]	Difference (%)
0.1	13.19	13.76	-0.57%
0.25	32.21	33.48	-1.27%
0.5	59.74	61.35	-1.61%
0.75	79.61	80.19	-0.58%
1.25	96.89	95.56	+1.32%
1.5	98.81	97.78	+1.03%

Table 3.14: Atkinson index for firm hydropower

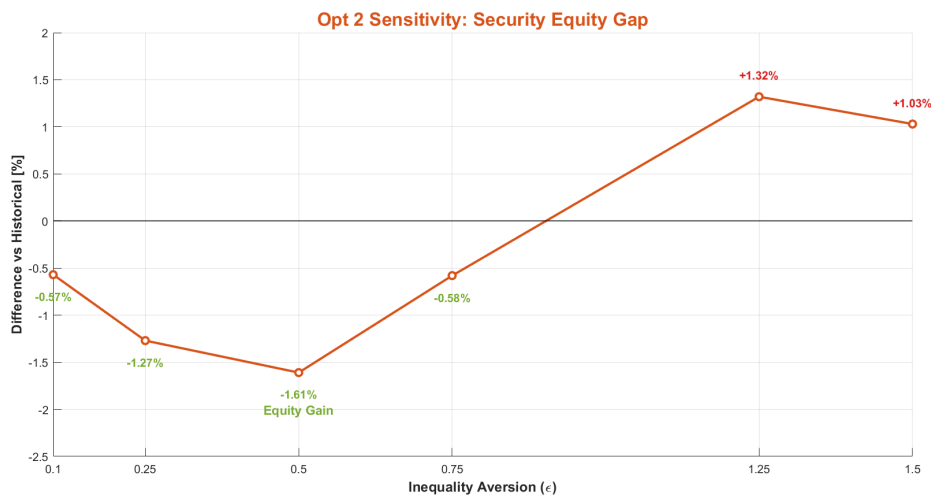


Figure 3.34: Atkinson index for firm hydropower

4 | Discussion

This chapter discusses the findings from the optimization, comparing the results of the pure optimization scenario against the geopolitically constrained one.

Introduction: the myth of the trade-off

The Mekong river basin represents a complex hydrological system where national interests conflict with the global optimum, as detailed in the introduction and state of the art chapters. The current paradigm is characterized by a lack of cooperation, in which secondary or downstream nations have historically been disadvantaged, suffering both from the negative externalities of upstream hydroelectric development and a structural deficit in their own energy production capabilities (Yu et al., 2024).

This basin stands as one of the better examples of complex global hydrological networks, encompassing six riparian nations (China, Myanmar, Laos, Thailand, Cambodia, and Vietnam). These actors have divergent political agendas, self-centered water management and production objectives, and an absence of international collaborative frameworks. From this perspective, historical water resource management within the basin is defined by what the literature terms hydro-hegemony (Zeitoun and Warner, 2006). In this context, upstream nations, China and Laos, exert primary physical control over the water resource, translating into asymmetrical power dynamics relative to downstream delta countries, like Vietnam and Cambodia. This configuration has engendered a highly fragmented management approach, analogous to the Tragedy of the Commons theorized by (Hardin, 1968): each sovereign actor has unilaterally pursued the maximization of its immediate hydroelectric interests, systematically neglecting the deleterious externalities imposed on the overall energy security of the basin.

Within this context, classical economic and resource management theories posit that any attempt to optimize a shared resource inevitably encounters the trade-off between efficiency and equity (Okun, 1975). According to this paradigm, maximizing total hydroelectric output (efficiency) necessitates concentrating production infrastructure at the most hydrologically advantageous sites, predominantly located upstream, thereby accepting a

consequent deterioration in resource distribution fairness (equity). Conversely, imposing an equitable distribution of resources would inexorably result in a systemic loss of overall productivity. The existing literature on the management of transboundary water resources (Yu et al., 2024) has frequently accepted this compromise as an immutable constraint: a system can produce a substantial volume of energy inequitably or produce less energy while prioritizing an egalitarian distribution .

Through the presentation of results derived from the two applied optimization models, this thesis aims to refute this assumption within the intricate geopolitical context of the Mekong river. The foundational hypothesis driving this analysis is that the historical management of the basin is so sub-optimal, stemming from a total vacuum of transboundary coordination, that its current operational state lies significantly below the theoretical Pareto frontier.

By deploying the Epsilon-NSGA-II multi-objective optimization algorithm and establishing the utopia point of the Pareto frontier as the ideal reference benchmark, this study demonstrates that the existing margin for improvement is vast enough to facilitate a simultaneous enhancement of both total production (efficiency improvement) and distributive energy security (equity improvement). Ultimately, the systemic inefficiency of the anarchic status quo acts as an hidden cost. Once eliminated through algorithmic cooperation, it releases sufficient latent resources to satisfy both productive demands and distributive imperatives, thereby rendering the traditional conflict between these two objectives largely obsolete.

The inefficiency of history

A critical review of the 2012–2022 historical hydroelectric production data reveals a hydrographic basin governed by nationalistic imperatives, without systemic coordination. While this fragmented approach yielded ostensibly substantial energy outputs, it crystallized the system in a state of inefficiency. The baseline aggregate data indicates a total hydroelectric production of approximately 194'338.14 GWh/year. Although this figure serves as the historical benchmark, subsequent chapters will demonstrate that it falls significantly short of the river's actual potential. The uncoordinated management paradigm effectively precluded the exploitation of crucial synergies between the massive upstream reservoirs (predominantly in China and Laos) and downstream productive requirements. This operational fragmentation squandered a latent energy potential that the proposed optimization framework successfully captures.

The most alarming indicator of the status quo concerns not the volume of energy gen-

erated, but rather its reliability. Firm hydropower, defined as the system's capacity to guarantee energy provision even during the most critical drought months, historically averaged 1'720.46 GWh across the basin. This metric exposes the intrinsic fragility of an anarchic management strategy: in the absence of coordinated releases from upstream reservoirs during the dry season, the basin failed to ensure robust and stable energy security. The disaggregated analysis by state clearly reveals that this security was an exclusive privilege. While upstream nations like China and, to a certain extent, Laos maintained good levels of guaranteed production, downstream countries suffer the burden of hydrological fluctuations without any mitigative compensation mechanisms. Myanmar, for instance, recorded critically low historical firm hydropower values (averaging approximately 2.58 GWh during the leanest months of the 2012–2022 assessment period), exposing its national security to severe climatic uncertainty.

To objectively quantify these structural disparities, the Atkinson index was applied to the historical dataset. The ensuing results corroborate the premise that the price of historical inefficiency was exacted squarely at the expense of equity.

- **Total production:** computed with an inequality aversion parameter of $\epsilon = 0.5$, the Atkinson index reached a critical threshold of 47.97%. This figure denotes an almost absolute concentration of productive capacity within a few dominant hubs, relegating the remaining riparian actors to negligible shares of the water resource.
- **Energy security (firm hydropower):** even more pronounced is the data concerning systemic resilience. Applying the same parameter ($\epsilon = 0.5$), the historical index for firm hydropower peaked at a severe 61.35%. This latter value transcends mere statistical representation; it encapsulates the numerical reality of an asymmetric risk profile. Under the historical framework, the probability of enduring energy deficits during drought periods was not uniformly distributed, but rather disproportionately penalized the basin's most vulnerable actors.

The paradigm that emerges from the 2012–2022 period perfectly exemplifies a non-cooperative Nash equilibrium, wherein the aggregation of individual, localized optima generated a mediocre global outcome. The system systematically under-produced relative to its potential (inefficiency) and distributed operational risks inequitably (inequality). It is precisely against the backdrop of these unsatisfactory historical baselines that the multi-objective optimization framework, detailed in the subsequent chapter, unveils its transformative potential.

Pure optimization

In the primary optimization scenario, the algorithm operated unconstrained by national quotas, tasked with optimizing the 20 highest performing reservoirs based on physical criteria (actual reservoir capacity). The outcome is a reconfiguration of the Mekong’s energy geography, driven by a logic of pure hydraulic efficiency. The identified optimal configuration massively concentrates infrastructural resources in Laos, selecting 11 out of the 20 available plants. Countries like Vietnam (2 plants), Cambodia (1 plant), and Myanmar (0 plants) witness their infrastructural participation reduced to a bare minimum. This spatial distribution is by no means accidental: the optimization model effectively elects Laos as the systemic battery, exploiting its favorable orography to maximize upstream water retention and regulate hydrological flows for the entirety of the basin.

The efficacy of this uncompromising, utilitarian strategy, which does not explicitly target equity as a primary objective, is evident in the quantitative output. The aggregate energy generation of the basin surges to 230’786.2 GWh/year, marking a substantial increase of +18.75% compared to the historical average.

A disaggregated analysis of national contributions clearly highlights the driving role of Laos, which sees its production grow by +30.35%. China, while retaining a limited portfolio of selected plants (3), also benefits from the optimized management framework, registering a +18.03% increase. Despite the upstream concentration of dam infrastructure, Cambodia records a production increase of +31.08%, empirically demonstrating that the benefits of regulated upstream flows propagate highly effectively to downstream actors. Figure 4.1 show the production share.

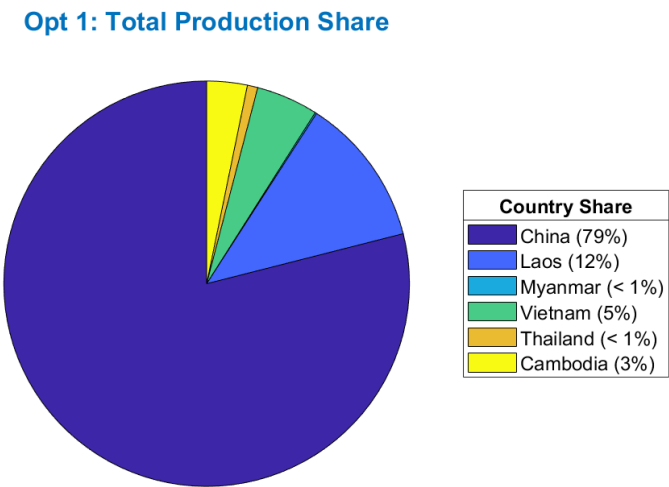


Figure 4.1: Total production share

The aggregate firm hydropower experiences a surge of +55.99%, escalating from the historical baseline of 1'720.41 GWh to 2'683.74 GWh. This metric encapsulates a fundamental operational dynamic: the coordinated management of large reservoirs in Laos and China allows for the sustained baseflow of the river during dry periods to a degree never achieved in historical practice.

- **Cambodia:** the most emblematic case is Cambodia. Despite having only a single plant selected in this optimal configuration, the nation's guaranteed energy (firm hydropower) explodes by +296.49% (from 126.97 GWh to 503.41 GWh). This provides empirical evidence that the energy security of downstream nations is dictated less by the domestic density of localized dam infrastructure, and far more by the cooperative management protocols governing upstream reservoirs.
- **China:** leveraging the cascade optimization methodology, China sees its firm hydropower increase by +49.25%, further consolidating an energy stability profile that was already robust in the historical dataset.
- **The victims:** nevertheless, the outcomes are not universally positive. In this scenario of pure efficiency, Vietnam and Thailand incur a penalty stemming from their geographic positioning and the algorithmic plant selection. The firm hydropower for Vietnam and Thailand declines by -21.66% and -12.44%, respectively. This embodies the true trade-off of unconstrained optimization: to maximize the global optimum and safeguard the most vulnerable downstream actors (Cambodia), the operational stability of certain intermediate riparian states is necessarily sacrificed.

The distributive analysis, conducted via the Atkinson index (calculated using an inequality aversion parameter of $\epsilon = 0.5$), dispels the prevailing myth that hydrological efficiency inherently breeds social inequity. The data demonstrates that the search of efficiency imposed by pure optimization is, in practical terms, more democratic than historical management practices.

- **On hydroelectric production:** despite the physical concentration of infrastructure in Laos, the distribution of productive benefits proves to be marginally more equitable than the historical baseline. The Atkinson index decreases from the historical 48.98% to 48.26%. While statistically modest, this result is politically highly salient: it proves that a system capable of producing significantly more power (+18.7%) does not achieve this growth at the expense of average distributive equilibrium, maintaining or slightly improving historical allocation shares.
- **Energy security (firm hydropower):** it is within this metric that the most pro-

found qualitative leap is observed. Equity in energy security improves more, with the Atkinson index dropping from the historical 61.35% to 59.07%. This indicates that coordinated flow management actively mitigates risk disparities among riparian states. Whereas historical security was an exclusive prerogative of upstream nations, the optimization model democratizes resilience: the integrated system affords superior protection to all actors, narrowing the vulnerability gap between the most secure (China) and the most historically exposed (Cambodia).

Contrary to the classical literature's projections regarding the efficiency-equity trade-off, Optimization Scenario 1 achieves a virtuous convergence. The technical maximization of water resources (selecting the absolute highest yield sites) yields a cooperation dividend so expansive that it simultaneously enhances total energy production, system wide security, and distributive fairness. In this paradigm, efficiency is not the antagonist of equity, but rather its fundamental prerequisite.

Figure 4.2 show the Atkinson index of the first optimization.

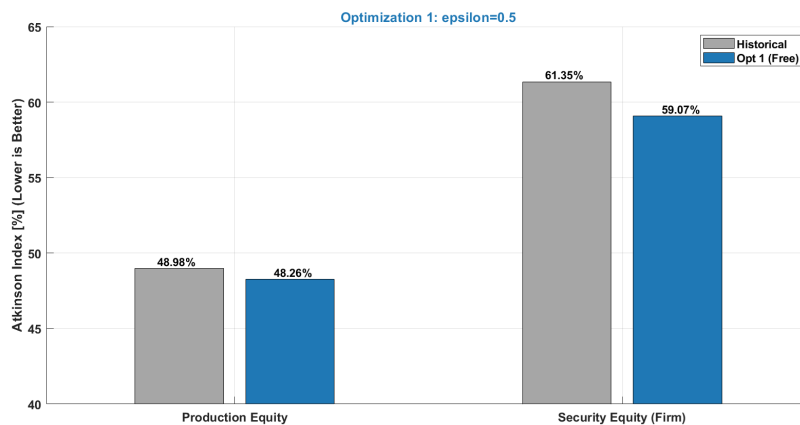


Figure 4.2: Atkinson index for the first optimization

The geopolitical optimization

Whereas the first scenario epitomized the hydrological ideal, the second optimization introduces the pragmatic realism of international politics. Within a transboundary basin like the Mekong, under a realistic framework of international cooperation, it is politically untenable for a single nation (Laos) to control over half of the strategic infrastructure, as the purely unconstrained solution suggested. Consequently, this second optimization introduces an a priori geographic equity constraint: no single country may host more than four reservoirs within the coordinated operational plan. This criterion radically reconfigures the basin's infrastructural map. The structural dominance of Laos is significantly curtailed (reduced from 11 to 4 selected plants), while actors that pure hydrological

logic would have otherwise marginalized or entirely discarded are forcibly integrated into the system. Under this framework, China, Thailand, and Vietnam see their participation capped at 4 plants each; Cambodia's allocation increases to 2, and Myanmar enters the system with 1 plant (notably, Cambodia and Myanmar fall short of the 4 reservoir maximum due to an absolute lack of viable structures within their respective sovereign borders).

The empirical results of this study underscore the robustness of systemic cooperation. Despite the geographic constraint, total production reaches 226'428.47 GWh/year, securing a +16.51% increase over the historical baseline. The global system concedes a mere 2% loss in production relative to the unconstrained optimization scenario (scenario 1) to achieve a sustainable geopolitical equilibrium. Even more salient is the resilience of energy security (firm hydropower): the constrained system guarantees 2'620'798.87 MWh of firm power, a metric nearly identical to the unconstrained scenario and a remarkable +52.34% improvement over historical management. This data provides definitive evidence that hydrological efficiency can accommodate a high degree of political compromise without systemic collapse.

Figure 4.3 show the production share.

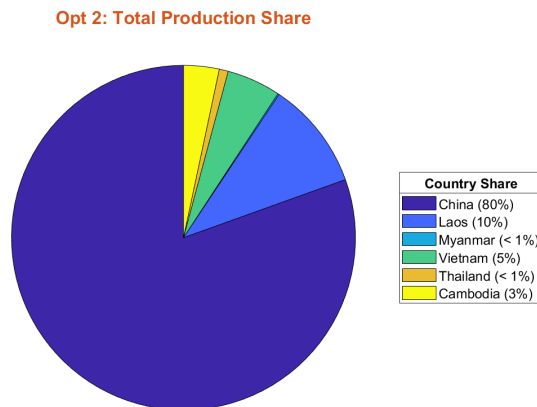


Figure 4.3: Total Production Share

A disaggregated, country level analysis of this scenario reveals diametrically opposed dynamics, highlighting that the geographic equity constraint does not distribute its benefits uniformly (figure 4.4).

- **Cambodia:** allocated two dams (compared to the single facility in the previous scenario), Cambodia experiences an explosion in its firm hydropower, surging by +353.52% against its historical baseline. From the perspective of Phnom Penh, this

political solution is unequivocally preferable to the technical one. The distributive constraint compels the system to heavily invest in downstream security, effectively transforming Cambodia from one of the basin's most vulnerable state into one of its most resilient.

- **Myanmar:** the forced inclusion of Myanmar (with 1 selected dam) proves counterproductive for the nation's own energy security profile. Its firm hydropower collapses by -38.12% relative to historical data. This exposes a critical latent risk: coercing the system to utilize infrastructure in hydrologically unfavorable regions (or managing them strictly for downstream basin wide benefits) can penalize local energy security unless mitigated by external financial compensation mechanisms independent of the optimization algorithm.

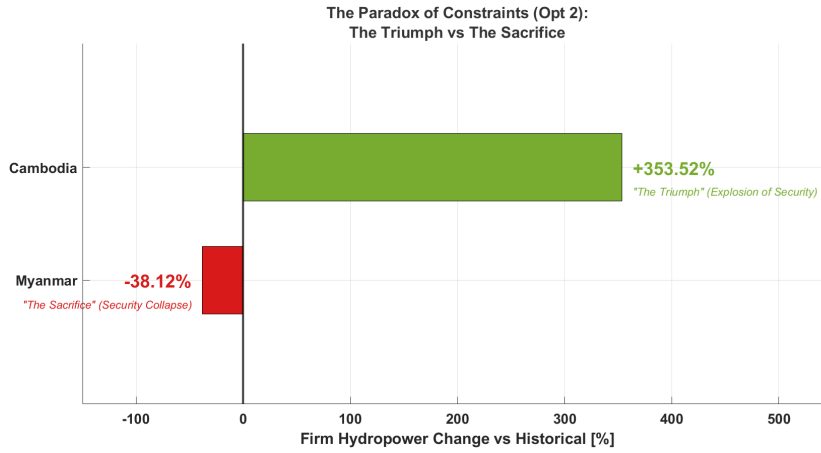


Figure 4.4: Winners and losers: the case of Cambodia and Myanmar

The application of the Atkinson Index, utilizing a moderate inequality aversion parameter ($\epsilon = 0.5$), provides the most sophisticated interpretive lens for this scenario. Intuitively, one might hypothesize that a more uniform physical distribution of dams (capped at 4 per country) would inherently yield a correspondingly fairer distribution of outputs. The empirical data, however, paints a different reality.

- **On total production:** the Atkinson index registers at 48.91%, denoting a deterioration in distributive equity (+0.94%) compared to the historical baseline. This confirms that, even when artificially constraining infrastructure, the capacity to generate massive energy volumes remains heavily concentrated in a few critical nodes (predominantly in China, which sustains high performance levels)
- **On energy security (firm hydropower):** here, the most compelling finding emerges. The Atkinson Index drops to 59.74%, representing a systemic improve-

ment over the historical baseline (61.35%). Confronted with optimization scenario 1 (which achieved 59.07%), this represents a slight regression in equity.

Figure 4.5 show the Atkinson index of the second optimization.

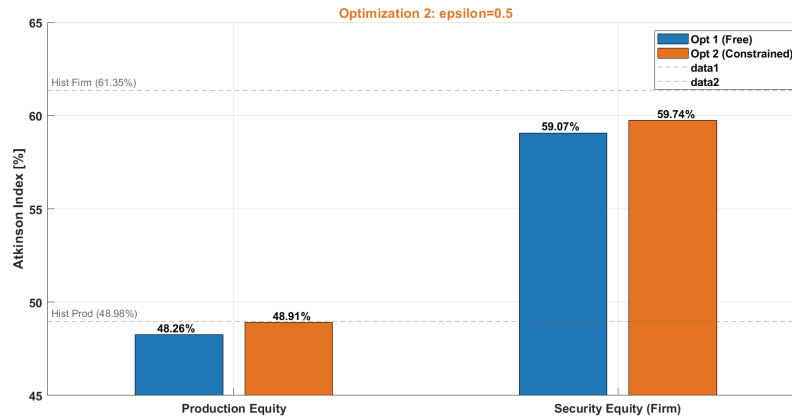


Figure 4.5: Atkinson index for the second optimization

Enforcing the geographic distribution of infrastructure (optimization 2) rendered the system marginally less capable of equalizing risk compared to a state of absolute hydrological freedom (optimization 1). Although the constrained system is fairer than historical management (-1.61% on the Atkinson scale), the rigid political constraint introduced a minor degree of distributive inefficiency.

Ultimately, the second optimization demonstrates the viability of design a politically palatable system (equitably distributed across sovereign borders) while sustaining exceptional systemic performance (+16% production, +52% security). However, the Atkinson analysis delivers a crucial caveat: infrastructural equity (the physical count of dams) does not automatically translate into maximum outcome equity. The "invisible hand" of the unconstrained hydrological algorithm (optimization 1) proved slightly more just in distributing energy security than the "visible hand" of rigid political planning (optimization 2).

Comparative analysis

A direct comparison of the two optimization scenarios allows us to quantify, for the first time, the price the Mekong basin must pay to transition from a purely technocratic management framework (optimization 1) to a geopolitically balanced one (optimization 2). An analysis of the performance differentials reveals that the inherent cost of this political compromise is surprisingly marginal:

- **In terms of total production (figure 4.6):** the transition from absolute algorithmic freedom to strict national quotas entails a marginal systemic loss of only 2.24% (dropping from the +18.75% gain in Scenario 1 to the +16.51% gain in scenario 2).
- **In terms of energy security (firm hydropower) (figure 4.7):** The reduction in systemic resilience is equally constrained, amounting to approximately 3.6% (decreasing from a +55.99% gain to +52.34%).

This finding holds profound implications for policymakers: it demonstrates that pushing the system to its absolute physical extremes (i.e., the massive concentration of infrastructure in Laos) is not a strict prerequisite for achieving exceptional basin wide outcomes. The democratic solution (Scenario 2) proves to be nearly as technically robust as the equity indifferent framework (scenario 1).

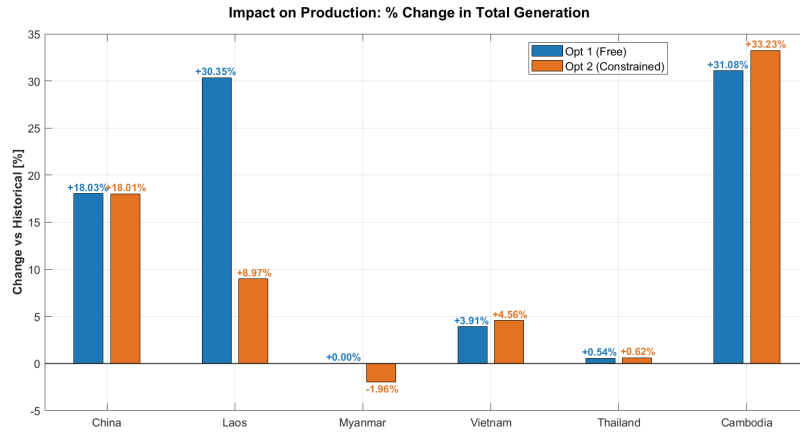


Figure 4.6: Impact on production: % change in total generation

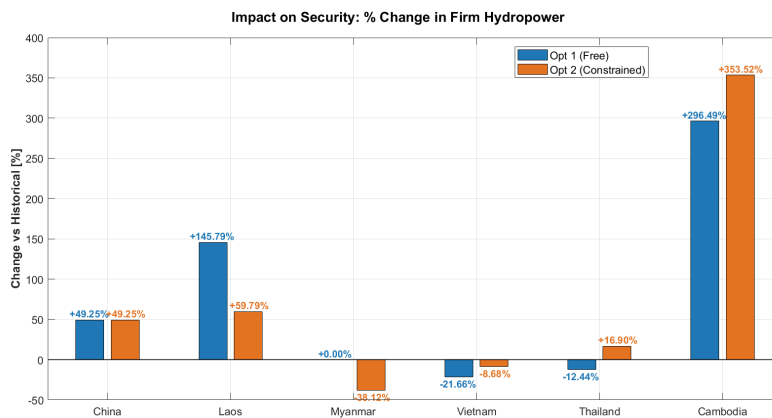


Figure 4.7: Impact on security: % change in firm hydropower

When the analytical focus shifts from absolute quantitative gains to the structural dis-

tribution of these benefits, employing the Atkinson Index with a moderate inequality aversion parameter ($\epsilon = 0.5$), a highly counterintuitive dynamic emerges, forming the theoretical core of this research. Benchmarking the three system states (historical baseline, optimization 1, and optimization 2) yields the following critical observations:

- **Hydroelectric production:** optimization 1 emerges as the most equitable framework overall, registering an Atkinson index of 48.26%. Curiously, the introduction of geographic constraints in scenario 2 slightly degrades this metric, pushing it up to 48.91%, a value virtually indistinguishable from the historical baseline (48.98%)
- **Energy security (firm hydropower):** it is within this metric that the comparison becomes truly decisive. Starting from a severe historical inequality baseline of 61.35%, both optimization scenarios markedly improve the situation. Nevertheless, optimization 1 (unconstrained) achieves a superior degree of equity (59.07%) compared to optimization 2 (59.74%)

Figure 4.8 and figure 4.9 show the general analysis of the variation of the Atkinson index.

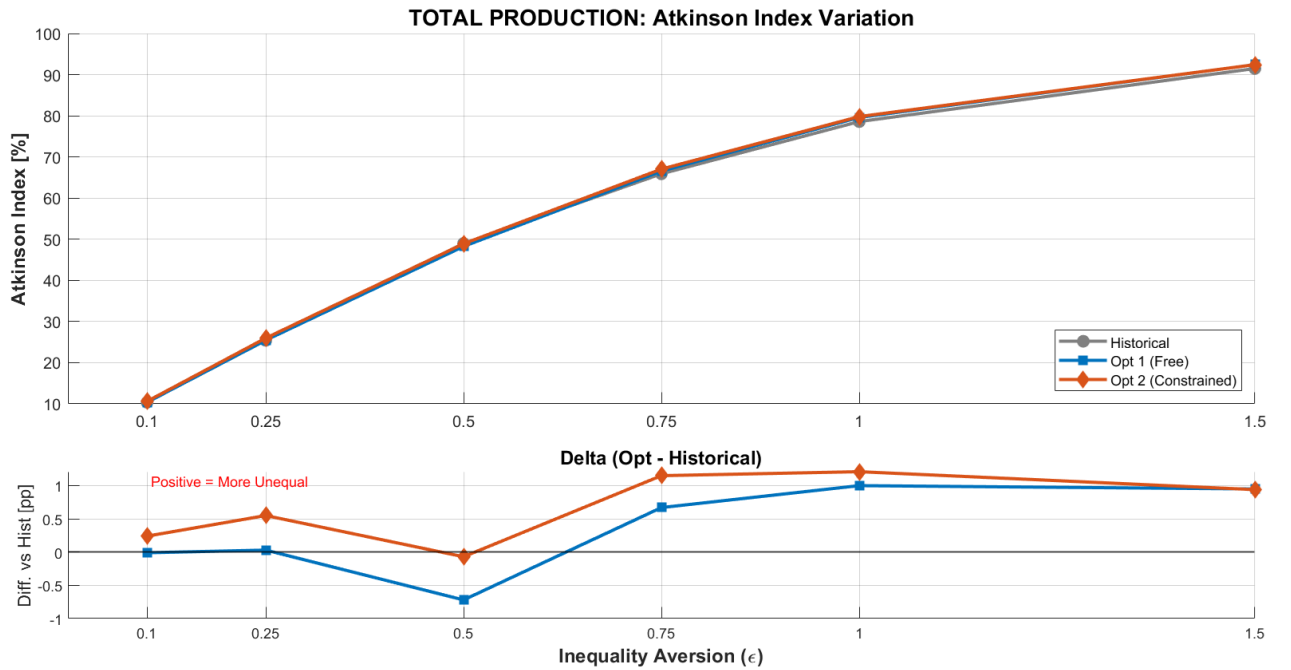


Figure 4.8: Atkinson index variation for production

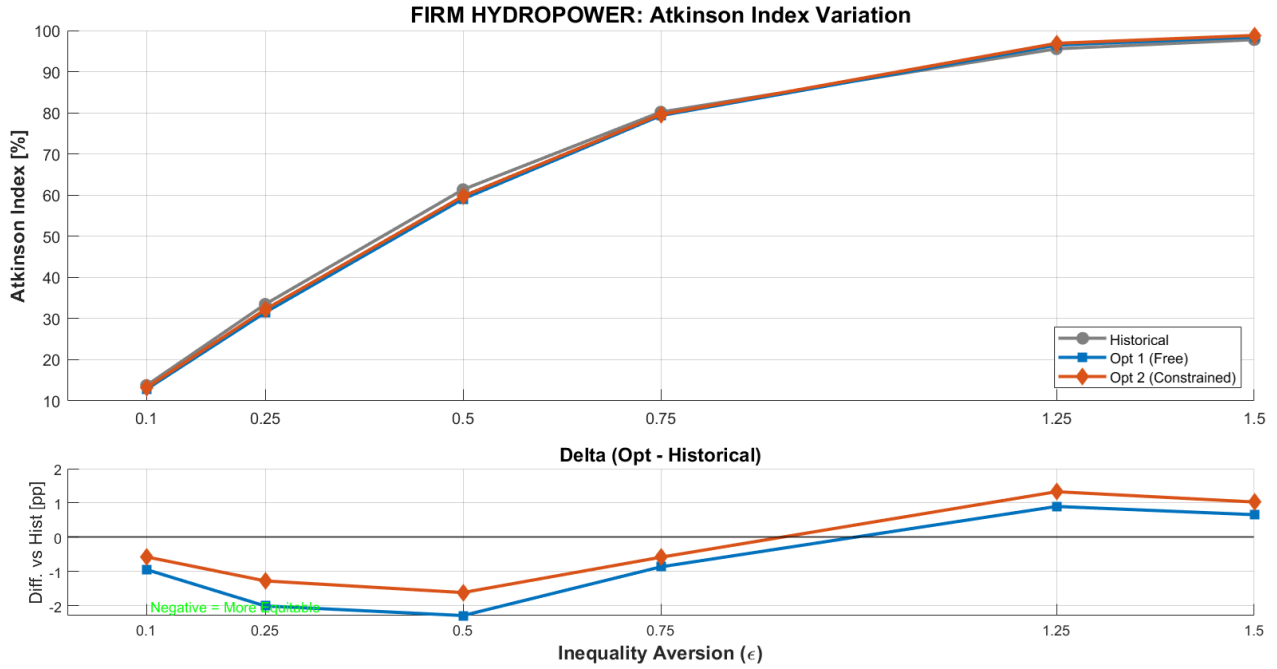


Figure 4.9: Atkinson index variation for firm hydropower

These data points reveal what can be defined as the Paradox of Apparent Equity. In scenario 2, an equality of opportunity (or infrastructural equity) was artificially mandated, capping each nation at a maximum of four reservoirs to preclude dominant geopolitical monopolies. Intuitively, one would expect this more balanced distribution of physical assets to engender a correspondingly fairer distribution of tangible outcomes. The Atkinson analysis, however, demonstrates the inverse: the system achieved greater outcome equity (specifically regarding firm hydropower) when permitted to freely concentrate resources at the most hydrologically efficient sites (scenario 1), rather than when coerced into geographic dispersion (scenario 2).

The underlying explanation is rooted in the physical nature of the water resource itself. Forcing the algorithmic selection of dams in geographically sub-optimal locations, solely to satisfy the national quotas of scenario 2, inherently degrades the overall efficiency of flow regulation. This systemic weakening of the hydrological "safety net" disproportionately impacts the weakest and most vulnerable actors within the basin, thereby rendering the ultimate risk distribution slightly more inequitable than in the scenario driven by pure efficiency.

In conclusion, this comparative analysis confronts decision-makers with a highly non-trivial policy dilemma:

- Scenario 1 maximizes both raw efficiency and substantive equity (the fairness of the actual results) but fundamentally fails to provide formal equity (by concentrating the vast majority of assets in Laos), thereby rendering it politically unfeasible.
- Scenario 2 guarantees formal equity (a fair physical distribution of dams) and maintains excellent operational performance, but it necessarily sacrifices a marginal degree of substantive equity relative to the theoretical systemic optimum.

Country-level analysis

This section provides a micro-level examination of the optimization outcomes, disaggregating the basin-wide data to evaluate the specific impacts on each riparian nation.

1. China (figure 4.10):

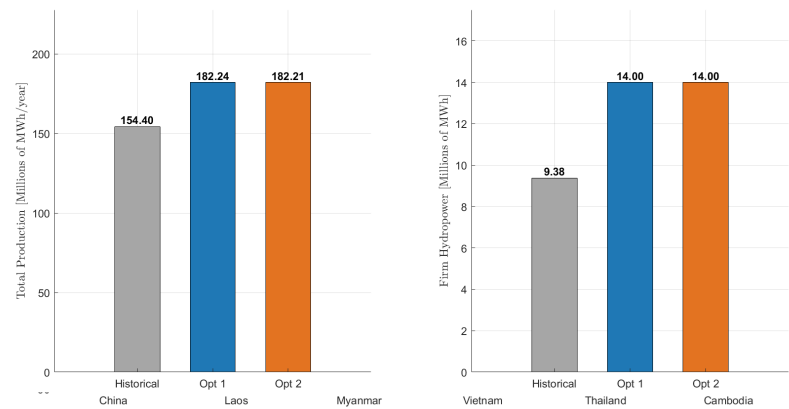


Figure 4.10: China: variations of production and firm hydropower

China’s profile underscores its dominant position within the basin. Total Production experiences a robust increase from the historical 154’401’288.60 GWh/year to over 180’000’000 GWh/year in both optimization scenarios. However, the most striking metric is its energy security. Firm hydropower leaps from 9’381.08 GWh to 14’001.68 GWh in optimization 1, a value that remains virtually identical in optimization 2 (14’001.68 GWh). This demonstrates that China’s upstream geographic advantage renders its energy security completely immune to the geographic constraints imposed in the second scenario. It remains the undisputed anchor of the basin’s power generation.

2. Laos (figure 4.11):

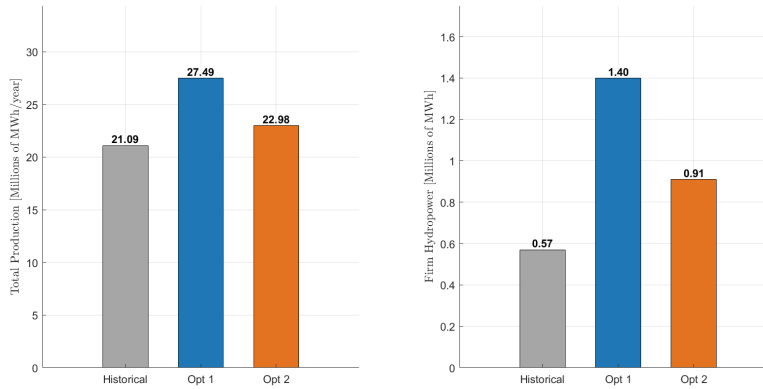


Figure 4.11: Laos: variations of production and firm hydropower

The data for Laos perfectly visually encapsulates the "battery" concept discussed in previous chapters. Under the unconstrained optimization 1, Laos experiences a massive surge: total production jumps from 21'092'104.27 to 27'493'977.73 GWh/year, and firm hydropower more than doubles, skyrocketing from 569.4 GWh to 1'399.5 GWh. However, optimization 2 severely penalizes Laos due to the 4 dam cap. While production drops back to 22'984 GWh/year, its firm hydropower takes a massive hit, falling to 909.8 GWh. Laos is the primary "donor" of systemic efficiency when political constraints are enforced.

3. Cambodia (figure 4.12):

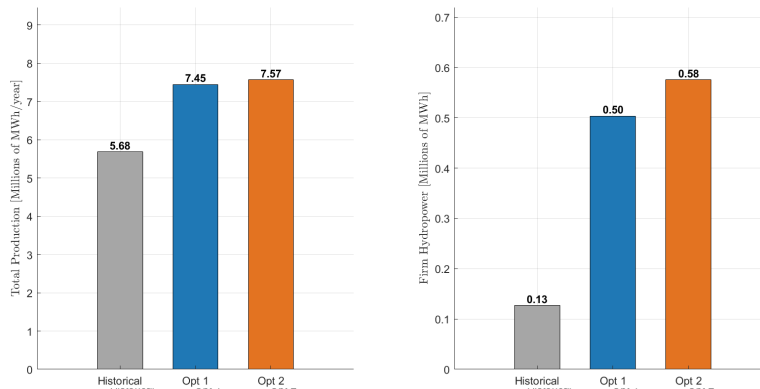


Figure 4.12: Cambodia: variations of production and firm hydropower

Cambodia emerges as the absolute greatest beneficiary of systemic coordination. While its total production grows steadily across the scenarios, its firm hydropower tells a story of transformation. From a vulnerable historical baseline of just 126.97 GWh, its guaranteed energy explodes to 503.41 GWh in optimization 1, and further increases to 575.81 GWh in optimization 2. The geopolitical constraint (opt 2) forces the system to invest in Cambodia's local infrastructure, making it the undeniable winner of the political compromise.

4. Vietnam (figure 4.13):

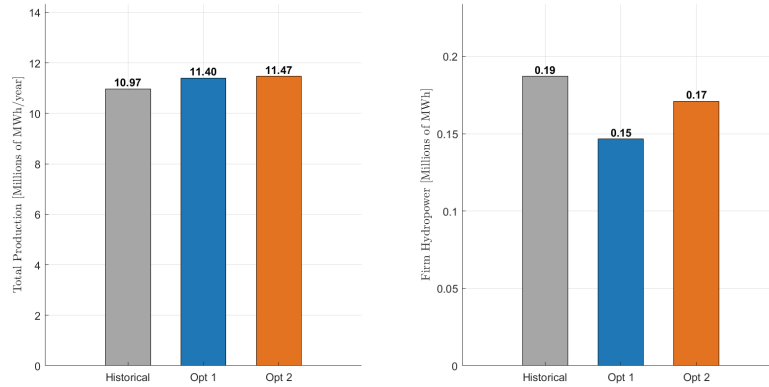


Figure 4.13: Vietnam: variations of production and firm hydropower

Vietnam's profile reveals the harsh realities of algorithmic trade-offs. Although it sees a slight, steady increase in Total Production, it pays a heavy price in terms of resilience. Its historical firm hydropower of 186.88 GWh drops significantly to 146.63 GWh under pure efficiency (optimization 1). While the political constraint of optimization 2 allows for a partial recovery (170.92 GWh), it still remains below the historical baseline. Vietnam represents a classic case where a state must sacrifice its own local security to facilitate the global optimum.

5. Thailand (figure 4.14):

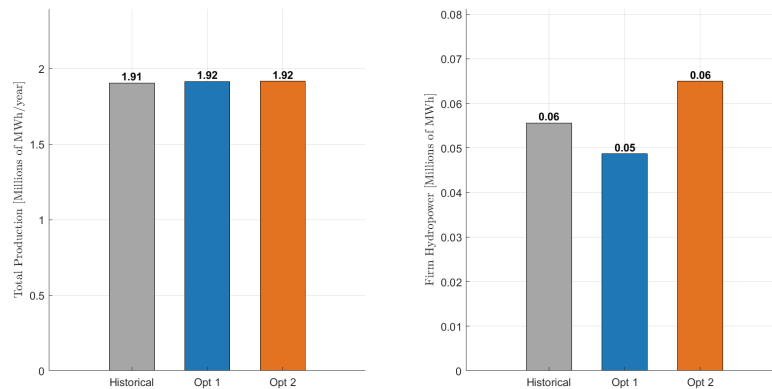


Figure 4.14: Thailand: variations of production and firm hydropower

Thailand exhibits a highly unique, fluctuating profile. Its total production remains remarkably static across all states. However, its firm hydropower is highly sensitive to the management paradigm. Under the pure efficiency of optimization 1, Thailand loses security. Yet, when geographic constraints are applied in optimization 2, it rebounds back,

surpassing its historical baseline. Thailand clearly benefits from a politically regulated system rather than a purely technocratic one.

6. Myanmar (figure 4.15):

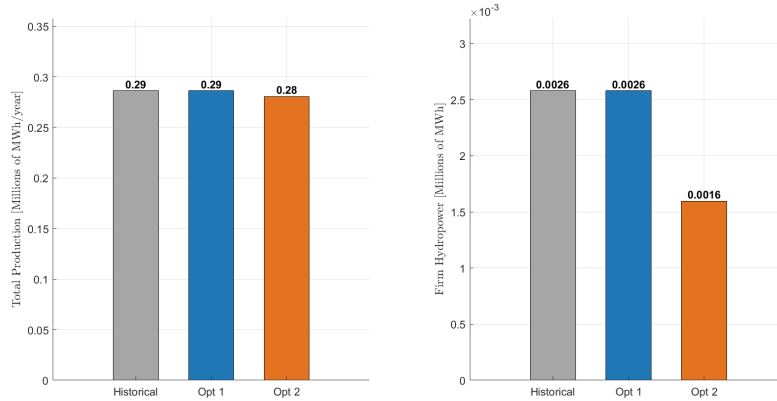


Figure 4.15: Myanmar: variations of production and firm hydropower

Myanmar remains the most marginal actor in the optimization framework. Its total production is negligible, dropping slightly. Its firm hydropower remains entirely unaffected by the unconstrained optimization 1. However, the forced inclusion mandated by optimization 2 proves highly detrimental, causing its guaranteed energy to collapse. Myanmar is the prime example of the "Paradox of Apparent Equity," where forcing infrastructure into suboptimal regions destroys local resilience.

Conclusions

An objective of this thesis was to ascertain whether the application of multi-objective optimization algorithms could structurally improve water resource management within the Mekong basin, thereby transcending the inherent limitations of historical practices. The empirical results obtained permit a definitive and affirmative response to this research question.

The analysis of the 2012–2022 period revealed that the status quo was afflicted by a systemic inefficiency so profound that it positioned the basin's operational state significantly below the optimal Pareto frontier. By capitalizing on this latent margin for improvement, both proposed optimization models generated a substantial "cooperation dividend": total hydroelectric production increased by between 16% and 18%, while systemic energy security (firm hydropower) registered a structural enhancement exceeding 50%. This outcome refutes the prevailing notion that, within the current geopolitical context of the Mekong, there exists an irreconcilable conflict between the maximization of energy pro-

duction and systemic security: coordinated algorithmic management effectively enables the simultaneous pursuit of both objectives.

However, the most salient contribution of this research lies in its critical analysis of systemic equity.

The results indicate that algorithmic optimization successfully mitigated inequalities in energy security (with the Atkinson index decreasing from the historical baseline of 61.35% to 59.07% in the unconstrained scenario). Nevertheless, it is imperative to emphasize that this improvement manifested as a positive spillover effect of maximized hydrological efficiency, rather than the intended outcome of a direct pursuit of social justice. The comparative analysis of the two scenarios demonstrates that imposing rigid geographic constraints (optimization 2, capped at four dams per country) does not automatically guarantee a substantive equity superior to that of the unconstrained scenario (optimization 1). Localized anomalies, such as Myanmar experiencing a 38% collapse in its energy security under the constrained model, starkly expose the inherent limitations of an indirect approach to equity.

The logical corollary is that if the overarching policy goal is to transform the Mekong into a genuinely equitable basin, it is insufficient to merely hope that hydrological efficiency will evenly distribute its dividends, nor is it adequate to impose rigid infrastructural quotas. Rather, as suggested by the forefront of current research, it is strictly necessary to integrate equity directly as a third objective function within the optimization algorithm itself. Only by mathematically treating equity as an endogenous variable, on par with energy production and security, will it be possible to architect solutions that strictly adhere to the no-harm principle, ensuring no riparian actor is disproportionately penalized.

In the absence of a fully equity driven multi-objective optimization, the findings of this thesis point toward a viable alternative policy framework: secondary compensation. The optimization models generated a massive energy surplus. This resulting economic surplus represents the crucial financial lever required to re-balance the geopolitical system.

Given that the unconstrained model (scenario 1) is both technically superior and, paradoxically, more equitable in terms of firm hydropower than its constrained counterpart, the recommended policy pathway would entail adopting the scenario of maximal hydrological efficiency (i.e., concentrating infrastructural production predominantly in Laos) while systematically utilizing the generated extra revenues to financially compensate those actors who either benefit the least or suffer from induced negative externalities.

Under this paradigm, engineering assumes the responsibility of maximizing the aggregate

production (efficiency), while political diplomacy and institutionalized Benefit Sharing mechanisms are tasked with divide the energy fairly (equity). Ultimately, this cooperative approach translates theoretical algorithmic gains into tangible, socio-economic well-being for all riparian nations within the basin.

5 | Conclusions and future research

This thesis addressed a critical challenges in transboundary water resource management: the quantification and optimization of distributive equity in the Mekong river basin. Through the integration of hydrological data, reservoir simulation models, and multi-objective evolutionary optimization algorithms (EMODPS), the study has gone beyond the qualitative approach typical of geopolitical analyses, providing a numerical assessment of current inefficiencies and latent opportunities for cooperation.

The retrospective analysis of the decade 2012-2022 provided the diagnosis of the status quo. Historical results confirmed the existence of an asymmetry in the basin management. In the context of the Mekong basin, upstream nations, China and Laos, exert primary physical control over the water resource, translating into asymmetric power dynamics relative to the downstream delta countries (Zeitoun and Warner, 2006).

The data confirm what was described in literature: the non-cooperation management of large upstream infrastructure, in particular the Lancang cascade in China and the tributaries in Laos, has been geared almost exclusively toward maximizing national energy profits, ignoring the hydrological repercussions on downstream riparian countries (Yu et al., 2024).

Consequently, historically, energy production and security have been characterized by a considerable lack of equity.

This lack of coordination has resulted in a sub-optimal system in two critical respects:

- **Production inefficiency:** the historical system has failed to exploit the temporal synergies between upstream releases and downstream demand, wasting significant energy potential.
- **Distributive inequity:** analysis of the equity indicator (Atkinson index) applied to historical data shows alarming disparities. While upstream countries have enjoyed stable and predictable production, lower Mekong countries, especially Cambodia and Vietnam, have suffered from flow volatility, with serious risks to energy

and agricultural security (confirming what is described in the literature (Yu et al., 2024)). The study shows that, historically, the absence of cooperation has acted as a multiplier of inequality.

The innovative core of the research lies in the results obtained through the first optimization. Comparing the historical scenario with the optimization scenario, the thesis reached a counterintuitive conclusion compared to the classical literature (Okun, 1975): in the Mekong basin, there is not necessarily a trade-off between efficiency and equity.

The optimization showed that coordinated management of releases throughout the basin can generate a surplus. The results indicate that it is possible to increase the system's total energy production (+18.75% compared to historical data) while improving the reliability of supply for the most vulnerable countries. Specifically, Cambodia saw its energy deficit reduced dramatically in the optimized simulations, benefiting from the optimized regulation of upstream flows.

This shows that the historical inequity is not an insurmountable physical constraint of the river system, but a direct consequence of inefficient management policies.

By increasing the overall energy production of the basin through technical cooperation, optimization has made it possible to distribute larger slices to all actors, reducing relative inequalities (improvement in the Atkinson index) without penalizing large producers.

Another important result emerges from the comparison with the constrained scenario, in which an attempt was made to impose fairness through rigid a priori operational restrictions. The analysis revealed that forcing equality through static engineering constraints reduces the flexibility of the system, leading to a decrease in overall production without generating proportional benefits in terms of distributive justice. This suggests that, in a complex context like the Mekong, without the use of a direct equity index as an objective function of the optimization, equity cannot be achieved by locking the system, but must emerge as a result of dynamic management that maximizes the use of water resources where it is most efficient.

In conclusion, this thesis suggests that energy security and equity in the Mekong basin can be pursued as compatible goals rather than mutually exclusive ones. The quantitative results offer an alternative to the traditional perspective (Yu et al., 2024), where the development of upstream countries comes at the expense of downstream nations. Instead, adopting a cooperative approach based on algorithmic optimization presents a viable pathway toward more balanced resource management.

The work highlights that achieving a fair and sustainable basin extends beyond technical and hydrological constraints, emphasizing the critical role of policy coordination and

cooperation. The tools developed in this study provide a solid scientific basis to support future cross-border negotiations, illustrating how a shift toward hydrological solidarity, together with international cooperation, represents one of the most promising pathways to significantly contribute to the long-term stability and prosperity for the entire region.

5.1. Further developments

Although the results of the optimizations conducted showed a cooperation dividend capable of improving both efficiency and equity compared to the historical status quo, the analysis highlighted that distributive equity emerged as a positive side effect of maximizing hydrological efficiency, rather than as a deliberate objective. To transform the Mekong basin into a truly equitable system, future research should move in two main directions:

- **Implementation of equity as an objective in optimization:** recent literature suggests that it is not enough to hope for an equitable distribution of efficiency dividends. A promising line of research is to directly integrate an equity indicator (such as the Atkinson index) as objective within the multi-objective optimization algorithm (epsilon-NSGA-II) (Yang et al., 2023).
 - Advantages of endogenous modeling: this approach would allow for the exploration of solutions that strictly adhere to the no-harm principle, ensuring that no riparian actor is disproportionately penalized.
 - Overcoming the trade-off: as demonstrated in the study on Lake Como cited in the state of the art (Yang et al., 2023), the explicit inclusion of an equity objective can generate a greater number of compromise solutions, mitigating conflicts between stakeholders and indirectly improving marginalized objectives as well.
- **Post-hoc policy and financial interventions:** if technical optimization fails to structurally resolve disparities, or if the most equitable solutions are technically less efficient, research should evaluate secondary compensation policy frameworks.
 - Benefit sharing mechanisms: optimization has been shown to generate a massive energy surplus. Future research could model how this economic surplus could be used as financial leverage to rebalance the geopolitical system, compensating nations that suffer negative externalities or benefit less from physical production.
 - Water-energy integration (DWECC): following the Dual Water-Electricity Co-

operation framework (Zhang et al., 2023), mechanisms could be explored in which electricity trade revenues are used to compensate for trade-offs in water allocation, simultaneously improving economic performance and resource equality.

In summary, the use of policies and programs aimed at increasing equity among stakeholders is a necessary step if we want to improve the current situation and achieve a more equitable basin in the long term.

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