Title: Macroeconomic impact of Climate change for a hydropower-led economy: A CGE analysis

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ABSTRACT

The study examines how climate change affects Bhutan's macroeconomy, with a focus on its hydropower sector. Hydropower has been the backbone of Bhutan's economy since the 1980s, playing a key role in economic growth, balance of payments and government finances. Although Bhutan is known for environmental preservation and is the first carbon-negative country, it remains vulnerable to climate shocks. Extreme weather events have been observed, yet their economic effects remain poorly understood. To address this, we built a recursive dynamic CGE model and a social accounting matrix tailored to Bhutan. The model incorporates seasonal differences in hydropower productivity and capital depreciation, and accounts for climate change effects on the broader economy. It differentiates between summer and winter electricity production to reflect seasonal hydro fluctuations and vulnerabilities. We simulated three scenarios until 2050: (i) decreased winter hydropower output due to less rainfall and snowfall, (ii) increased infrastructure depreciation from climate stress, and (iii) a combination of productivity decline and depreciation. Results indicate that productivity reductions alone have a limited economic impact, while increased depreciation causes significant effects across the economy. It lowers electricity output and exports, increases winter electricity imports, and raises investment needs to sustain hydropower capacity, thereby crowding out private-sector investments elsewhere. Consequently, economic growth slows, and government revenue declines. The findings highlight Bhutan's growing macroeconomic risk from climate change, driven by dependence on hydropower. They emphasize the importance of diversification, climate-resilient infrastructure, and the establishment of a resilience fund for future disasters.

Keywords: CGE, Hydropower, Economic growth, Climate change, monsoon, Macroeconomic simulation.

1. INTRODUCTION

Situated in the foothills of the eastern Himalayan region, Bhutan is endowed with significant water resources, enabling the country to pursue major hydroelectric development, mainly through run-of-the-river schemes. While the first hydropower plant started with the construction of a 360-kilowatt (kW) power plant in Thimphu in 1967, followed by the construction of various mini-hydropower plants in five Dzongkhags (Tshering & Tamang, 2004), the major development of the hydropower project came with the construction of 336 Megawatt (MW) hydropower plant through a bilateral agreement with the Government of India. Since then, hydropower has become the main source of electricity and a major driver of the economy as shown in Figure 1.

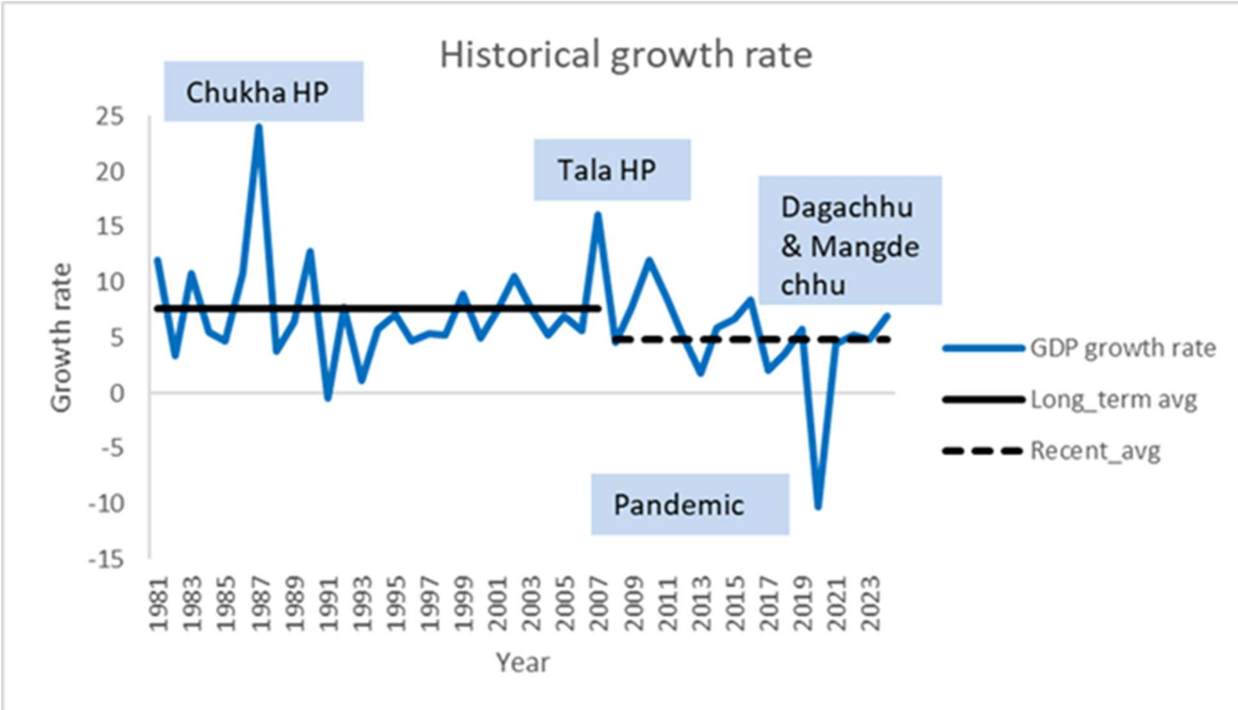


Figure 1: Historical growth rate and major growth episode

Bhutan's electricity is powered by green and renewable energy sources, which is predominantly based on hydropower generation. As of June 2024, the installed generation capacity of hydropower stands at 3,490 MW, with an estimated potential of up to 33,000 MW (Ministry of Energy and Natural Resources[MoENR], 2025). Solar and wind energy account for a marginal share of the energy mix, with contributions of about 6 MW.

As the industrial composition within the economy shifts, including the lifestyle of households, in recent years, the domestic energy demand has also increased rapidly - by more than 100% since 2022 - and is projected to further increase in the medium term.[1] Against this backdrop of increasing demand and untapped hydropower potential, the renewable energy roadmap 2040 proposes expanding hydropower capacity by an additional 11,008 MW between 2024 and 2034 and 4,304 MW between 2034 and 2024, thereby quadrupling the installed capacity by 2040 (MoENR, 2024).

The additional generation capacity would not only meet the rising demand but also enhance foreign exchange earnings through exports. Financing these projects will also require substantial external resources, which come with their own financial and macroeconomic risks. Beyond this, a major emerging challenge for the sector is the impact of climate change on hydropower generation and, consequently, on the broader economy. As hydropower relies heavily on river flows, which depend on both glacial melt and rainfall, it remains highly vulnerable to changing climate conditions.

Under the RCP 8.5 scenario, rainfall is anticipated to decrease by 0.9% on average during the winter months over the 2021-2050 period, which could reduce production capacity during this already dry season and increase dependence on energy imports (National Center For Hydrology and Meteorology, [NCHM] 2019).

[1] DMDF, FY 2025-26, Q1 MEF file

Furthermore, glacial melt and increased heavy rains during the monsoon are expected to increase sediments and maintenance costs as hydropower equipment and infrastructure deteriorate more rapidly.

Typically, in Bhutan, the monsoon season, between June and September, receives more than 70% of the annual rainfall (NCHM, 2026); as a result, damage to infrastructure is most severe during this season. The climate change projection report (NCHM, 2026) projects that by 2040, annual rainfall will decrease slightly in eastern Bhutan, while in the rest of the country, it is likely to increase under the worst-case scenario and remain similar by 2060. However, by 2100, the intensity of rainfall is projected to exceed the baseline (NCHM, 2026), thereby intensifying damage to infrastructure.

On the contrary, during the winter months (December to February), rainfall is typically lower, and mountain regions receive snow. NCHM (2026) reports that all regions in Bhutan are likely to experience increased rainfall compared to the baseline under all climate change scenarios until 2060. While it is projected that rainfall by 2100 will remain similar to that of 2060, the increase is likely to be smaller in northern and north-western districts.

Additionally, it is also reported that, due to increased climate change events, the glacier mass balance is also projected to become more negative (NCHM, 2026). The negative mass balance indicates increased glacial melting. Such development is also disastrous not just for the downstream settlements but also the hydropower infrastructure located downstream. The climate change project report (NCHM, 2026) projects that glaciers in the Wang Chhu, Manas Chhu and Punatsang Chhu basins are likely to be highly negative under RCP8.5. This trend is likely to be exacerbated by 2100. Consequently, the decreased glacier mass balance is likely to increase runoff in the basins initially but decrease in the long run. This poses a significant threat to livelihoods and the macroeconomy.

Given the importance of hydropower to Bhutan's economy and its vulnerability to climate risks, a dynamic CGE model is used to assess the impacts. The analysis uses the model to simulate the transmission of a climate change shock through the electricity sector and compares it with a counterfactual scenario in which it does not. Nonetheless, there are limitations to the tool, which cannot capture all effects, including estimates of climate change impacts.

The next section describes the data the CGE model relies on, while Section 3 outlines the model's main features. Section 4 presents both the reference scenario and the simulation results. The paper concludes with a policy recommendation.

2. DATA

Consistent with the supply and use tables (SUT), the social accounting matrix (SAM) of Bhutan considers 33 industries and 50 commodities (National Statistics Bureau, 2023).[2] The SAM distinguishes two categories of labor, salaried and self-employed, and two categories of households (urban and rural). The government accounts consider a variety of fiscal income sources: taxes on imports (customs duties, sales tax and green tax), taxes at the point of sale and excise duty, royalties and personal and corporate income taxes. The rest of the world account consists of the current debits and credits of the balance of payment. The firm's account is a hybrid account that receives the operating surplus net of consumption of fixed

[2] Although there are 48 commodities in the SUT, it has been agreed that electricity should be presented separately from other utilities. Also, electricity production/consumption was further split between summer and winter to account for the differences in precipitations. See appendix A for the list of sectors and commodities.

capital and of royalties, and property payments from other agents. Its expenditures basically consist of property income received by all other agents.

The SAM development uses the 2017 SUT [3] as the source of data for all industry and commodity accounts. For the other accounts, the main sources of information are data from the balance of payment, fiscal information from the Department of Macro-Fiscal and Development Finance (DMDF), and Bhutan Living Standard Survey reports[4].

Table 1 presents the hydro projects considered in the scenarios, while Table 2 shows how the projects affect installed capacity, along with the associated costs of their development and the future interest payments on the loans required for the development phase.

Table 1: Hydroelectric Projects

Project Name	Capacity (MW)	Operational year	Project Name	Capacity (MW)	Operational year
1. Punatsangchhu-I	1,200	2029	17. Sunkosh	4,060	2034
2. Punatsangchhu-II	1,020	2025	18. Yurmochhu	24	2030
3. Burgangchhu	54	2025	19. Wangchhu	900	2034
4. Yungichhu	32	2025	20. Parochhu	33	2030
5. Suchhu	18	2024	21. Gongri	740	2034
6. Jomori	90	2027	22. Jerichhu	1,800	2034
7. Druk Bindu-I	18	2026	23. Dangchhu	170	2032
8. Druk Bindu-II	8	2026	24. Sherichhu	53	2031
9. Gamri-I	54	2027	25. Jigmechhu	64	2031
10. Begana	25	2027	26. Komachhu	363	2033
11. Kholongchhu	600	2029	27. Jongthang	237	2033
12. Dorjilung	1,125	2031	28. Kuri-Gongri	2800	2039
13. Gamri-II	85	2029	29. Dorokha	550	2035
14. Bunakha	180	2032	30. Chamkharchhu-II	590	2037
15. Nyera Amari-I & II	404	2031	31. Chamkharchhy-IV	364	2038

Source: DMDF

Table 2: Annual Data

	Installed capacity (MW)	Capital costs (M Nu.)	Interest payment (M Nu.)
2024	2,462	13,871	2,952
2025	3,568	29,628	3,179
2026	3,594	62,526	5,057
2027	3,763	115,763	7,154
2028	3,763	141,986	7,796
2029	5,648	164,883	12,578
2030	5,705	175,395	15,915

[3] https://www.nsb.gov.bt/download/11979/

[4] National Statistics Bureau of Bhutan (2017) and (2022)

2031	7,351	215,494	16,467
2032	8,471	224,538	16,519
2033	9,071	212,088	22,985
2034	16,571	168,658	22,779
2035	17,121	78,572	51,292
2036	17,121	70,177	49,706
2037	17,711	55,249	46,014
2038	18,075	41,415	43,466
2039	20,875	34,098	41,937
2040	20,875	13,871	46,806

Source: DMDF

In addition to the above data, we also set a list of parameters exogenously as presented in Table 3.

Table 3: List of parameters

Category	Description	Parameter	Value	Source/Remarks
Production	CES Elasticities between labor and capital index by industry	σ_j^{VA}		Bhattacharya et al (2018)
		Agriculture	0.78	
		Mining	0.96	
		Metal	0.96	
		Manufacturing	0.96	
		Petroleum product	0.96	
		Electricity	0.91	
		Consumer retail	0.39	
		Other	0.59	
Trade	Armington elasticities between imports and domestic production index by commodities	σ_i^M		Bhattacharya et al (2018)
		Agriculture	2.28	
		Mining	0.65	
		Metals	0.65	
		Manufacturing	0.91	
		Petroleum product	0.61	

		Other	0.99		
Trade	CET elasticity between exports and domestic production	σ_i^X			
		All commodities	0.24		Dorji (2023)
Households	LES Income elasticities for different food subcategories indexed by households	**sigma_Y(i,h)**	***Rural***	***Urban***	Minten, B. and Dukpa, C. (2010)
		Cereals/pulses	0.37	0.25	
		Dairy	0.61	0.32	
		Fish/meat	0.55	0.37	
		Fruit	0.5	0.32	
		Vegetables	0.4	0.25	
		Beverages	0.5	0.38	
		Oil	0.34	0.26	
		Spices	0.35	0.29	
		Other food	0.97	0.65	
	Frisch parameter	Frisch		-2.5	Shutes et al 2023
	Income elasticity values	Agriculture, livestock, and processed food		0.4	
		Forestry, mining and manufacturing		1.5	
		Fuels and electricity		2.2	
		Construction		1.2	
		Utilities, trade, transport, communications, and services		2.2	

3. METHODOLOGY

The model used is an adaptation of the PEP 1-t standard model.[5,6] It is a recursive dynamic CGE model: each period is solved as a static equilibrium, subject to the variables inherited from the preceding period.

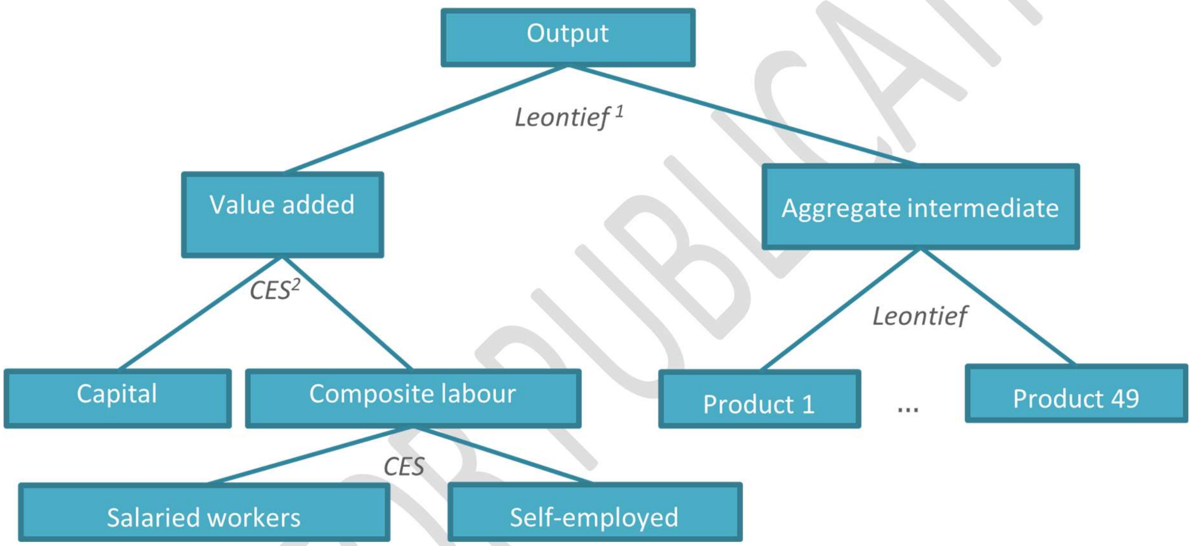
[5] For a description of the PEP 1-t model see Decaluwé et al. (of climate change on productivity, a climate change factor is added to the value-added equation and set to zero for all sectors except electricity in the2013)

[6] Equations and variables are presented in Appendix B. For a complete description of the model see Robichaud (2025).

In each period, firms are assumed to operate in a perfectly competitive environment. They maximize their profits, subject to their production technology, and consider commodity and factor prices as given (price-taking behavior). Figure 2 describes the nested structure of production.[7]

To account for the impact of climate change on productivity, a climate change factor is added to the value-added equation and set to zero for all sectors except electricity in the simulation. Also, since electricity consumption projections show a sharp increase in the coming years, reflecting the development of more energy-intensive industries, we introduce an adjustment factor in the intermediate demand function[8] that is computed endogenously in the reference scenario so that the electricity consumption path matches the projection. Under simulation, however, electricity demand is endogenous, and the adjustment factor is set exogenously. In addition, a dummy variable is introduced to allow the exclusion of specific sectors.

Figure 2: Nested Production Structure



[1] Leontief function: inputs are not substitutable (perfect complement)
[2] CES: Constant Elasticity of Substitution: inputs are imperfect substitutes

Industries can produce more than one product that can either be sold on the domestic market or exported. This supply behavior is represented by nested constant elasticity of transformation (CET) functions: on the upper level, aggregate output is allocated to individual products; on the lower level, the supply of each product is distributed between the domestic market and exports. Buyer behavior is symmetrical to producer behavior: it is assumed that goods are heterogeneous with respect to their origin.

To account for the particularities of the electricity market, the electricity production has been split between summer production (May to October) and winter production (November to April). The same has been done on the commodity side. It is assumed that the domestic price is exogenous throughout the year. During the

[7] Such nested structures are common in CGE models and it is usually expected inputs are better substitutes to one another at lower levels of the hierarchy.
[8] See equation X7

summer, suppliers provide whatever quantity is domestically demanded at that given price, and whatever quantity is left is then exported. During winter, a fixed share of electricity is exported, and the rest is sold on the domestic market. If ever demand during winter exceeds domestic supply, electricity will be imported.

The demand for goods and services consists of intermediate demand, household consumption demand, investment demand, public administration demand, and demand for transport or trade margins. Households' demand is derived from Stone-Geary utility functions, which include a minimum level of consumption for each commodity. The overall budget for government current expenditures in goods and services is distributed among education, health and public administration in fixed shares. Demand for investment purposes includes both gross fixed capital formation (GFCF) and changes in inventories (exogenous). Investment is savings-driven, and total savings, net of inventory changes, are allocated to commodities in fixed shares.

In each region (rural or urban), households are endowed with an exogenous amount of labor they can supply on the market. They can either work in Bhutan or outside the country, and they base their decision on the wage rate they can get in each market. A CET function is used here to represent any friction workers can face. The wage rates a worker can earn for his work outside Bhutan are exogenous, while the wage they earn in Bhutan is determined by market conditions. Unemployment is modeled through a wage-curve.[9]

The stock of capital in each industry at a given period is equal to the stock of the preceding period, minus depreciation, plus the volume of new capital investment in the preceding period. Additional depreciation due to climate change is also considered and set to zero in the reference scenario. The hypothesis is that new capital comes online one period after the investment has been made. Investment in public industries (health, education and public administration) is exogenous. For all other sectors, the allocation of new private capital between categories and industries follows a modified version of the Jung-Thorbecke (2001) investment demand specification, so the volume of new capital allocated to an industry is proportional to the existing stock of capital and the proportion varies according to the ratio of the rental rate to the user cost of that capital, which may be interpreted as Tobin's *q*.

To accumulate capital in the electricity sector, projected hydropower developments through 2039 are imposed. Indeed, annual capacity growth is not linked to the investment made in a given year but rather to investments sustained over several years. Thus, for the electricity sector only, both investment and capital stock are exogenous for the 2017-2039 period. The investment required to achieve the realization of additional hydropower infrastructure is financed through external funds, and most of the resources required (workers, machinery, material, etc.) is expected to come from outside Bhutan, with a third of the resources required for the development of hydroelectric infrastructures to be provided domestically. Part of the total savings in the economy is thus devoted to these projects and would not be available for the development of other industries. This amount is exogenous for the same period (2017-2039).

After this development phase, capital stock in the electricity sector remains unchanged, with investment set to cover infrastructure depreciation. Hence, overall capital stock remains at the same level for the 2039-2040 period, unless there is an impact from climate change, in which case, there is a one-period lag in

[9] Blanchflower and Oswald (1995)

repairing the infrastructure. Of course, electricity production during summer and winter uses the same infrastructure.

The current government budget surplus or deficit (positive or negative savings) is the difference between its revenue and its expenditures. The latter consists of transfers to agents, including interest payments related to the development of the electricity sector, and current expenditures on goods and services. Royalties collected on natural resources are considered, and thus, the hydropower development will affect the amount received by the government. In the current closure of the government account, real current expenditures on goods and services are fixed, and any variation in the government income will translate into a change in its surplus/deficit.

The rest of the world receives payments for the value of imports, part of the income of labor (foreigners working in Bhutan) and transfers from domestic agents – including the payment of interest – whereas foreign spending in the domestic economy consists of the value of exports, transfers to domestic agents and payments to Bhutanese working abroad. The difference between foreign receipts and spending is the amount of rest-of-the-world savings, which are equal in absolute value to the current account balance, but of opposite sign. In the current closure, the current account balance is exogenous, and the nominal exchange rate is the numeraire.

Supply and demand equilibrium must be verified for the goods and services market and for the factors of production market. Prices are thus determined endogenously in the model to clear markets, except for electricity, whose price is assumed to be exogenous. Electricity producers first satisfy the domestic market, and whatever is left is exported. All world prices are fixed, and it is assumed that Bhutanese producers can export as much as they want at world prices (small country assumption).

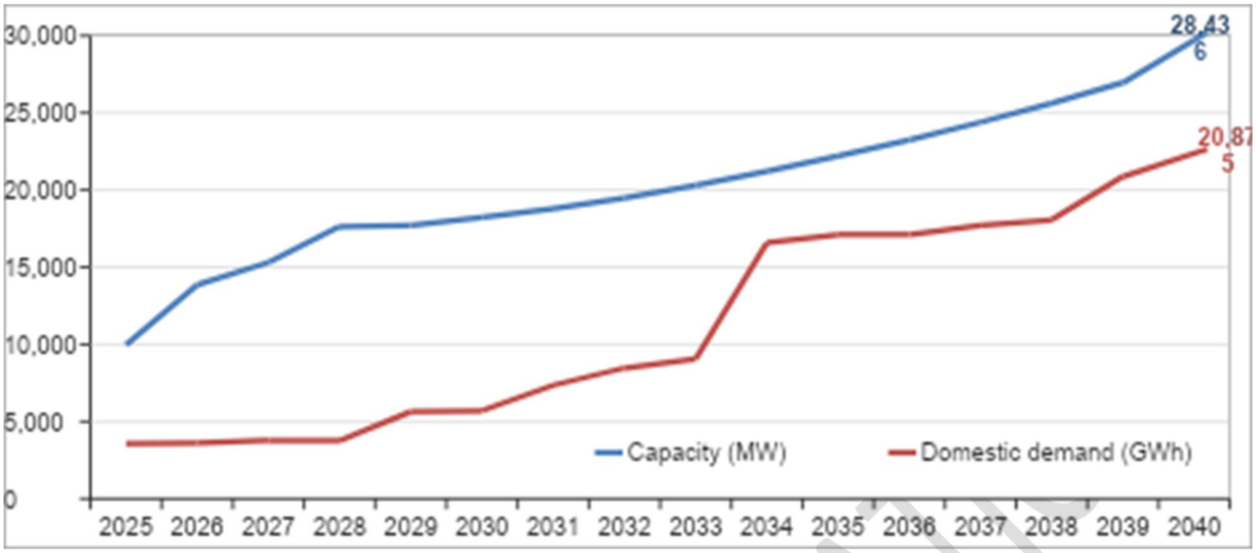
4. SCENARIOS AND RESULTS

REFERENCE SCENARIO

The reference scenario describes the path the economy would follow if new hydropower projects, as per the renewable energy roadmap 2040, come online, as presented in the previous tables, and if there is no climate change impact on electricity production. It is also assumed that 30 percent of the resources required for the construction of the new hydropower infrastructures will be sourced from the domestic market, and the domestic energy demand evolves over time as per the DMDF projection. Under simulation, however, domestic energy demand is not exogenous; it adjusts to the introduced shock.

The installed capacity of the hydroelectricity projects and the domestic demand under the reference scenario is highlighted in Figure 3.

Figure 3: Installed capacity (MW)and domestic energy demand (GWh)



Source: DMDF

SIMULATION SCENARIOS

As electricity production is linked to rainfall, which is expected to decline during the winter season, we simulated a decrease in electricity sector productivity during this season. The decrease is introduced gradually through a cumulative annual productivity shock of -0.01% starting in 2030, and -0.02% from 2040 onward.

Climate change is also assumed to negatively affect the capital stock in the electricity sector, as extreme weather events lead to more frequent repairs and maintenance. To account for the gradual deterioration of physical assets due to climate-related stress (e.g., increased maintenance needs, reduced equipment lifespans, and weather-induced damage), we assumed that climate change would result in a 1% annual depreciation of infrastructure and equipment starting in 2040.

Overall, we consider three scenarios: a change in productivity due to climate change, a change in asset depreciation due to climate change and a combined shock as indicated in Table 3:

Table 4: Simulation Scenarios

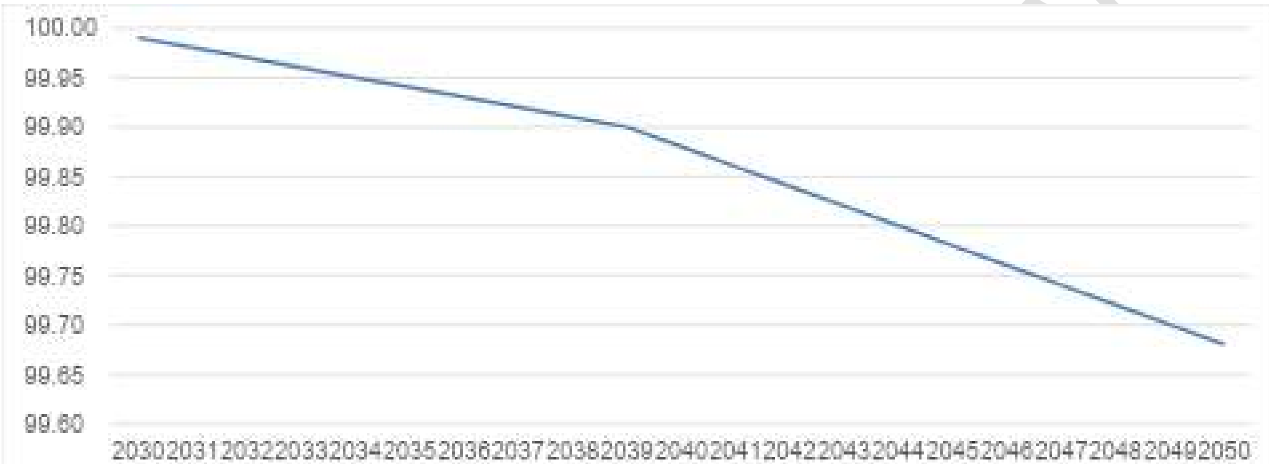
Scenarios		**Description**	**2030**	**2040**	**2050**
SIM_1		Change in productivity in the electricity sector during winter	-0.01%	-0.02%	-0.02%
SIM_2		Change in asset depreciation	—	1%	1%
SIM_3		Change in productivity in the electricity sector during winter	-0.01%	-0.02%	-0.02%
	+	Change in asset depreciation	—	1%	1%

SIMULATION RESULTS

Impact on the electricity sector

The productivity shock in the electricity-winter sector affects the climate change factor within the sector. As such, under SIM_1 and SIM_3, the climate change factor declines gradually over time relative to the reference scenario, with an additional drop after 2040 as highlighted in Figure 4.

Figure 4: Climate Change Factor
(reference = 100)



Source: Computed from the CGE model results

The impact on productivity at the end of the simulation period is approximately -0.3%, which is rather small; thus, our analysis could be considered minimal. On the other hand, changes in asset depreciation increase the electricity sector's depreciation rate, which affects the capital stock and the investment required to maintain production capacity, as indicated in Table 4. Indeed, the additional costs of maintaining the infrastructure represent about a 30% increase in annual maintenance costs compared to the reference scenario.

Table 5: Impact on capital stock and investment level
(in percentage change from reference scenario)

	CAPITAL STOCK IN THE ELECTRICITY SECTOR			INVESTMENT IN THE ELECTRICITY SECTOR		
	SIM_1	SIM_2	SIM_3	SIM_1	SIM_2	SIM_3
2041	-	-1.0	-1.0	-	30.7	30.7
2045	-	-1.0	-1.0	-	30.7	30.7
2050	-	-1.0	-1.0	-	30.7	30.7

Source: Computed from the CGE model results

Reduced productivity in the electricity sector during winter has a direct negative impact on value added, while the higher depreciation rate of capital further reduces the production capacity of existing hydroelectric infrastructure throughout the year. As shown in Table 5, under SIM_1, where only the productivity shock is applied, electricity production during the winter season is below what it would have been under the reference scenario, and this gap increases progressively from –0.01% in 2030 to –0.34% by 2050 relative to the reference scenario, while electricity production during summer is not affected. Under SIM_2, which captures the impact of increased asset depreciation, electricity production declines more sharply during winter and summer, from –0.26% in 2040 to –1.14% by 2050. The combined effects in SIM_3, incorporating both productivity and capital depreciation shocks, result in a reduced electricity production compared to the reference scenario throughout the year. Electricity production during winter is below the reference level (from –0.01% in 2030 to –1.48% by 2050), while production during summer is less affected (up to -1.14% in 2050).

Table 6: Impact on electricity production and exports
(in percentage change from reference scenario)

	During winter			During summer		
Production	SIM_1	SIM_2	SIM_3	SIM_1	SIM_2	SIM_3
2030	-0.01	-	-0.01	-	-	-
2035	-0.06	-	-0.06	-	-	-
2040	-0.13	-0.26	-0.39	-	-0.27	-0.26
2045	-0.23	-1.09	-1.32	-	-1.09	-1.09
2050	-0.34	-1.14	-1.48	-	-1.14	-1.14
Exports						
2030	-0.01	-	-0.01	-	-	-
2035	-0.06	-	-0.06	-	-	-
2040	-0.13	-0.26	-0.39	-	-0.35	-0.35
2045	-0.23	-1.09	-1.32	-	-1.36	-1.35
2050	-0.34	-1.14	-1.48	-	-1.44	-1.43

Source: Computed from the CGE model results

As expected, reduced electricity production relative to the reference scenario translates into lower exports. As exports are a fixed share of output during winter, the impact on exports is the same as the impact on total production. During the summer, whatever remains after meeting domestic demand is exported; thus, the decline is slightly higher than the fall in production.

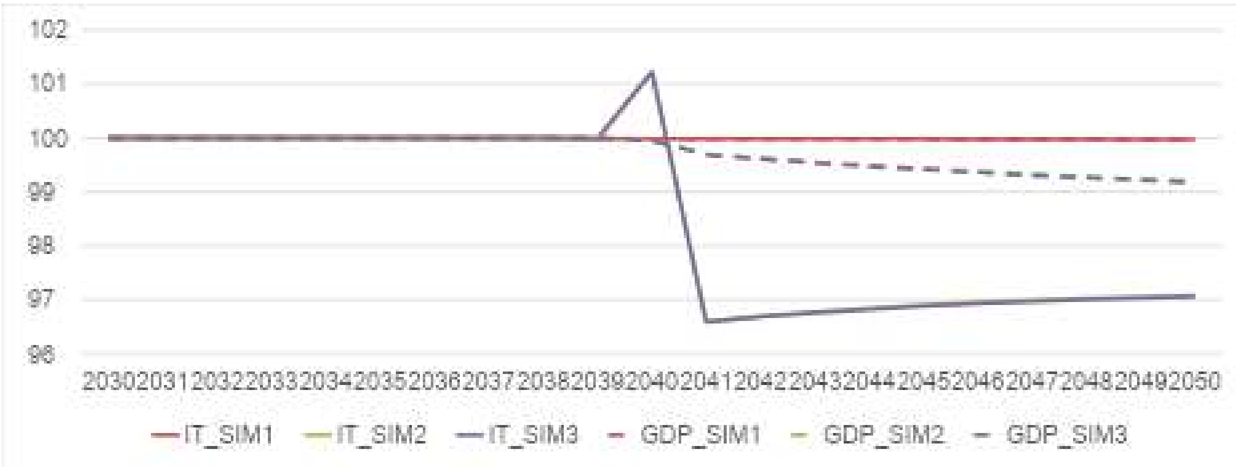
Impact on private investment and GDP

The overall impact on the economy depends on the relative importance of the electricity sector, which is projected to grow over time. In the reference scenario, the electricity sector accounts for 17% of total value added in 2025, rising to more than 25% by 2050, underscoring its importance in the economy. Hence, any adverse impact on the hydropower sector, through depreciation of productivity or capital stock, reduces output and profitability, ultimately leading to lower aggregate economic activity and investment.

Besides, as discussed earlier, increased depreciation leads to greater investment in the electricity sector to maintain infrastructure. This additional amount invested annually is not available for other investment purposes, and thus, the rest of the economy is deprived of the investment that would otherwise have taken place. Figure 5 shows the impact on real private investment, net of investment in the electricity sector, along with the impact on real GDP at basic prices.

While the loss of productivity has not much impact on either real investment nor real GDP, we see that the depreciation of physical assets in the electricity sector leads to investment levels below what they would have been in the reference case, reflecting a crowding-out effect as resources are reallocated from other private sectors toward the electricity sector for repairs and maintenance. This pattern constrains real capacity expansion and limits long-term growth potential, leading to GDP levels that are below the reference levels. Since productivity has little impact, the paths for SIM_2 and SIM_3 are the same.

Figure 5: Impact on non-electricity real private investment and real GDP at basic prices
(reference = 100)



Source: Computed from the CGE model results

Impact on electricity demand and imports

Unsurprisingly, demand for electricity throughout the year follows the same pattern as GDP, as shown in Table 6. The impact on demand is negligible for SIM_1, while electricity demand is slightly below what it would have been without climate change.

Table 7: Impact on demand for electricity
(in percentage change from reference scenario)

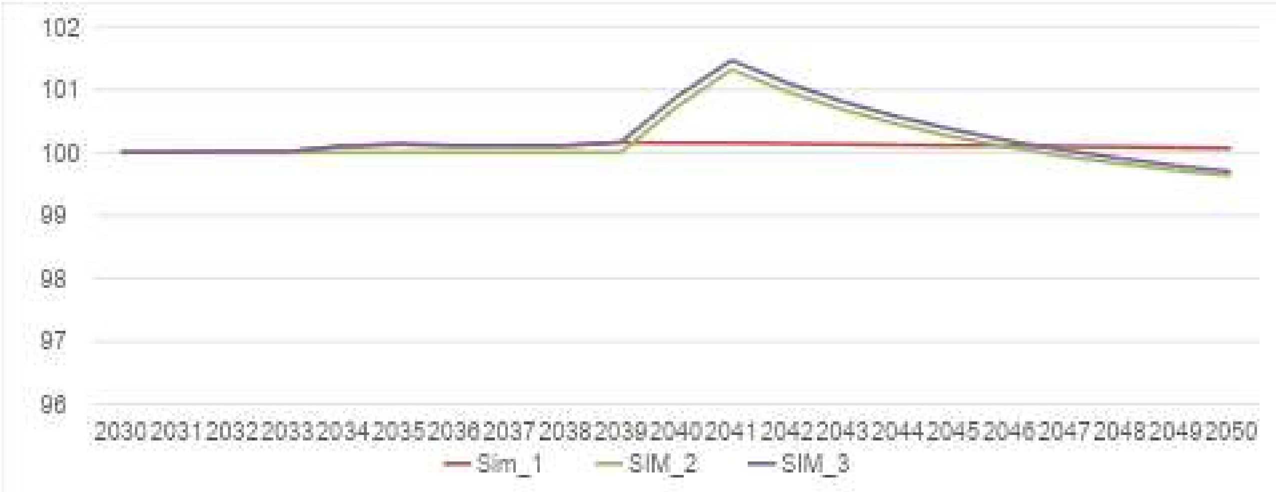
	DURING WINTER			DURING SUMMER		
	SIM_1	SIM_2	SIM_3	SIM_1	SIM_2	SIM_3
2030	0.00	-	-	-	-	-
2035	-0.02	-	-0.02	-	-	-
2040	-0.05	0.02	-0.03	-	0.02	0.01
2045	-0.08	-0.48	-0.56	-	-0.49	-0.49
2050	-0.10	-0.69	-0.79	-0.01	-0.69	-0.70

Source: Computed from the CGE model results

Imports are expected to rise to meet domestic demand. Consequently, the demand-supply gap is bridged through increased electricity imports during the winter months, as shown in Figure 6. Hence, under SIM_1, imports rise slightly, compared to the reference scenario, from 2030 onward to offset reduced domestic generation. In contrast, SIM_2 and SIM_3 show a sharp increase in electricity imports around 2040–2041, reflecting heightened pressure on domestic supply due to reduced productivity and higher capital depreciation in the electricity sector. From 2047 onward, the decrease in domestic demand outweighs the decline in production, and imports fall below what they would have been in the absence of climate change impacts.

Figure 6: Impact on electricity import during winter

(reference = 100)



Source: Computed from the CGE model results

Impact on government income

Loss of productivity results in lower profitability of the sector during winter. This, in turn, directly affects the amount of hydropower royalty revenue, subsequently impacting overall government income. As illustrated in Table 6, the royalties collected are below what they would have been without climate change, and the difference is greater after 2040 as the climate-induced stress intensifies: -0.35 %, -0.92% and -1.26% relative to the reference scenario under SIM_1, SIM_2 and SIM_3, respectively, by 2050.

Table 8: Impact on hydropower royalty and government income
(in percentage change from reference scenario)

	ROYALTIES			GOVERNMENT INCOME		
	SIM_1	**SIM_2**	**SIM-3**	**SIM_1**	**SIM_2**	**SIM_3**
2030	-0.01	-	-0.01	-	-	-
2035	-0.07	-	-0.07	-0.01	-	-0.01
2040	-0.13	0.17	0.04	-0.02	-1.67	-1.68
2045	-0.24	-0.93	-1.16	-0.03	-1.99	-2.02
2050	-0.35	-0.92	-1.26	-0.04	-1.70	-1.74

Source: Computed from the CGE model results

The decline in productivity and profitability in the hydropower sector results in lower government income, but electricity royalties constitute only a small portion of overall government income. Most of the impact on government income is thus driven by the overall economic activity. This explains why, until 2040, the decline in government income is lower than the rate of decline in hydropower royalty revenue. However, 2040 onward, under SIM_2 and SIM_3, the total government income declines at a much faster rate relative to the royalty revenue decline, reflecting not only the decline in hydropower royalties' revenue but also the impact from the contraction of economic activity and private investment, amplifying the government's revenue shortfall relative to the reference scenario.

Impact on households and the labor market

With reduced economic activity, unemployment across all labor categories increases marginally in all scenarios. The size of the impact across the different simulations follows the impact on GDP: a negligible impact under SIM_1 and greater impacts under SIM_2 and SIM_3. By 2050, the unemployment rate increases across all worker types, with the largest effect on urban workers, for whom the unemployment rate would be 0.26 and 0.43 percentage points higher for salaried workers and the self-employed, respectively, under SIM_3. The impact on rural workers is negligible across all scenarios.

Table 9: Impact on unemployment rate in 2050
(change in percentage points compared to the reference)

		Benchmark value	SIM_1	SIM_2	SIM_3
Urban	Salaried	4.6%	0.01	0.24	0.26
	Self-employed	4.6%	0.00	0.42	0.43
Rural	Salaried	0.8%	0.00	0.04	0.04
	Self-employed	0.8%	0.00	0.07	0.07

Source: Computed from the CGE model results

As unemployment rises and the economy slows, the household's disposable income is expected to be lower than it would have been in the reference scenario. Again, the impact is negligible under SIM_1 and greater under SIM_3. Table 9 shows that urban households' disposable income is expected to be 1.25% lower by 2050 relative to the reference case under SIM_3, while rural households would see a negligible decline of 0.16 %. Impacts on real consumption are similar to the ones on disposable income under SIM_1, but greater under SIM_2 and SIM_3, suggesting a slight increase in the consumer price index (CPI). This impact on CPI is driven by increased demand for investment goods (construction, equipment, etc.) needed to repair damage to hydropower infrastructure. Overall, urban households' real consumption is 2% below the reference level in 2050 under SIM_2 and SIM_3, while it is 0.4% lower for rural households.

Table 10: Impact on households
(in percentage change from reference scenario)

	URBAN HOUSEHOLDS			RURAL HOUSEHOLDS		
	SIM_1	**SIM_2**	**SIM_3**	**SIM_1**	**SIM_2**	**SIM_3**
Disposable income						
2035	-0.01	0.00	-0.01	-0.01	0.00	-0.01
2040	-0.02	-0.83	-0.84	-0.01	0.14	0.13
2045	-0.03	-1.32	-1.35	-0.02	-0.29	-0.31
2050	-0.03	-1.21	-1.25	-0.02	-0.14	-0.16
Real consumption						
2035	0.00	0.00	0.00	0.00	0.00	0.00
2040	-0.01	-1.01	-1.02	0.00	0.09	0.00
2045	-0.02	-1.74	-1.76	-0.01	-0.34	0.09
2050	-0.03	-1.97	-2.00	-0.01	-0.43	-0.35

Source: Computed from the CGE model results

POLICY RECOMMENDATIONS

In this paper, we evaluate the macroeconomic impacts climate change might have on the hydropower sector. The results highlight that climate-induced reductions in hydropower productivity and capital stock have broad economy-wide implications, affecting output, investment, fiscal revenues, and household welfare.

Overall, the loss in productivity and accelerated capital depreciation in the electricity sector lead to:

- A decline in electricity production during the winter months results in increased electricity imports to meet domestic demand.
- A decline in electricity exports throughout the year.
- Lower royalty revenues from hydropower generation, which directly reduce government income.
- Higher investment requirements in the electricity sector to replace damaged or depreciated infrastructure, while private investment in other sectors declines
- A gradual decline in real GDP
- Increase in unemployment across households, affecting households' real consumption.

Although the overall macroeconomic impacts remain moderate, the findings underscore the hydropower sector's critical role in sustaining long-term growth and fiscal stability. They also highlight the economy's vulnerability to climate-induced shocks and the need for policy responses that promote diversification and resilience. The government may consider channelling a portion of hydropower royalties or climate adaptation funds to support affected sectors, enhance private investment in non-energy activities, and reduce dependence on hydropower revenues to build a more balanced and climate-resilient economic structure**.**

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