Europe's Dying Battery: How to Ensure the Longevity of Hydropower in the Alps

I. Executive Summary

Stretching across 1,200 km, the Alps pass through eight different countries: France, Monaco, Italy, Switzerland, Liechtenstein, Germany, Austria, and Slovenia. In all of these, the vast mountain range serves as an economic hub of activity, a vital freshwater source, a cornerstone for biodiversity, and a premier source of energy by means of hydroelectric power. Despite this critical role, glacial retreat now jeopardizes regional stability. This paper proposes **three investor actions**—integrating hydrogeological risk assessments, climate scenario modeling, and relevant financial instruments — alongside **three government measures**: transnational hydropower audits, ecological corridor development, and glacier-grid vulnerability disclosures. Not only can these recommendations potentially stave off the imminent melting of glaciers in the Alps, but they can also provide avenues to strengthen climate resilience and protect infrastructure.

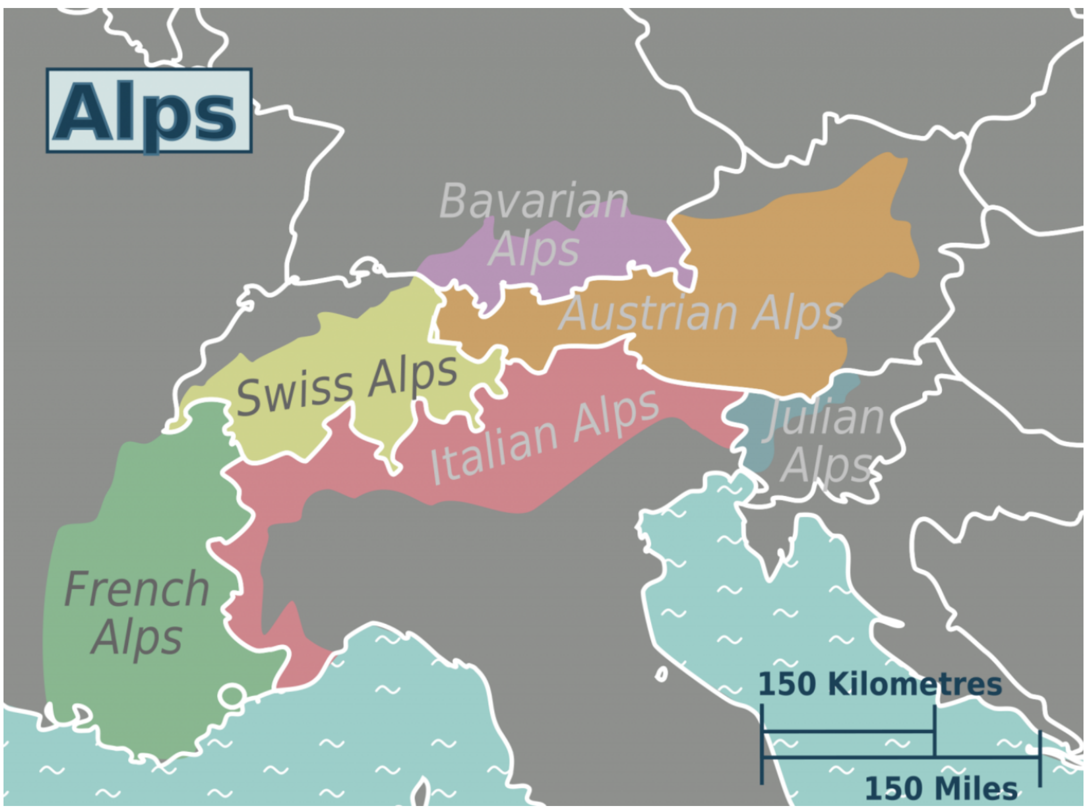

Figure 1: the Alps (map)[1]

[1] THE ALPS, OVERVIEW & FACTS. (2021). https://mountainsmagleb.com/2021/04/09/the-alps-overview-facts/

II. Alpine Countries' Reliance on Hydropower

Glacial meltwater sustains hydropower generation across Alpine nations by providing consistent year-round flow—a unique advantage now threatened by climate-driven ice loss. The country analyses below reveal how historical infrastructure investments collide with emerging environmental stresses, exposing interconnected vulnerabilities in Europe's "water battery."

Austria

During the Nazi regime, Austria was strategically designated as a "coal substitute energy base," leveraging its steep Alpine terrain to rapidly expand hydropower infrastructure. This foundational phase continued in the 1950s with the construction of large-scale dams under the Marshall Plan, establishing the structural framework for Austria's current network of 2,882 hydropower plants.[2]

Hydropower currently accounts for 64% of Austria's electricity generation (2016 figures), with projections indicating an increase to 74%. To date, 68% of the country's technically feasible hydropower potential has been developed, reflecting its heavy reliance on this renewable energy source.[3]

As Austria approaches the limits of its hydropower potential, new development of hydropower can cause tension with sustainability goals. Because of the heavily concentrated hydropower infrastructure in Austria, further expansion runs the risk of diverting water, reducing flow variability, and destroying aquatic ecosystems.[4] This means that preserving current systems and ensuring they are sustainable takes priority over generating new hydropower plants.

France

France's energy landscape has undergone significant transformations since the late 19th century, with hydropower playing a pivotal yet evolving role. During the Industrial Revolution, the country's surging energy demand, coupled with scarce domestic coal and oil reserves, drove the rapid development of over 20 hydroelectric plants along the upper Rhône River in the early 20th century.[5] These facilities became the cornerstone of southeastern France's electrification, powering both households and industrial operations while serving as a critical driver of industrialization.

However, the post-World War II strategic shift toward nuclear energy dramatically altered this dynamic. By 2016, nuclear power dominated France's electricity mix, accounting for 72.3% of total generation, while hydropower's contribution dwindled to just 12.2% (or 19.1% when including other renewables such as wind, biomass, and solar).[6] Most hydroelectric facilities were relegated to a secondary role, primarily operating as run-of-river (ROR) plants without storage capacity, which severely limited their ability to participate in grid balancing or energy storage.

[2] Wagner, B., Hauer, C., Schoder, A., & Habersack, H. (2015). A review of hydropower in Austria: Past, present and future development. *Renewable and Sustainable Energy Reviews*, 50, 304–314. https://doi.org/10.1016/j.rser.2015.04.169
[3] Wagner, B., Hauer, C., Schoder, A., & Habersack, H. A review of hydropower in Austria: Past, present and future development.
[4] Wagner, B., Hauer, C., Schoder, A., & Habersack, H. A review of hydropower in Austria: Past, present and future development.
[5] Piron, V. Hydropower and navigation development on the Rhône River (France). https://archive.iwlearn.net/mrcmekong.org/download/Presentations/regional-hydro/3.3%20CNR%20-%20MRC%20Regional%20Consultation%20sans%20comment.pdf
[6] Métais, L. (2019). Reaching 40 percent renewable electricity generation in France by 2030: How to combine boosting the economy and environmental sustainability. *The Public Sphere: Journal of Public Policy*. https://psj.lse.ac.uk/articles/79

The core dilemma lies in run-of-river (ROR) hydropower's dependence on stable flows—now threatened by glacial retreat causing summer generation volatility—while nuclear baseload demands constrain its peak-shaving role (i.e., supplying extra power during periods of high electricity demand), compounded by stalled modernization of aging infrastructure.

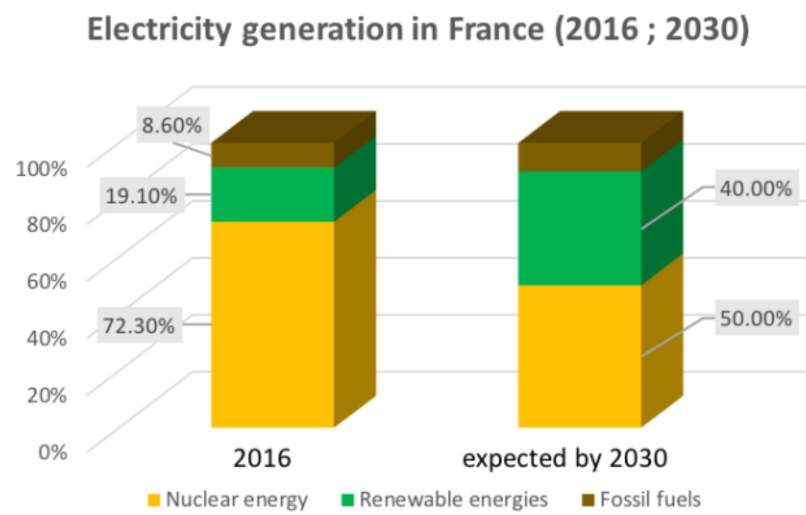

Figure 2: Electricity generation in France (2016,2030) [7]

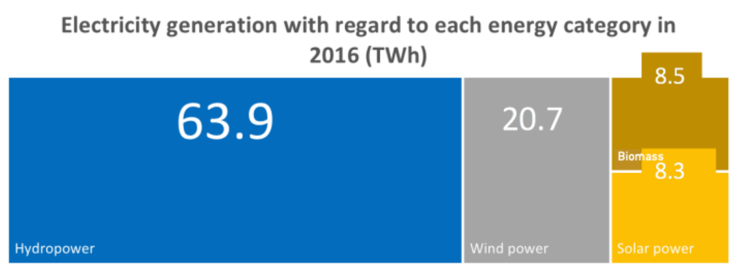

Figure 3: France's Electricity generation with regard to each energy category in 2016 [8]

Germany

Germany's hydropower sector has been shaped by historical contingencies and faces contemporary constraints. The devastating 1897 floods precipitated large-scale dam construction for flood control[9], while during the Nazi era, hydropower expansion was strategically pursued to conserve coal for synthetic fuel production to support the Luftwaffe.[10]

Currently, Germany's hydropower capacity has stayed stagnant over many years and has plateaued. Those capabilities have hovered around 5,500 MW, and the reason is that German hydropower potential

[7] Métais, L. Reaching 40 percent renewable electricity generation in France by 2030: How to combine boosting the economy and environmental sustainability.
[8] Métais, L. Reaching 40 percent renewable electricity generation in France by 2030: How to combine boosting the economy and environmental sustainability.
[9] Hobot, A. (2025). Hydroelectric dams in the Sudetenland until 1945 – a history that still protects us. https://wodnesprawy.pl/en/hydroelectric-dams-in-the-sudetenland-until-1945-a-history-that-still-protects-us/
[10] Marc Landry: Europe's Battery: The Alps in the Fossil Fuel Age. (2021). https://cla.umn.edu/austrian/news/marc-landry-europes-battery-alps-fossil-fuel-age

is "largely exhausted, or, where such potential still exists, the negative environmental impacts do not justify the construction of new power plants."[11]

Germany faces a hydropower dilemma: aging dams must adapt to glacial melt-induced flow variations, but new projects face strict environmental laws. Meanwhile, the AfD's (Alternative for Germany) push to revive nuclear and dismantle wind turbines highlights growing societal divisions over energy transition costs.[12]

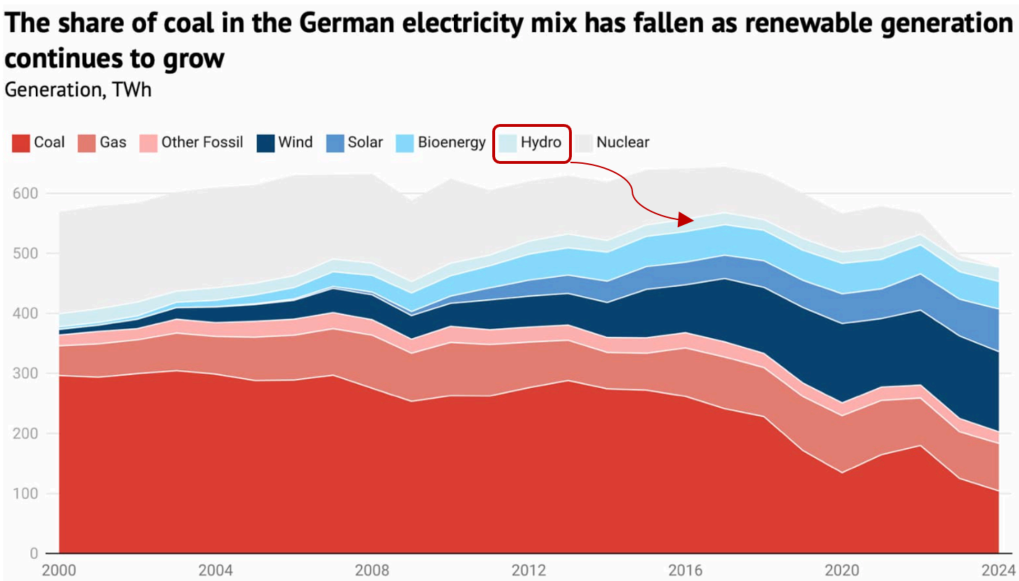

Figure 4: The share of the power structure in Germany[13]

Italy

The development of hydropower in Italy has been intrinsically linked to the country's industrial growth, with dam construction accelerating after World War I and consolidating following World War II. However, this expansion faced a dramatic turning point with the 1963 Vajont Dam disaster, which resulted in over 2,000 fatalities and exposed critical deficiencies in geological risk assessment.[14] This tragedy prompted significant improvements in safety standards and led to a marked slowdown in new dam construction.

Hydropower remains a cornerstone of Italy's energy system, accounting for a substantial share of national electricity production. In 2022, hydroelectric plants generated 48,200 GWh, representing 42% of the country's renewable energy output. This production has grown at an average of 0.5% per year from 2012 to 2020, which is lower than the global average growth rate of 2.8%.[15]

---

[11] Lehneis, R., Harnisch, F., and Thrän, D. (2024). Electricity Production Landscape of Run-of-River Power Plants in Germany. *Resources*, *13*(12), 174. https://doi.org/10.3390/resources13120174
[12] Q&A: What does the new German coalition government mean for climate and energy? (2025). RECCESSARY. https://www.reccessary.com/en/news/new-german-coalition-government-climate-energy-policy
[13] Q&A: What does the new German coalition government mean for climate and energy? RECCESSARY.
[14] Graf von Hardenberg, W. (2011). *Expecting disaster: The 1963 landslide of the Vajont Dam.* Arcadia, (8). Arcadia Collection: Technology and Expertise. https://www.environmentandsociety.org/arcadia/expecting-disaster-1963-landslide-vajont-dam
[15] Comoglio C., Castelluccio S., and Fiore, S, (2023). Environmental reporting in the hydropower sector: analysis of EMAS registered hydropower companies in Italy. *Front. Environ. Sci.* 11:1178037. https://doi.org/10.3389/fenvs.2023.1178037

While glacial melt accelerates sediment inflow, thereby increasing wear on aging turbines, Italy's hydropower sector faces an even more pressing challenge: its dam infrastructure—averaging over 65 years old—consequently requires urgent rehabilitation not only to maintain structural integrity but also to ensure continued functionality amid these compounding pressures.[16]

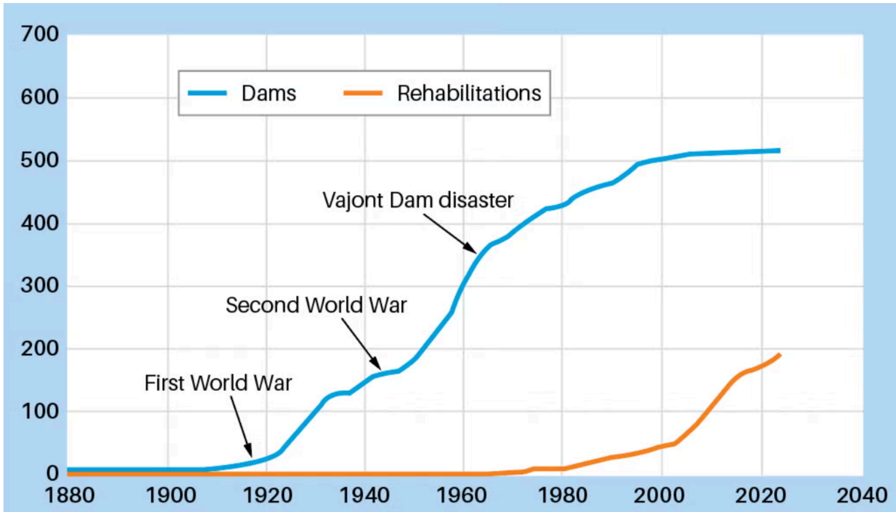

Figure 5: Comparison between the construction trend of dams in Italy and the trend of rehabilitation interventions[17]

Liechtenstein

Liechtenstein presents a unique case of early renewable energy adoption coupled with persistent external dependence. Since the 1920s, hydroelectric power has served as the principality's primary domestic energy source, utilizing environmentally sustainable run-of-river systems well-suited to its constrained topography.[18] However, the 1924 customs union with Switzerland institutionalized energy import dependence, which persists today with 90% of total consumption sourced externally from France and Switzerland.[19]

Remarkably, while domestic production accounts for merely 10% of national energy needs, hydropower generates approximately 75% of this share (66 GWh annually).[20] The sector retains significant untapped potential, with projections suggesting capacity could increase to 78 GWh through optimization of existing infrastructure.[21] This demonstrates both the limitations and opportunities of Liechtenstein's energy landscape - constrained by geography yet possessing underutilized renewable resources that could reduce import dependence.

[16] Stocks, C. (2025). Preserving Italy's dams: rehabilitation strategies for aging infrastructure. https://www.waterpowermagazine.com/analysis/preserving-italys-dams-rehabilitation-strategies-for-aging-infrastructure/
[17] Stocks, C. Preserving Italy's dams: rehabilitation strategies for aging infrastructure.
[18] Energy in Liechtenstein. Wikipedia. https://en.wikipedia.org/wiki/Energy_in_Liechtenstein
[19] Petra, W. (2024). Liechtenstein's dependency on imported energy. *EBSCO*. https://www.ebsco.com/research-starters/power-and-energy/liechtensteins-dependency-imported-energy
[20] Petra, W. Liechtenstein's dependency on imported energy. *EBSCO*.
[21] Petra, W. Liechtenstein's dependency on imported energy. *EBSCO*.

Monaco

The Principality of Monaco's extreme geographical constraints - a mere 3.3 km coastline spanning 195 hectares with maximum elevation of 163 meters - preclude conventional hydropower development due to absent altitude differentials and river systems.[22] This geographic determinism has created complete energy dependence, with nearly 100% of electricity imported from France's grid, exposing the microstate to external supply risks and European energy market volatility.[23]

Nevertheless, Monaco demonstrates surprising renewable potential within its spatial limitations. While traditional hydropower remains unfeasible, emerging technologies like building-integrated solar, micro-hydro systems, and tidal energy projects in reclaimed land developments (e.g., Portier Cove eco-district[24]) offer pathways to reduce energy vulnerability. These innovations highlight how microstates can leverage marine environments to mitigate geographic energy constraints.

Figure 6: Mareterra – Portier Cove.[25]

Slovenia

Slovenia's hydropower history dates back to the late 19th century, with early plants like Završnica (1915) and Fala (1918) laying the foundation for its modern energy system. Post-independence (1991), focus shifted to rehabilitating war-damaged infrastructure, slowing new hydropower development.[26]

[22] d'Hauteserre, A.-M. (2001). Bridging the culture–nature divide in Monaco. *Landscape and Urban Planning, 57*(3–4), 209–223. https://doi.org/10.1016/S0169-2046(01)00205-5
[23] Shirke, A. (2025). *Monaco's future sustainable energy*. https://www.abhijeetshirke.in/monacos-future-sustainable-energy/
[24] Mareterra – Portier Cove. https://www.lacosta-properties-monaco.com/en/monaco-districts/mareterra/
[25] Mareterra – Portier Cove. https://www.lacosta-properties-monaco.com/en/monaco-districts/mareterra/
[26] Hočevar, M., Novak, L., Drešar, P., & Rak, G. (2022). The Status Quo and Future of Hydropower in Slovenia. *Energies*, *15*(19), 6977. https://doi.org/10.3390/en15196977

In 2022, Slovenia's hydropower capacity was 1,265 MW, with predictions for it to grow to 1,310 MW by 2030.[27] While this number pales in comparison to other countries' capacities, hydropower does not make up a large majority of renewable energy production in Slovenia.

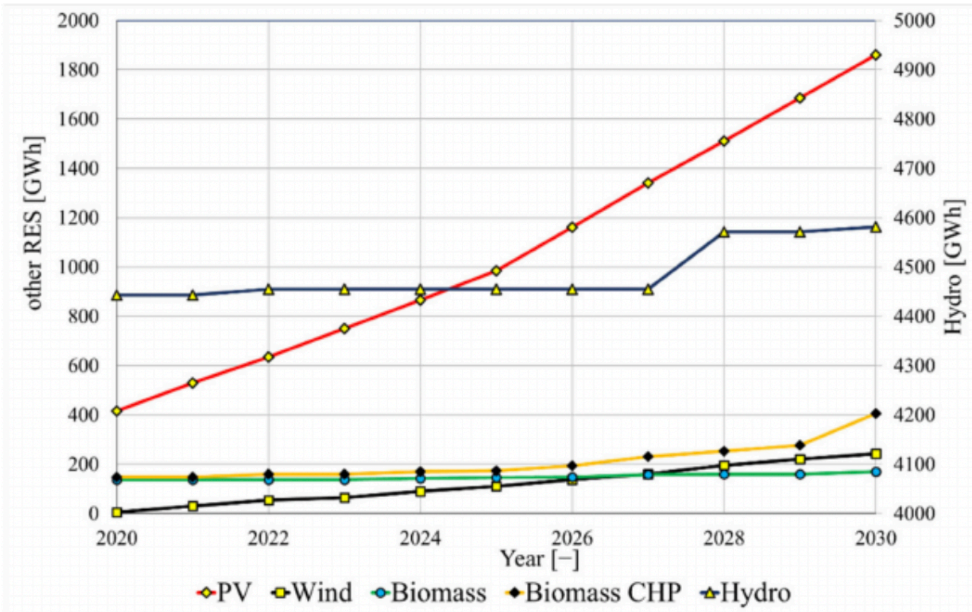

Figure 7: Assumed Renewable Energy Sources uptake in Slovenia from 2020 to 2030 according to NECP[28]

Rather, Slovenia focuses on its solar power capabilities (photovoltaic energy production, PV). Many Slovenian rivers (Sava and Ljubljanica, Drava, Soća and Idrijca, Mura, and Kolpa) have the potential to be great sources of hydropower, but similarly to Liechtenstein, the potential of these sources remains largely untapped, with only 41.5% of Slovenian hydropower potential being used.

Watercourse	Available (GWh/y)	Technically Available (GWh/y)	Used (GWh/y)	% of Use
Sava and Ljubljanica	4134	2794	512	18.5
Drava	4301	2896	2833	97.8
Soča and Idrijca	2417	1442	491	34
Mura	928	690	0	0
Kolpa	310	209	0	0
other	7370	1114	284	25.5
total	19,440	9145	4125	41.5

Figure 8: Energy potential of Slovenian rivers[29]

[27] Hočevar, M., Novak, L., Drešar, P., & Rak, G. The Status Quo and Future of Hydropower in Slovenia.
[28] Hočevar, M., Novak, L., Drešar, P., & Rak, G. The Status Quo and Future of Hydropower in Slovenia.
[29] Hočevar, M., Novak, L., Drešar, P., & Rak, G. The Status Quo and Future of Hydropower in Slovenia.

Switzerland

Switzerland's hydropower infrastructure was largely established between the 1950s and 1970s through extensive dam construction in the Alpine region. As of 2015, the country had 604 hydroelectric plants with capacities ≥300 kW, producing an average annual output of 36,031 GWh - with Alpine cantons contributing approximately 63% of total generation.[30]

Remarkably, over 95% of Switzerland's electricity derives from low-carbon sources, predominantly hydropower which supplies more than half of national demand, complemented by solid biomass.[31]

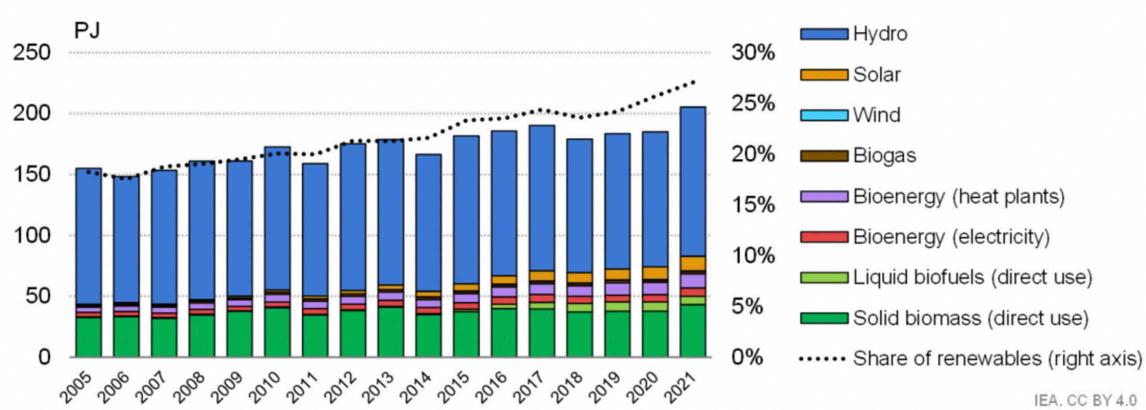

Figure 9: Renewable energy compared to total energy consumption in Switzerland[32]

In 2022, hydroelectricity accounted for 52.8% of domestic production and 54.6% of consumption, ranking Switzerland as Europe's sixth-largest hydropower producer with a 6% continental share.[33]

This well-developed system nevertheless faces emerging challenges from climate variability and the need for enhanced storage capacity to maintain grid stability amid increasing renewable integration.

III. The Problem

If European states are utilizing copious amounts of hydropower and are largely successful in doing so, where does the problem stem from?

The temperature increase from climate change only temporarily helps ROR hydropower stations. Through the increasing water flow from melted glaciers, there will be more production of energy for the time being. However, as glaciers continue to melt, this increase is unsustainable and will eventually come to a stop absent significant change in humanity's treatment of this valuable natural resource.

The warming effects of climate change force the glaciers in these mountain ranges to retreat upward. Rising temperatures reduce snow accumulation and lower-altitude ice, which means that only glaciers in higher elevations that still support ice formation survive. Current studies confirm that without drastic intervention, over 90% of Alpine glaciers will vanish by 2100. In Austria's Tyrol region—a proxy for the

[30] Hydropower in Switzerland. Wikipedia. https://en.wikipedia.org/wiki/Hydropower_in_Switzerland#cite_note-:0-2
[31] IEA (2023). Switzerland 2023: Energy Policy Review. *International Energy Agency.* https://iea.blob.core.windows.net/assets/b6451900-e6ef-45a8-922d-117520e09a82/Switzerland2023.pdf
[32] IEA. Switzerland 2023: Energy Policy Review. *International Energy Agency.*
[33] Hydropower in Switzerland. Wikipedia.

entire Alps—researchers warn that even limiting warming to 1.5°C may only preserve fragmented 'dead ice' remnants lacking glacial dynamics.[34] Five glaciers completely disappeared in the Ötztal and Stubaital regions between 2006 and 2017. Under the current trajectory of 2.7°C warming, one of the scientists notes 'the window of opportunity is closing very quickly.'[35]

The following figure depicts the volume of glaciers in the European Alps from 2003 to 2100 under three Representative Concentration Pathways (RCPs), which represent different greenhouse gas emission scenarios. RCP 2.6, the blue line, portrays the low-emissions scenario that might occur under heightened levels of climate mitigation. On the other hand, RCP 4.5 and 8.5 show mitigation scenarios that may not be taken as seriously, resulting in more glaciers being lost. The shaded areas around each line represent the uncertainty and error that goes along with predictions, and the 2.6, 4.5, and 8.5 delineate the radiating forcing values in the year 2100. These radiating forcing values are measured in watts per square meter(W/m²), and under the RCP 2.6 - which is the most optimistic and likely the hardest to achieve scenario - glacial loss levels off in 2060.

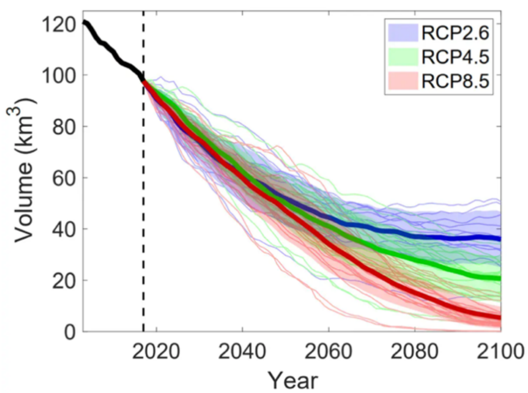

Figure 10: Evolution of total glacier volume in the European Alps between 2003 and 2100[36]

Furthermore, the United Nations named 2025 as the International Year of Glaciers' Preservation, and the European region is losing glacier volume and area at the fastest rate in the world.[37] Accelerated melting is also erasing critical climate archives: 2018–2020 ice cores from Switzerland's Corbassière glacier show meltwater has flushed out trace chemicals (e.g., ammonium, nitrate) needed to reconstruct past climates,[38] with lead scientist Margit Schwikowski confirming "a threshold has been crossed—runoff is literally washing away atmospheric history".[39]

Another study that utilizes deep-learning-aided 3D ice-flow modeling with data assimilation also predicts that there will be a massive amount of ice loss in the European Alps. Through the usage of satellite

[34] Zekollari, H., Schuster, L., Maussion, F., et al. (2025). Glacier preservation doubled by limiting warming to 1.5 °C versus 2.7 °C. *Science, 388*(6750), 979–983. DOI: 10.1126/science.adu4675

[35] Hartl, L., Schmitt, P., Schuster, L., et al. (2025). Recent observations and glacier modeling point towards near-complete glacier loss in western Austria (Ötztal and Stubai mountain range) if 1.5 °C is not met. *The Cryosphere, 19*, 1431–1450. https://tc.copernicus.org/articles/19/1431/2025/

[36] Zekollari, H., Huss, M., and Farinotti, D. (2019). Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble, *The Cryosphere*, 13, 1125-1146. https://tc.copernicus.org/articles/13/1125/2019/

[37] WMO. (2025). *European State of the Climate: Extreme Events in Warmest Year on Record*. https://wmo.int/news/media-centre/european-state-of-climate-extreme-events-warmest-year-record

[38] Huber, C.J., Eichler, A., Mattea, E., et al. (2024). High-altitude glacier archives lost due to climate change-related melting. *Nat. Geosci.* **17**, 110–113. https://doi.org/10.1038/s41561-023-01366-1

[39] Berndorff, J. (2024). Glacier melting destroys important climate data archive. *Paul Scherrer Institute (PSI)*. https://www.psi.ch/en/news/media-releases/glacier-melting-destroys-important-climate-data-archive

observations, historical glacier data, and physical ice dynamics, this model concludes that Alpine glaciers will decline by 34% in volume and 32% in area by 2050.[40] The model largely attributes this loss to long-term climatic inertia, which is the lag between past greenhouse gas emissions and how those emissions impact the world. Because the world has already built up these greenhouse gas emissions, some glacial melt is inevitable, but this does not mean that the predicted level of melting is inevitable. Rather, these findings bring out the urgency in acting now.

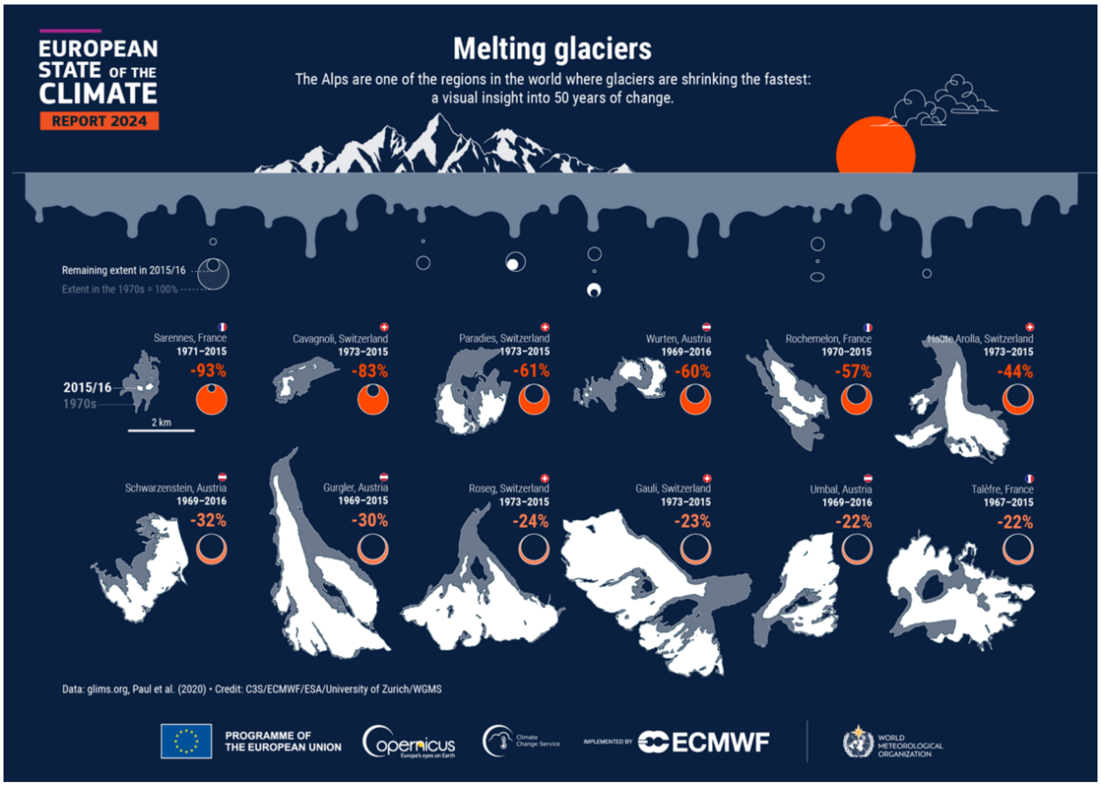

Figure 11: Alpine glacial melt over the last 50 years[41]

Glacier loss also introduces sediment yield and reservoir sedimentation into water sources, meaning that more sand and silt flow downstream into rivers.[42] This can damage the equipment necessary to produce hydropower while also elevating the risk of natural disasters like avalanches and landslides. A constant need to fix and renew damaged equipment may cause a decrease in investment in hydropower facilities, as they could be seen as unsustainable. As plants potentially shut down, a decrease in energy production from hydropower inevitably follows, resulting in a loop that can lead to the end of glacial hydropower in Europe.

Even under the status quo, this significant loss of glacier mass and volume may be considered inevitable because of the long-term effects of past actions. With this in mind and how reliant European states are on hydropower, it becomes increasingly important to begin mitigating this loss as soon as possible.

[40] Cook, S. J., Jouvet, G., Millan, R., et al. (2023). Committed Ice Loss in the European Alps Until 2050 Using a Deep-Learning-Aided 3D Ice-Flow Model with Data Assimilation. *Geophysical Research Letters*, *50*(23), e2023GL105029. https://doi.org/10.1029/2023GL105029
[41] WMO, *European State of the Climate: Extreme Events in Warmest Year on Record*.
[42] Boes, R., & Hagmann, M. (2015). *Sedimentation countermeasures*. ResearchGate. https://www.researchgate.net/publication/327137518_Sedimentation_countermeasures_examples_from_Switzerland

The following recommendations offer stakeholder-specific actions aimed at mitigating the loss of the Alps in a way that is feasible for investors and governments.

IV. Recommendations

Responsible Alpha has three recommendations for investors, as follows:

Investor Recommendation #1:

*Investors should not only increase investment of hydropower in the Alpine region, but they should also **incorporate hydrogeological risk assessments** when deciding capital allocation for projects in the Alps.*

Investor Recommendation #2:

*Investors should also broadly **integrate climate scenario analyses** into investment decisions to mitigate the risk of common natural disasters in glacial areas like glacial lake outburst floods (GLOFs) and avalanches.*

Investor Recommendation #3:

*Investors with infrastructure and energy systems reliant on Alpine resources should **adopt contingent liability-linked financial instruments** (glacier-indexed catastrophe bonds and insurance for snowmelt) and use geo-spatial exposure mapping to **identify portfolio assets** located in snow-fed or glacier-dependent catchments.*

Responsible Alpha has three recommendations for governments, as follows:

Government Recommendation #1:

*Governments in the Alpine Region should **audit national hydropower systems** that rely on glacial runoff, specifically runoff sourced to the Alps, and look for other avenues to generate natural, sustainable energy.*

Government Recommendation #2:

*Governments should **cooperate and fund the development of Alpine ecological corridors**, designate cold-climate conservation zones, and monitor biodiversity and animal migration stemming from climate change.*

Government Recommendation #3:

*Governments should **publish glacier-adjusted grid vulnerability assessments** to verify and pinpoint dependencies on Alpine resources, specifically glaciers. These reports should delineate the effects of glacier loss on seasonal hydropower generation and grid reliability for its constituents and corporations.*

V. A Call to Collective Action

The Alpine region's energy landscape has undergone significant evolution since the 1970s, when environmental concerns led to widespread opposition to large-scale hydropower projects, significantly slowing their development. Today, as we confront the urgent challenges of climate change and global warming, there is renewed interest in hydropower as a low-carbon energy solution - though with important modifications to historical approaches.

Current discussions focus not on massive dam projects of the past, but rather on micro-hydropower systems that minimize environmental impact. Furthermore, innovative hybrid solutions are emerging, particularly in Switzerland and neighboring Alpine nations, where floating solar photovoltaic systems are being deployed on existing reservoirs - effectively creating dual-use renewable energy infrastructure.[43]

At Responsible Alpha, we recognize this pivotal moment in sustainable energy development. As we witness accelerating environmental changes in the Alps, the need for thoughtful collaboration has never been greater. Preserving this vital ecosystem while meeting energy demands requires shared commitment from all stakeholders. Investors have a unique opportunity to support these innovative hybrid solutions that balance energy production with environmental protection, while governments must establish the policy frameworks needed for sustainable development.

The coming years will be decisive. By working together - through responsible investment, science-based policymaking, and cross-border cooperation - we can help ensure the Alps continue to provide clean energy, fresh water, and natural beauty for generations to come. This is not just an environmental imperative, but an investment in Europe's sustainable future.

Together, through innovation and collaboration, we can transform the Alps into a global model for sustainable hydropower that balances clean energy needs with fragile ecosystem preservation.

[43] Landry, M. (2025). *Mountain battery: The Alps, water, and power in the fossil age*. Stanford University Press. https://www.environmentandsociety.org/mml/mountain-battery-alps-water-and-power-fossil-age#:~:text=In%20this%20book%2C%20Marc%20Landry%20shows%20how%20dam-building,and%20produce%20electricity%20for%20use%20throughout%20the%20continent.