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Original Research Article

Through energy droughts: Hydropower's ability to sustain a high output

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ABSTRACT

Previous research has highlighted concerns about week-long energy droughts in renewables-based energy systems. Reservoir hydropower could offer a viable solution to mitigate such energy shortfalls. However, current energy systems models often oversimplify hydropower by assuming it can operate continuously at maximum output. This study investigates the ability of reservoir hydropower to sustain a high output and thereby mitigate energy droughts. In contrast to most energy system models, the hydropower model used in this study includes cascading, head dependency, turbine efficiency curves and environmental constraints. We estimate that Swedish hydropower can sustain between 77% and 96% of its installed capacity for one week, with the higher end of this range achievable during spring. This range in sustained output is equivalent to about 3 GW, or about 20% of average demand in Sweden, which underscores the importance of understanding the operational limitations of hydropower. Our findings indicate that river bottlenecks, primarily due to regulations on maximum flows, are the main factor limiting hydropower's ability to sustain higher outputs. With the upcoming renewal of environmental permits for hydropower plants in Sweden, these findings provide valuable insights for policymakers. The importance of analysing hydropower's ability to sustain high outputs is not unique to Sweden; the method proposed in this study can serve as a critical tool for similar assessments in other hydro-rich countries. Moreover, the sustained output capabilities demonstrated in this study challenge the prevalent simplified representations of hydropower in energy models, highlighting the need for more sophisticated modelling approaches.

1. Introduction

Variation management strategies are essential in renewables-based energy systems to ensure that the demand can be met at all times despite variations in wind and solar power production. Energy storage, expansion of transmission grids, demand-side management, and dispatchable generation technologies are the key strategies discussed in the literature [1–9]. Furthermore, reservoir hydropower has been argued to provide flexibility in renewables-based systems [10–16]. In this study, we analyse the ability of reservoir hydropower to provide capacity during a sustained period of low availability of supply relative to demand, a so-called *energy drought*.

In contrast to many other variation management strategies, hydropower has been used in power systems for decades, and has long been recognised for its operational flexibility. In Sweden, hydropower has contributed significantly to system flexibility by providing diurnal production to follow load, seasonal storage capabilities, and grid stability. However, the shift towards renewable energy systems could alter the way in which hydropower is optimally utilised. A recent study by Öberg et al. [17] has revealed a notable shift in hydropower's operational dynamics, in that the conventional daily production cycle is becoming less pronounced, influenced by the increasing integration of wind power into the electricity system. This trend suggests a re-evaluation of hydropower's role, which may be transitioning from its traditional focus on meeting intra-day demand fluctuations to accommodating the variability of renewable energy sources on different time-scales.

Energy systems that have a large share of renewables face numerous challenges related to variability, ranging from short-term issues such as maintaining frequency control and adapting to hourly load changes to persistent supply shortages due to factors such as low-wind periods or technology failures. Researchers have explored hydropower's role in addressing these challenges across different time-scales. Phillips et al. [15] have developed a framework to assess hydropower's potential for enhancing short-term grid resilience after a disturbance, highlighting reservoir hydropower's critical role in managing disruptions. Yang et al. [18] have quantified the quality of short-term regulation of hydropower and the burden placed on generation equipment, and they have also evaluated burden relief strategies under different future

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variable renewable energy (VRE) scenarios. Extending the research to intra-day variations, Thapa et al. [16] have examined the capacity of a cascaded reservoir hydropower system to meet daily demand peaks under various operational constraints, and they have identified some key factors influencing intra-day flexibility. However, hydropower's potential to mitigate week-long energy droughts is poorly explored. Such droughts can result from, for instance, weather phenomena [19–24], technical failures in transmission lines [25,26], and emergency shutdowns of nuclear power plants [27,28].

This study fills the knowledge gap by evaluating hydropower's ability to sustain a high output over extended periods, thereby assessing its capacity to counteract energy droughts. Rather than relying on historical data, which are insufficient because the demand for a high output for long periods of time has not been pressing enough, we employ a model. As has been advocated both by the International Energy Agency (IEA) and the National Renewable Energy Laboratory (NREL), energy system models have too simple a representation and cannot accurately assess hydropower's flexibility [29,30]. Hence, this study employs a detailed model of the hydropower infrastructure to offer insights into its potential to maintain a high level of output for 1–3 weeks. In addition, we investigate the extent to which this ability depends on limitations on how much water can be released through, or passing, each plant. These flow limitations can be due to regulations, technical capacities, or hydrological factors, some of which may be subject to change depending on their impact on energy performance and environmental concerns. We also map seasonal patterns, exploring the relationship between variations in the ability to sustain output at different times of the year and energy drought occurrences.

This study focuses on Sweden as a case study, but the importance of such an analysis extends globally, especially to regions that are heavily dependent upon reservoir hydropower, like South America, Canada, China, Central Africa, and parts of the USA and Europe.

2. Methods

The goal of this work was to determine the maximum possible output that hydropower plants across multiple rivers can sustain simultaneously for 1–3 weeks in the presence of strong economic incentives. To assess this ability, we use a detailed hydropower optimisation model that maximises profits. We simulate high-demand conditions by introducing high market prices and thereby mimicking real-world economic incentives for increased production.

The remainder of the Methods section is organised as follows. First, we introduce and define two key metrics — *Sustained capacity* and *Sustained production* — to quantify sustained output (Section 2.1). Next, we provide an overview of the detailed hydropower optimisation model that we use for the analysis (Section 2.2). We then explain how energy droughts are represented and how the study is designed to test hydropower's ability to sustain high output for different lengths of energy drought periods at different times of the year (Section 2.3). Subsequently, we explain water flow limitations in rivers and how that is implemented in the model (Section 2.4). Next, we present three flow limitation scenarios that we introduce to explore how limits on flows passing each power plant could affect hydropower's performance (Section 2.5). Finally, we summarise the test design and all model runs conducted in this study (Section 2.6).

2.1. Measuring sustained output

To address energy droughts effectively, we require technologies that can meet the demand throughout these critical periods. This study introduces two metrics to evaluate the ability to sustain a high output: *Sustained capacity* and *Sustained production*.

- *Sustained capacity* is defined as the consistent power output that hydropower plants can guarantee throughout a specified period. This metric is measured as a percentage of the maximum capacity of the plants.

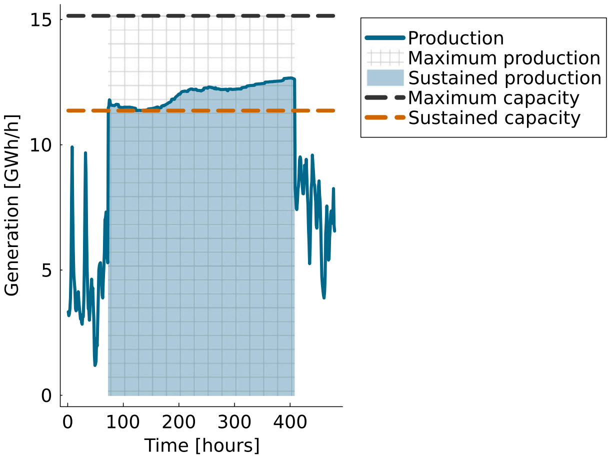


Fig. 1. Illustration of the definitions of the *Sustained capacity* and *Sustained production* metrics. The figure depicts hydropower production levels over a 20-day period, highlighting the metrics during a simulated 14-day energy drought.

- *Sustained production* is defined as the total electrical energy generated during a specific period. This metric is expressed as the percentage of the maximum possible production, i.e., the total production from hydropower plants running at maximum capacity throughout this period.

Fig. 1 shows the hydropower production profile over 20 days with a simulated 14-day energy drought in the middle and shows the metrics of *Sustained capacity* and *Sustained production* applied to this example.

2.2. Model overview

The methodology we use to represent hydropower in a detailed manner is derived from the approach outlined previously by Ek Fälth et al. [31] (described as model B:L in that paper). Briefly, it is a linear optimisation model that maximises profit for a set of hydropower plants subjected to deterministic spot prices over a full year with hourly resolution. The model represents each component of the river systems, including reservoirs, flow paths with their respective flow times, and individual turbines at each power plant with their respective efficiency curves. Turbine efficiencies are modelled using piece-wise linear approximations of actual non-linear efficiency curves, while the head-dependent production is linearised via a Taylor approximation. Furthermore, the model incorporates environmental constraints, such as minimum flow requirements and seasonally dependent minimum and maximum water levels.

To ensure the accuracy of the linear model used in this study for evaluations of sustained output, we conducted a sensitivity analysis using a full non-linear model without linearisations of head-dependency and efficiency curves (described as model A in [31]). This sensitivity analysis confirmed that the linearised model used in this study accurately replicates the results regarding the ability to sustain high output levels, as compared to using a full non-linear model. Figure A.6 in the Supplementary material presents this sensitivity analysis.

In addition to the technical features in the original model described in [31], we implemented, for the purpose of this study, more realistic constraints on the allowed water flow at each hydropower plant. These constraints are dictated by regulations (due to ecological and social considerations) and technical capacities, thus enhancing the model's realism. Moreover, as will be demonstrated in this study, the constraints on water flow rates significantly impact the potential for sustained hydropower output, underscoring their importance in accurately addressing the main research question. Further details of these water flow limitations are presented in Section 2.4.

The next section details the geographic scope of the model, which includes a majority of Sweden's hydropower capacity.

Table 1
The modelled Swedish hydropower capacity, presented as the percentages of total installed capacity in Sweden, both in aggregate and by Nord Pool price area.

	Total	SE1	SE2	SE3	SE4
Share [%]	92	98	99	72	0
Modelled capacity [GW]	15.13	5.24	7.99	1.90	0
Installed capacity [GW] [32]	16.40	5.36	8.08	2.64	0.32

2.2.1. Geographic coverage of the modelled hydropower

The installed hydropower capacity in Sweden is about 16 GW, and in 2022 about 70 TWh of the Swedish electricity generation originated from hydropower, corresponding to 41% of the total electricity production [32]. Our model covers 92% (about 15 GW) of the hydropower capacity in Sweden, encompassing nine major rivers (Luleälven, Skellefteälven, Umeälven, Indalsälven, Ångermanälven, Ljungan, Ljusnan, Dalälven and Göta älv, including Klarälven + Uvån + the stretch below Vänern), incorporating around 240 reservoirs and power plants, each of which is equipped with 1–10 turbines. Table 1 presents the geographic coverage of the modelled hydropower, segmented by Nord Pool price area.

2.2.2. Data overview

For the parameterisation of our model across the nine rivers, we employed an extensive data set spanning from Year 2016 to Year 2020. This data set includes the hourly production levels, water levels at both the intake and outlet, turbine discharge rates, and spillage across the 240 reservoirs and power plants included in our analysis. All the companies that own these facilities provided the data under confidentiality agreements.

The input data for the parameterised model include the spot prices for each bidding area from Year 2016 to Year 2020, sourced from Nord Pool, and the hourly site-specific water inflow data for all rivers, as provided by the Swedish Meteorological and Hydrological Institute (SMHI) and the Water Regulation companies (Vattenregleringsföretagen), also under confidentiality agreements. In addition, the hourly intake water levels were used to determine the start and end reservoir levels for each model run.

2.3. Representing energy droughts in the model

To evaluate the ability of hydropower to sustain high outputs during periods of energy droughts, we simulated conditions of high demand by incorporating constant high market prices into historical price profiles. This method allows us to mimic the economic signals that would trigger hydropower plants to operate at increased output levels, mimicking real-world energy droughts.

2.3.1. Drought duration scenarios

To examine how the ability to sustain high output varies with different durations of energy droughts, we modified historical price profiles to include *one, two* or *three* consecutive weeks at a constant high price. These three drought duration scenarios are visualised as “Drought duration scenarios” in dark orange in Fig. 5.

The price at the high-price weeks was set at 5000 SEK/MWh (approximately 430 €/MWh). This pricing level was selected as a substantial incentive for high production levels; for reference, the peak price on the Swedish spot market in Year 2023 was 3760 SEK/MWh. Fig. 2 demonstrates an example.

We conducted a sensitivity analysis to confirm that the price level of 5000 SEK/MWh effectively motivates maximum sustained output during these high-price intervals. The findings, detailed in Figure A.6 in the Supplementary material, reveal that even a significantly higher price of 50,000 SEK/MWh did not increase the sustained output. This result confirms that our chosen price level effectively encourages Swedish hydropower plants to maximise their outputs during critical high-demand periods, assuming that prices during the remainder of the year align with the historical levels recorded between 2016 and 2020.

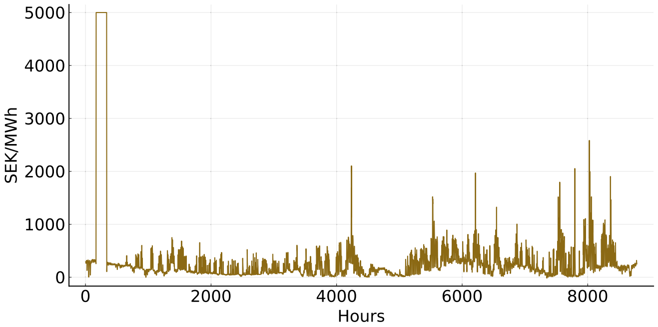


Fig. 2. Example of a price profile with an introduced high-price period of 1 week in region SE3 in January 2020.

We utilised a model that has perfect foresight, incorporating deterministic water inflows and spot prices. To reduce the risk of overestimating the sustained outputs – a consequence of using a model that is capable of precisely planning water releases and levels with complete foresight – we strategically introduced the high-price period just 1 week after the initial modelled hour. This approach restricts the model’s ability to optimise water levels in advance, thus enhancing the realism of our results for sustained output.

2.3.2. Droughts at different times of the year

To investigate how timing influences the sustained output capabilities of Swedish hydropower, we simulated energy droughts in each month individually. To cover differences in annual inflow between years, we conducted one full-year model run for each month (as the start month) for four different years (2016–2019). To clarify, we modelled January 2016 to January 2017 with the high-price period in January 2016 and replicated this for all months and years up to December 2019 to December 2020. This methodological approach enabled us to assess how the timing of energy drought periods affects sustained production levels, as influenced by variations in inflow and initial reservoir levels. These are visualised as “Time periods” in light blue in Fig. 5.

2.4. Water flow limitations

Water flow limitations due to regulations, technical capacities, or hydrological factors can create bottlenecks at specific points along the river, significantly affecting the abilities of the hydropower plants in that river to sustain high outputs, as demonstrated by the findings of this study. This section provides an overview of how we define river bottlenecks and how they impact the ability to sustain high output levels. It further explains how water flow limitations were integrated into our model. Section 2.5 details the three flow limitation scenarios analysed in this study.

2.4.1. Bottlenecks affecting the ability of hydropower to sustain a high output

River flow rates typically increase as one moves downstream, due to the convergence of tributaries as the river progresses towards the sea. However, the larger reservoirs in Swedish river systems, which serve as substantial seasonal water storage facilities, are predominantly located upstream. In contrast, some downstream reservoirs can only hold enough water for a few days of full-capacity generation. Therefore, sustaining high production levels at downstream plants for prolonged periods requires the release of water from these larger upstream reservoirs, so as to compensate for the limited capacities of

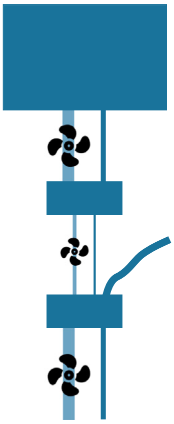


Fig. 3. Conceptual representation of a river system, illustrating the concept of bottlenecks that can exist at various points along a river. The diagram depicts a series of reservoirs and turbines, with a large upstream reservoir followed by smaller ones downstream. It highlights how varying turbine capacities can create bottlenecks, particularly when a lower-capacity turbine is situated between higher-capacity turbines. Given the present regulatory frameworks and infrastructure, whereby the allowed flow through a plant (either through the turbine or in the spillway) generally is limited to the maximum flow capacity of the plant's turbines, these bottlenecks diminish the ability to sustain high levels of hydropower production.

smaller downstream reservoirs.

Bottlenecks arise where the allowed water flow rate of one plant is lower than others upstream or downstream, impeding water transfer. Fig. 3 conceptually illustrates such a bottleneck. Consider a river system with a large upstream reservoir connected to a turbine and spillway with high-flow capability. Further downstream lies a smaller reservoir with a turbine and spillway that is capable of lower flows, followed by another small reservoir that is equipped with a high-flow turbine because it receives additional water from a tributary. The most-downstream turbine cannot sustain maximum capacity without rapidly depleting its reservoir, because even if ample water remains upstream, it cannot bypass the bottleneck (the middle turbine) quickly enough. Moreover, the most-upstream turbine cannot run at full capacity indefinitely without risking an overflow at the intermediary reservoir.

2.4.2. Flow limits in the model

The permit under which hydropower plants operate can limit the amount of water that they can release through turbines or in spillways, as well as the rate at which they can change water flows. For instance, some power plants can operate with so-called *short-term regulation*, i.e., frequently changing the water flows withdrawn from their closest reservoir, while others do not.

Since some plants have the right to conduct short-term regulation, whereas some can only change their water flows at a limited rate of change, we introduced two variables to represent the flow constraints in our model: long-term spillage, $L_{t,p,p2}$; and short-term spillage, $S_{t,p,p2}$. The long-term spillage has the upper bound $l_{t,p,p2}$, as in Eq. (1). The right to regulate water in the short term includes both spillage and the water released in the turbines. Thus, we set the sum of the short-term spillage, $S_{t,p,p2}$, and the turbine discharge, $D_{t,p,p2}$, to be below the upper bound for short-term regulation, $s_{t,p,p2}$, as in Eq. (2). Index t represents time, and the indices p and $p2$ represent the passage from plant p to downstream plant $p2$.

$$L_{t,p,p2} \leq l_{t,p,p2} \tag{1}$$

$$S_{t,p,p2} + D_{t,p,p2} \leq s_{t,p,p2} \tag{2}$$

To restrict the rate of change in long-term spillage, we introduced constraints that limit the increase and decrease of long-term spillage from hour to hour. The parameter i represents the allowed increase each hour, and d represents the allowed decrease each hour.

$$L_{t,p,p2} \leq L_{t-1,p,p2} + i_{t,p,p2} \tag{3}$$

$$L_{t,p,p2} \geq L_{t-1,p,p2} - d_{t,p,p2} \tag{4}$$

In our flow limitation scenarios, we applied either short-term spillage or long-term spillage to each plant. In reality, it could be that one is allowed to release water above the limit for short-term regulation if that water release is carried out with slow changes to the flow. However, allowing for both long-term and short-term spillage in our model requires some model development since the current implementation would lead to the possibility of having short-term spillage on top of the long-term spillage, thereby changing the flow rates faster than is allowed above the upper limit for short-term regulation.

2.5. Flow limitation scenarios

To explore the impacts of bottlenecks on sustained output, we examined the following three scenarios with different upper bounds on spillage: *Present regime*, *Reduced bottlenecks*, and *Unrestricted*. These three scenarios are visualised as "Flow limitation scenarios" in light orange in Fig. 5.

2.5.1. Present regime scenario

Sweden's current regulatory framework for hydropower production involves the issuing of specific permits for each plant. These permits typically impose restrictions on permissible water flow rates at specific points along the river. Some power plants can operate with short-term regulation, while others do not. For instance, reservoirs that are not directly linked to power plants frequently lack such permissions. Based on discussions with specialists from power production companies and water regulation authorities in Sweden, we conclude that power plants that are authorised to engage in short-term regulation are generally permitted to adjust flows rapidly between any minimum flow requirement and the maximum capacity of their installed turbines. In this study, for the *Present regime* scenario, we have assumed that all reservoirs that are connected directly to power plants are entitled to regulate their water flows on a short-term basis. We have further assumed that flows that exceed the maximum capacity of the installed turbines, plus any mandatory minimum spillage requirements, are not permitted except during periods when the inflow exceeds the turbine's maximum flow capabilities. Consequently, for these reservoirs, the upper limit on short-term regulation [s in Eq. (2)] is set each hour by the greater of the maximum flow capacity of installed turbines or the present inflow to that reservoir. Furthermore, the upper limit on long-term spillage [l in Eq. (1)] is set at zero.

For reservoirs that are not directly connected to a power plant, we set the short-term regulation [s in Eq. (2)] to zero and permit long-term spillage [l in Eq. (2)] every hour, equal to either the maximum inflow recorded that calendar month during the period of 2016–2020 or the mean inflow for the same period, whichever is greater during that hour.

2.5.2. Reduced bottlenecks scenario

In this scenario, we identified all power plants in which the maximum flow capacity of the installed turbines was lower than that of any of the upstream plants. Following this approach, approximately 30% of all power plants were classified as bottlenecks. For these identified bottlenecks, we increased the allowed short-term regulation [s in Eq. (2)] to match the maximum flow capacity of the turbines in the upstream plant. This adjustment resulted in an average increase of 20% in the maximum water flows at these plants. When comparing these

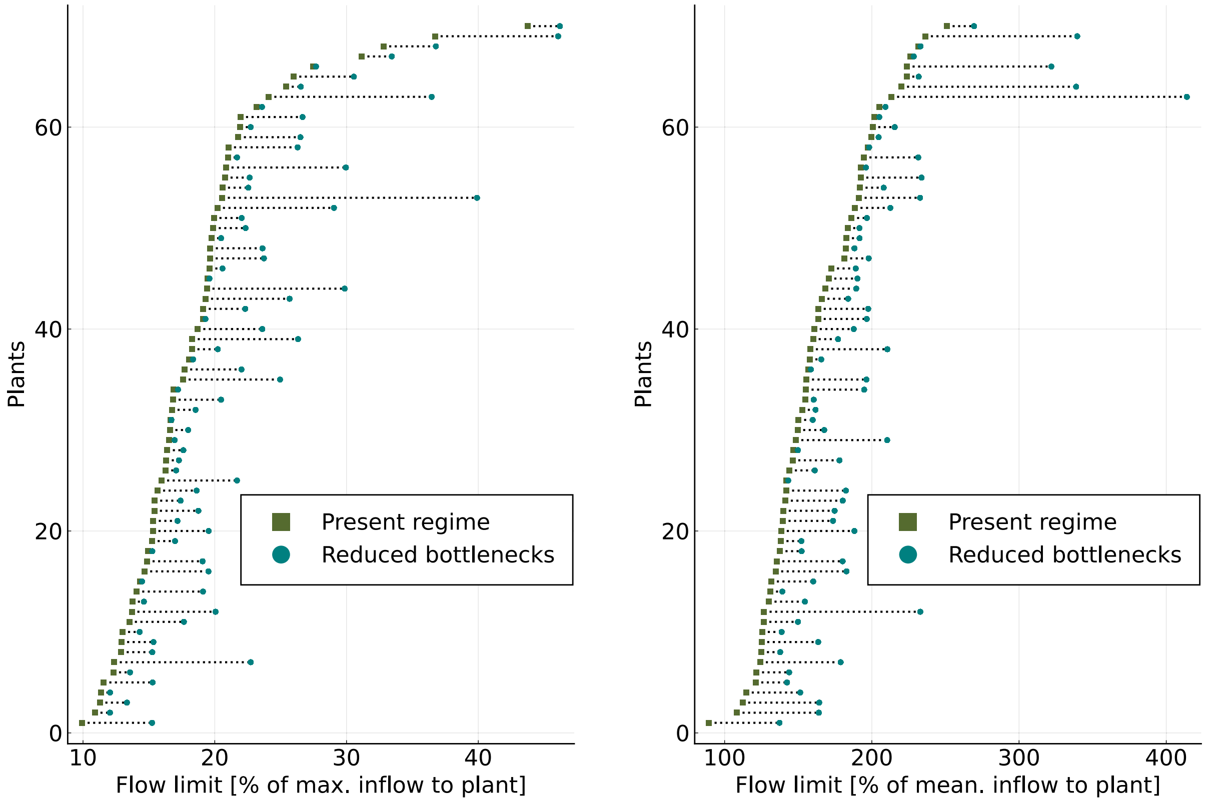


Fig. 4. Overview of the 70 hydropower plants (out of approximately 240) identified as bottlenecks. The figure compares flow rate limitations at bottleneck sites under the *Present regime* and *Reduced bottlenecks* scenarios, highlighting adjustments made to improve performance during energy droughts. The left panel presents flow rate limits as a percentage of the maximum inflow to the plant, while the right panel shows them as a percentage of the mean inflow.

revised flow rate limits to the maximum recorded inflow for each plant (including the inflow to all upstream plants) over the period of 2016–2020, we found that the limits increased from an average of 18% to 22% of the maximum inflow. Similarly, when compared to the average inflow during the same period, the spillage limits rose from an average of 163% to 194% of the mean inflow. Details of these adjustments to the flow rate limits, in relation to both the maximum and average inflows, are illustrated in Fig. 4.

2.5.3. *Unrestricted scenario*

In the *unrestricted* scenario, the upper limits on short-term regulation [$\overline{s}$ in Eq. (2)] were removed for all power plants and reservoirs. Thus, all the plants, including reservoirs without directly connected power plants, were allowed to regulate water without an upper limit. Note that we retained the upper limits on turbine discharge. Thus, we effectively increased the spillage limits.

2.6. *Test setup*

The test setup integrates the various elements described in the Methods section to systematically evaluate hydropower's ability to sustain high output under different conditions. An overview of the setup is presented in Fig. 5.

The study focuses on three key factors that influence sustained hydropower production:

- **Energy drought duration** – The impact of drought length is assessed through three scenarios, representing one-, two-, and three-week energy droughts.
- **Timing of energy droughts** – To investigate seasonal differences in the ability of hydropower to sustain high output, we assess energy droughts in each of the 12 months. To account for inter-annual variability, we repeat the analysis for four different years, resulting in 48 distinct time periods.
- **Flow limitations** – The role of flow bottlenecks is analysed through three flow limitation scenarios:
  - *Present Regime* (existing constraints on water flows),
  - *Reduced Bottlenecks* (relaxed constraints to enhance sustained output), and
  - *Unrestricted* (no flow limitations).

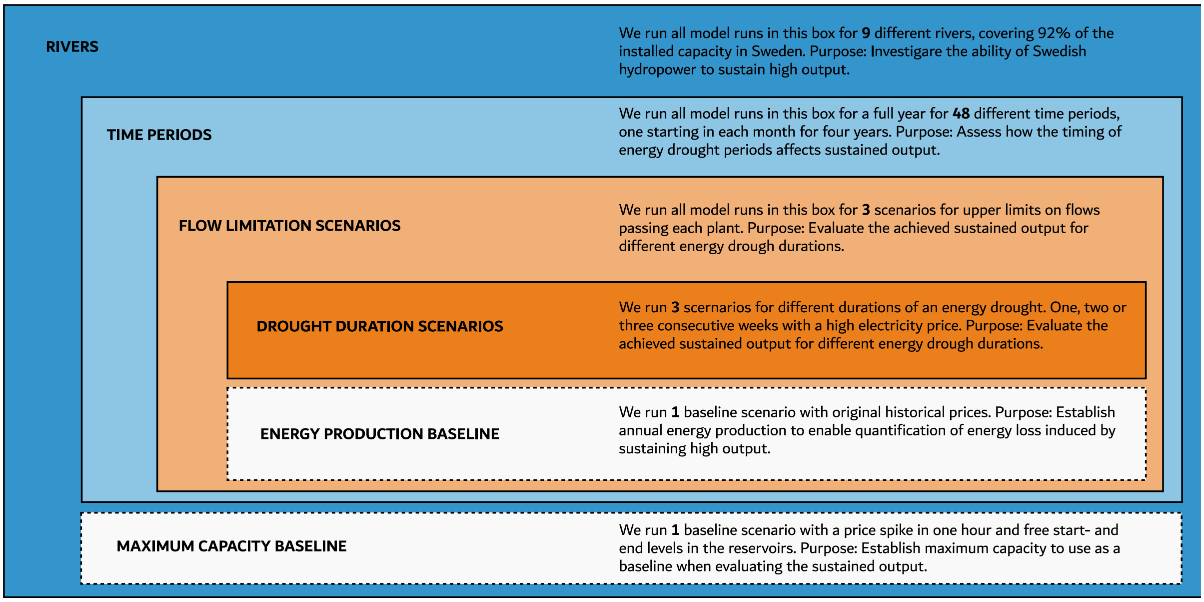
The study includes assessments for nine different river systems. In total, more than 5000 model runs were carried out, covering all combinations of drought durations, time periods, and flow limitation scenarios. This setup allows for a detailed examination of how hydropower's ability to sustain high output is influenced by drought conditions and operational constraints.

In addition to these scenario-based runs, baseline runs were conducted to establish reference points for annual energy production and maximum capacity, as described in the following section.

2.6.1. *Baseline runs as reference points for energy production and capacity*

To establish reference points for energy production, baseline runs were conducted using original historical spot prices. These runs were performed for all flow limitation scenarios, time periods, and rivers, aligning with each drought duration scenario (see the topmost white dashed box in Fig. 5). Comparing these with the energy drought runs allowed us to quantify the annual production loss resulting from sustaining high output during energy droughts. This loss is caused by spillage at bottlenecks, which occurs to sustain high production during high-price energy drought weeks, as this yields higher overall profits than reducing spillage.

Maximum turbine capacities are not directly specified in our model but are inferred from several factors: the maximum turbine flows, the varying head levels derived from intake and outlet elevations, and the configuration of the turbine efficiency curves. To determine the



RIVERS

We run all model runs in this box for **9** different rivers, covering 92% of the installed capacity in Sweden. Purpose: Investigare the ability of Swedish hydropower to sustain high output.

TIME PERIODS

We run all model runs in this box for a full year for **48** different time periods, one starting in each month for four years. Purpose: Assess how the timing of energy drought periods affects sustained output.

FLOW LIMITATION SCENARIOS

We run all model runs in this box for **3** scenarios for upper limits on flows passing each plant. Purpose: Evaluate the achieved sustained output for different energy drough durations.

DROUGHT DURATION SCENARIOS

We run **3** scernarios for different durations of an energy drought. One, two or three consecutive weeks with a high electricity price. Purpose: Evaluate the achieved sustained output for different energy drough durations.

ENERGY PRODUCTION BASELINE

We run **1** baseline scenario with original historical prices. Purpose: Establish annual energy production to enable quantification of energy loss induced by sustaining high output.

MAXIMUM CAPACITY BASELINE

We run **1** baseline scenario with a price spike in one hour and free start- and end levels in the reservoirs. Purpose: Establish maximum capacity to use as a baseline when evaluating the sustained output.

Fig. 5. A summary of all the model runs conducted in this study. The innermost box represents 3 Drought duration scenarios (one, two and three weeks; dark orange), each applied under 3 Flow limitation scenarios—*Present Regime*, *Reduced Bottlenecks*, and *Unrestricted* (light orange). These scenarios were tested across 48 time periods (12 months × 4 years; light blue) for 9 different rivers (dark blue). Baseline runs, conducted to establish reference points for annual energy production and maximum capacity, are visualised in white dashed boxes. In total, this results in over 5000 model runs.

maximum capacity for each river, we ran the model with a short high-price period lasting only one hour, allowing for optimised initial and final reservoir levels. This approach provides a meaningful reference for comparing the *Sustained Capacity* during high-price weeks to the maximum possible capacity.

Baseline runs for energy production and maximum capacity are represented by white dashed boxes in Fig. 5.

3. Results & discussion

3.1. Hydropower capacity can be sustained at high levels over several weeks

Our findings reveal that hydropower can sustain high production levels over several weeks. Under current infrastructure and regulatory conditions, the Sustained capacity of Swedish hydropower ranges from 67% to 96%, depending on the time of year and the durations of high-price periods. On average, across all months spanning the period of 2016–2019, the Sustained capacity for a 1-week period was 84%, decreasing to 78% for a 3-week period. Regardless of the season or year, Swedish hydropower consistently maintained at least 67% of its total capacity for up to 3 weeks. These results are illustrated in Fig. 6 for the *Present regime* scenario, which showcases hydropower's Sustained capacity over one to three consecutive weeks. The results obtained for Sustained production are very similar to those for Sustained capacity and are, therefore, not shown here, although they are provided in Figure A.1 in the Supplementary material. Furthermore, the results for the sustained output divided according to Nord Pool price areas in Sweden are presented in Figures A.2 and A.3 in the Supplementary material.

Further examination of Fig. 6 indicates that the variation in hydropower's ability to sustain output over 1 week versus 3 weeks is less significant than the variation observed across different months and years, as highlighted by the magnitudes of the variability within each violin. This suggests that the timing of energy droughts plays a more critical role than drought duration in determining hydropower's capacity to maintain output during these periods.

We have modelled and analysed 92% of Sweden's installed hydropower capacity, focusing on the largest and most flexible river systems. Since the remaining capacity primarily consists of plants with lower levels of operational flexibility, the results for sustained output should not be extrapolated to this remaining capacity. It is also worth noting that we assumed that all power plants would be available for production at all times. In reality, owing to planned and unplanned shutdowns for maintenance and failures, the actual sustained production may occasionally be lower than is indicated by our results.

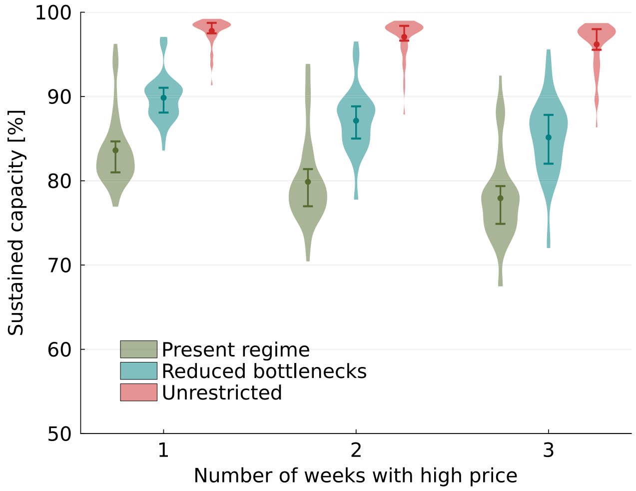


Fig. 6. An illustration of the Sustained capacity of hydropower over a period of one to three consecutive weeks of high electricity prices for three different operational flow limitation scenarios. Each violin shows the results for each month over four different years. The dots represent the mean values, while the lines extending from the dots indicate the 25th to 75th percentile range. The colour-coding corresponds to the following operational flow limitation scenarios: *Present regime* with current regulations and infrastructure (green); *Reduced bottlenecks* with a higher upper limit on spillage in bottlenecks (blue); and *Unrestricted*, with unrestricted spillage (red). The different scenarios highlight the influences of operational constraints on the ability of hydropower to sustain a high output during energy droughts. The results shown are based on approximately 5000 model runs. Refer to Section 2.6 for details of the test setup.

Furthermore, the unpredictable natures of the inflow and prices pose challenges for production planning, limiting the flexibility of hydropower compared to the deterministic model's idealised approach used in this study. For instance, deterministic models may completely empty or fill reservoirs with confidence because they know precisely when new water will arrive and when a high-price period will appear. This cannot be accomplished in practice, as it may lead to exceeding the upper and lower bounds of reservoir content due to incorrect inflow forecasts. We introduced the high-price period only 1 week after the initial modelled hour, to reflect more accurately the actual conditions and to reduce the over-estimation of flexibility from the deterministic model. This adjustment restricts the model's ability to optimise the water levels before encountering the high-price period. Nevertheless, even with this modelling approach, using a deterministic model still somewhat over-estimates the possibilities for hydropower to sustain output.

3.2. Adjusting the allowed water flows at bottlenecks enhances hydropower output during energy droughts

The current regulatory regime for hydropower production in Sweden includes limitations on allowed water flow rates in different sections along the river. The regulations generally permit operators to run water through or bypass power plants up to the maximum flow capacity of the installed turbines, except during high-inflow periods when more-significant water flow rates are allowed or forced. Bottlenecks arise when the maximum flow capacity of the turbines in a power plant is lower than that of plants upstream or downstream, thereby impeding water transfer. For more details on bottlenecks, see Section 2.4 *Water flow limitations*.

To explore the impacts of bottlenecks on sustained output, we examined two alternative scenarios, as detailed in Section 2.5. First, we analysed an *Unrestricted* scenario, in which the upper limits on water flow rates were removed at each hydropower plant, while maintaining maximum turbine flows, thereby effectively increasing the spillage limits. Allowing unrestricted spillage throughout the river could raise the sustained output to > 95% on average for periods of up to 3 weeks (illustrated by the red violins in Fig. 6), as compared to 77% under current regulatory regimes (green violins in Fig. 6). However, unrestricted spillage entails severe risks, such as flooding and erosion. Although unrealistic, this scenario indicates the impact of current water flow rate limits on sustained output and serves as an upper bound on the possibilities for sustained output.

Second, we evaluated a more targeted approach that allowed water flows to exceed the turbine flow capacities at identified bottleneck sites. The adjustments to the allowed water flows were made without increasing the maximum turbine flow capacities, thus only increasing the spillage limits. Sections 2.4 and 2.5 describe how and why flow limits were expanded at bottlenecks, and Fig. 4 shows adjustments to the flow rate limits as shares of both the maximum and average inflows.

In this *Reduced bottlenecks* scenario, Sustained capacity averages 90% for 1 week and 85% for 3 weeks (blue violins in Fig. 6). This marked improvement over the *Present regime* scenario demonstrates that adjusting spillage regulations at bottlenecks notably enhances hydropower's performance during energy droughts. Nevertheless, while the benefits of increasing flow limits are clear, they must be carefully balanced against potential environmental and social impacts, which could have negative effects on the river ecosystems and the communities that depend on them.

Our analysis did not capture all the complexities related to spillage, since we were constrained by data limitations. Each power plant operates under individual permits that regulate the release of water. We generalised these regulations by setting the upper limits on water flows through the turbines or in spillways to be equal to the maximum installed turbine flow. This assumption is based on consultations with experts from power production companies and water regulation authorities. Furthermore, water flows are restricted during wintertime due to ice formation in rivers and the risk of mechanical issues, likely resulting in a reduced ability to sustain output during the colder months. Given the generalisation of permits and the omission of the ice-related problems, our results should be viewed as indicative of the potential for sustained high output in Swedish hydropower rather than definitive calculations.

Furthermore, it is important to note that achieving sustained high-level production in rivers fundamentally depends on maintaining high flow rates throughout the entire river system. Our approach focused on increasing the spillage limits to improve flow at bottlenecks. Another effective solution could be to expand the turbine flow capacity by installing additional turbines at these critical points. Such an expansion would enhance the river system's ability to sustain high output and increase capacity while avoiding the increased annual energy losses associated with higher spillage.

3.3. Higher sustained hydropower capacity can be obtained during periods of high natural inflow and high reservoir levels

Our findings reveal notable variability in the sustained output across the *Present regime* and *Reduced bottlenecks* scenarios, as illustrated by the green and blue violins, respectively, in Fig. 6. Fig. 7 shows the 1-week Sustained capacity by month for three operational scenarios: *Present regime*, *Reduced bottlenecks*, and *Unrestricted*. The *Unrestricted* scenario consistently demonstrates sustained capacities >98%, except from March to May. This decrease can be explained by current operational practices, whereby reservoir levels are typically at their lowest before the spring run-off due to intentional winter draw-downs to meet the high demand and to accommodate anticipated spring recharge. Consequently, diminished reservoir volumes limit the capacity for full output over 1 week, and reduced head heights in plants with significant reservoir level variability decrease the energy potential, thereby affecting the power output. This also explains the downward trend in Sustained capacity observed from November to March in both the *Present regime* and *Reduced bottlenecks* scenarios (Fig. 7).

In addition, Fig. 7 charts the total natural inflow to the modelled rivers over the year as a percentage of the maximum observed, illustrating the correlation between inflow and Sustained capacity. A fluctuating inflow throughout the year affects the permitted spillage levels, as high-level spillage is only allowed during periods of naturally high inflow, such as during snowmelt or consistent rainfall, as detailed in Section 2.4. Consequently, the potential for high sustained output is greater during these high-inflow periods, as is evident in both the *Present regime* and the *Reduced bottlenecks* scenarios. This pattern arises from the design of the spillage constraints; natural inflow typically exceeds turbine capacity mainly in the springtime and occasionally in autumn, dictating spillage limits only during these periods. Allowing higher flows leads to a higher Sustained capacity because it enables water to bypass bottlenecks, and downstream plants can maintain high production levels using water from upstream reservoirs. For the same reasons, months with higher variability in terms of inflow also exhibit greater variability of Sustained capacity. Notably, the sustained output in April appears low despite there being a high inflow. This discrepancy is due to two factors: (1) the peak inflows typically occur at the end of April, whereas we introduced the high price period in the middle of the month; and (2) as discussed above, reservoir levels are generally lower before the spring run-off due to the high demand during wintertime and the anticipated recharge.

Thus, two primary factors determine the ability of hydropower to sustain a high hydropower output: (1) the water levels in the reservoirs; and (2) more critically, the permitted flow rates. These factors contribute to significant variability in hydropower's ability to sustain a high output throughout the year and across different years, as illustrated in Fig. 7. However, it is important to consider that future changes in inflow patterns driven by climate change, as well as adjustments made to reservoir management in response to these inflows and evolving energy demands, will alter the yearly differences in hydropower's potential to sustain output.

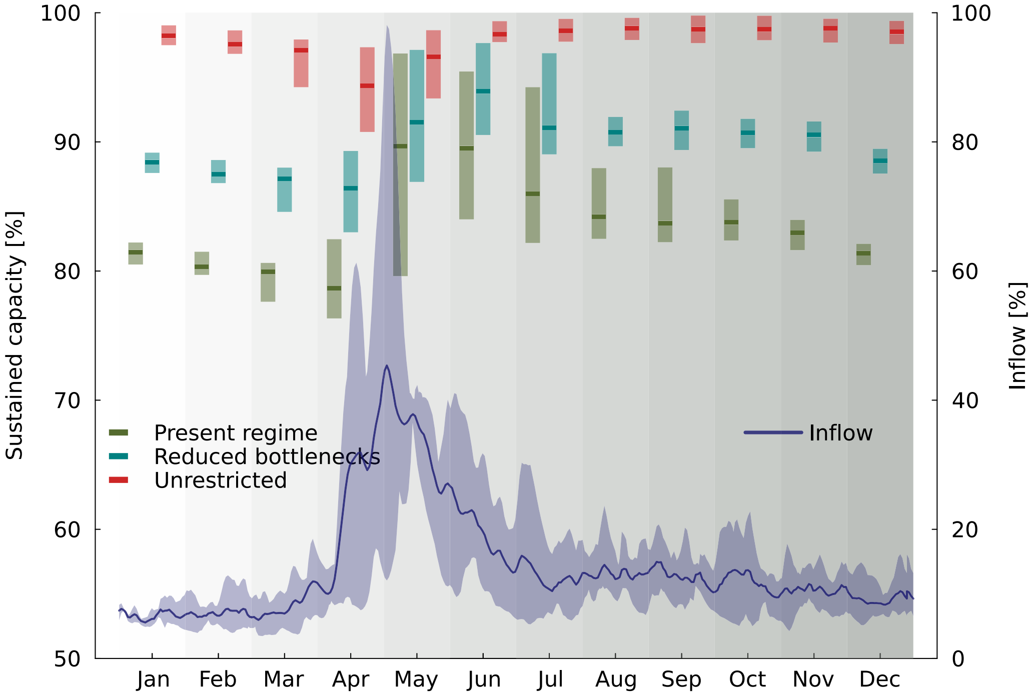


Fig. 7. A comparison of the monthly Sustained capacity of Swedish hydropower under three operational scenarios and the natural inflow throughout the year, illustrating how today's hydrological cycle influences hydropower's ability to sustain a high output. The Sustained capacity values under the *Present regime* (green), *Reduced bottlenecks* (blue), and *Unrestricted* (red) scenarios are shown in box plots, which display the range and mean values for each month. The line graph represents the total inflow as a percentage of the maximum recorded. The shaded area behind the line graph indicates the variability of the inflow for the modelled period of 2016–2020.

3.4. High sustained capacity creates annual energy losses

Achieving a high sustained hydropower capacity inevitably reduces the annual energy output, primarily due to increased spillage at bottlenecks and, to a lesser extent, reduced turbine efficiencies at maximum flows. Fig. 8 illustrates the annual production losses that are entailed by a high Sustained capacity, contrasting the outputs from scenarios involving elevated market prices with scenarios that have historical price levels. In the *Unrestricted* scenario (Fig. 6), sustaining an average capacity of 96%–98% results in a loss of about 0.8% of the annual production for each week of sustained high output, as depicted by the red violins in Fig. 8. Meanwhile, with the current regulations and infrastructure, an average Sustained capacity of 78%–84% is achievable (as shown in the *Present regime* scenario in Fig. 6), with a corresponding lower loss of about 0.2% of yearly production per week.

In summary, sustaining a high output from hydropower, so as to counteract energy droughts, leads to some energy losses, amounting to 0.2%–0.8% of annual production for each week of sustained output. This should be considered within the broader context of energy system needs. While losing renewable energy might appear to be negative in terms of the pursuit of a transition to a carbon-neutral energy system, the flexibility provided by hydropower is critical for renewables-based energy systems. It is generally more challenging to find renewable sources that offer this level of flexibility than to generate renewable energy in bulk.

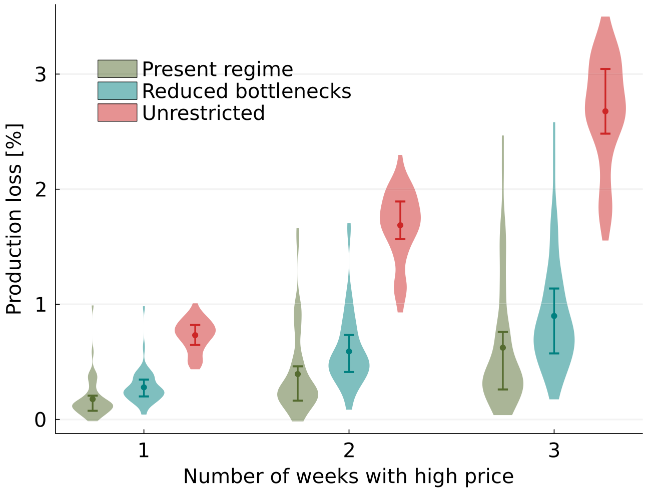


Fig. 8. Losses in yearly production associated with sustaining high output levels, comparing the yearly production obtained with elevated market prices with the yearly production obtained with historical price levels. Each violin represents the results for each month over 5 different years. The dots represent the mean values, while the lines extending from the dots indicate the 25th to 75th percentile range. The colour-coding corresponds to the following operational scenarios: *Present regime*, with the current regulations and infrastructure (green); *Reduced bottlenecks*, with a higher upper limit on spillage in bottlenecks (blue); and *Unrestricted*, with unrestricted spillage (red).

3.5. What does hydropower's sustained capacity, as measured in this study, imply for the management of energy droughts?

Our analysis demonstrates that Swedish hydropower can deliver between 67% and 96% of its installed capacity during critical periods of 1–3 weeks. This capability under-scores the significant potential of hydropower to ensure the energy supply during multi-week energy droughts. However, evaluating the adequacy of this sustained output requires the consideration of several key factors.

First, the relevance of sustained hydropower output depends on its share of the energy mix. In Sweden, the lowest observed sustained output of 67%, approximately 10 GW, can fulfil about 40% of the peak electricity demand and 68% of the average electricity demand. At the higher end, a Sustained capacity of 96%, equivalent to 14.5 GW, could meet almost 60% of the peak demand and almost 100% of the average electricity demand. These values highlight the significant role that hydropower plays in enhancing the resilience of a renewable energy system, although they also point to the need for additional energy sources during severe energy droughts. The broad range of observed sustained outputs, with a 4.5 GW difference between the highest and lowest outputs – equivalent to the capacity of three to four Swedish nuclear reactors – underlines the need to evaluate carefully hydropower's sustained output capabilities when developing strategies to counteract energy droughts.

Moreover, Sweden's energy system's interconnection with the rest of Europe adds complexity to the assessment. While this interconnectivity often acts as a buffer against local shortages by enabling trade in energy, it also poses risks when energy droughts occur simultaneously across the continent, thereby amplifying the demand for reliable back-up solutions.

Second, the timing and seasonality of the hydropower output relative to energy droughts are crucial. Energy droughts are more likely to occur during the wintertime in today's European electricity system [20,22,23], and this trend may intensify with climate change [24]. Moreover, historical data indicate that the winter months (December to February) are the periods of peak demand in Sweden [33], due to the use of electric heating. Our findings reveal that the ability of Swedish hydropower to sustain a high output is weakest during the winter months (November to March). This observation aligns with periods identified in recent literature as most susceptible to energy droughts. Unfortunately, this means that the seasons with the highest risk of energy shortages coincide with the periods during which there is a reduced capacity for hydropower to deliver high outputs.

3.6. Understanding hydropower's role in future energy systems

While our study does not directly evaluate the role of hydropower in future energy systems by integrating a detailed representation within an energy system model, it offers valuable insights that can facilitate such assessments in future research. Our findings can be used to establish more realistic assumptions regarding hydropower's ability to sustain a high output, compared to those used in the simplified representations that are commonly found in existing energy system models.

Energy system model studies have shown that reservoir hydropower can provide important flexibility in renewables-based systems [10,11]. However, these models often assume that hydropower's Sustained capacity is 100% as long as there is water in the reservoirs. Our research indicates that the actual capacity to sustain high output can sometimes be as low as 67%. Models that over-simplify hydropower's capabilities may thus overestimate the resilience provided by hydropower and underestimate the need for additional assets that can provide backup during energy droughts.

In contrast, some models that explore renewable energy systems use historical hydropower data to parameterise their representations. Such data have not historically shown the high sustained outputs that our study suggests are possible, due to the lack of economic incentives for such performance in previous energy systems. Therefore, relying on historical data to predict hydropower's operation in future energy systems will likely under-estimate its flexibility.

The influences of economic incentives on sustained output are significant, as sustaining a high output involves a trade-off between maximising output during high-price periods and saving water for hours with lower prices. In addition, as we have shown, sustaining a high output entails a reduction of annual production, adding to this trade-off. We conducted a sensitivity analysis to determine whether the price level used in our study (5000 SEK/MWh, approximately 430 €/MWh) effectively encourages maximising the sustained output during high-price periods. This analysis demonstrated that even at a substantially higher price of 50,000 SEK/MWh, the sustained output did not increase, thereby affirming that our chosen price point efficiently motivates Swedish hydropower plants to reach maximum output during these critical periods, given that prices during the remainder of the year align with the historical levels recorded from 2016 to 2020. Details of this sensitivity analysis are depicted in Figure A.6 in the Supplementary material.

Flow rate limitations in the rivers are crucial when considering periods of elevated market prices. Interestingly, limits on flow rates had a marginal impact when only historical prices were considered, as in the past there were limited incentives for hydropower plants to sacrifice water to sustain high output. This represents a critical take-away message with respect to the use of historical data for model validation: factors that may seem to be irrelevant under the conditions of current energy systems and price structures could take on importance as new incentives emerge in future energy systems.

3.7. Policy implications and future research

Sweden is initiating a comprehensive process of reissuing environmental permits for approximately 2000 hydropower plants across the country, starting in Year 2024 [34,35]. Our study highlights the critical role of bottlenecks in influencing hydropower's ability to sustain high output and, consequently, the hydropower sector's capacity to mitigate energy shortages during periods of low wind or other critical phases for the energy system. While discussions surrounding the new environmental permits often revolve around how to regulate minimum flows to facilitate fish migration, among other things, this study underlines the importance of also discussing upper flow limits. We highlight the potential to enhance hydropower's ability to sustain high output through updates to environmental permits, particularly by allowing increased spillage or maximum turbine flows. However, these considerations must be carefully balanced against the risks of significant environmental consequences.

Given that hydropower constitutes a significant share of the energy system in many parts of the world, it is important to understand whether hydropower can sustain output at, for example, 50% or close to 100%, so as to evaluate the need for other types of back-up assets to ensure the supply during energy droughts. However, generalising the results of this study to other hydro-rich nations requires careful consideration, as each region presents unique technical and environmental challenges that affect the ability to sustain high output levels. Therefore, further studies of other regions are warranted to generate more robust conclusions about the broader applicability of our findings.

4. Conclusions

This study provides a comprehensive analysis of Swedish hydropower's ability to sustain high output levels during extended periods of energy droughts, offering valuable insights for both national and global energy systems. In summary, the main contributions of this study are:

- Swedish hydropower can sustain between 67% and 96% of its installed capacity over 1 to 3 weeks. The variation in the ability to sustain output over the year identified in this study is equivalent to the capacity of three to four Swedish nuclear reactors, highlighting the need to understand hydropower's operational limits when developing strategies to address energy droughts.
- River bottlenecks, which result from regulations, technical capacities, or hydrological factors that restrict maximum flow rates, pose a major constraint on the ability of hydropower to sustain high output. Adjusting regulations or technical capacities, particularly by increasing spillage limits at critical bottleneck locations, can significantly improve hydropower performance during energy droughts.
- Under the present regime of flow limits at hydropower plants, the ability to sustain output is strongly influenced by seasonal variations in natural inflow. Higher sustained output is more achievable during periods of increased inflow.

Looking forward, the findings of this study can be applied in three key ways. First, the upcoming renewal of environmental permits for hydropower plants in Sweden presents a timely opportunity for policymakers to revise regulations on maximum flow rates, potentially enhancing hydropower's ability to sustain output during critical periods. Second, the common assumption in current energy models that hydropower can sustain maximum output as long as water is available in reservoirs is challenged by our findings, which demonstrate that sustained output can be significantly lower. This underscores the need for more detailed hydropower modelling and regulatory considerations in energy system planning, both in Sweden and globally. Third, the methodology developed in this study offers a valuable tool for future research, enabling the exploration of operational limits regarding sustained output in other hydro-rich nations, thereby contributing to a more comprehensive understanding of hydropower's role in mitigating energy droughts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rser.2025.115519.

Data availability

The authors do not have permission to share data.

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