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Assessing Hydropower Potential under Shared Socioeconomic Pathways Scenarios Using Integrated Assessment Modelling

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Abstract: The world is facing a global sustainability crisis affecting environmental systems and society. Addressing these issues requires a multi-dimensional approach that can integrate energy, water, and environment Systems, as well as provide scientific policy advice. In this study, an updated version of an Integrated Assessment Model (IAM) was used, together with new data compatible with Shared Socioeconomic Pathways (SSPs) projections, to significantly improve the work developed before. SSP climate data (temperature, precipitation, and total radiative forcing) and socioeconomic data (population and GDP) were loaded into the IAM, together with different scenario parameters. By analyzing varying socioeconomic scenarios, mitigation efforts, and adaptation strategies, this study assesses their impact on primary energy demand and, consequently, their impact on hydropower potential production. Our results show diverse energy paths, strongly dependent on the future scenario. Energy demand could increase up to 160%; however, several projections foresee a decline in hydropower production to minus 46% due to both climate change and socioeconomic transformation. Our findings highlight the importance of considering a range of potential future scenarios in energy planning and policy development. The varied outcomes across the considered scenarios emphasize the need for flexibility in strategies to accommodate for uncertainties and address the challenges posed by divergent trajectories in hydropower use and renewable energy shares.

Keywords: hydropower potential; IAM (Integrated Assessment Models); SSPs (Shared Socioeconomic Pathways); renewable energy; climate change impacts; mitigation and adaptation

1. Introduction

As the global demand for clean and sustainable energy continues to rise, the search for renewable energy sources has become paramount. Among these sources, hydropower stands out as a reliable and well-established option that helps reduce dependence on fossil fuels, which are currently responsible for half of the low-carbon electricity generated worldwide, and mitigate climate change [1]. Hydropower can play a significant role in supporting other renewable energy sources and contributing to a diversified and sustainable energy mix [2,3]. There are several ways in which hydropower can complement and support other forms of renewable energy. Water stored in reservoirs created by dams can act as a base load power source and provide consistent and continuous power generation, compensating for short-term and seasonal variations and intermittency in other renewable sources such as solar and wind power [4,5]. Additionally, hydropower production can be deployed as needed and can be rapidly dispatched to the grid to match fluctuations in electricity demand, helping to maintain a stable and reliable power supply [6]. The increasing relevance of renewable energy sources (RESs) highlights the benefits of being able to store energy more efficiently, especially considering the variability and uncertainty of some RESs, such as wind and solar power. Pumped hydroelectric energy storage is a well-established technology for energy storage at a large scale, being an effective way to store large amounts of energy and balance the intermittent nature of some RES [7,8]. However, realizing the full potential of hydropower requires more than just acknowledging its current significance. The development and efficient utilization of hydropower resources requires a thorough assessment, one that goes beyond the technical aspects and delves into the intricate intersections of economic, social, and environmental dimensions [9,10]. This comprehensive evaluation is essential for developing sustainable strategies that not only optimize energy production but also consider the broader implications on society and the environment [1].

Despite hydropower's significance in the transition to renewable energy sources, uncertainties and challenges persist. The impact of climate change on hydropower production, especially considering alterations in precipitation and temperature regimes, requires thorough investigation. Integrated Assessment Models (IAMs) play a central role in sustainability evaluation by providing a comprehensive framework for analyzing and understanding the complex interactions between the various components of a system [11–13]. These models can integrate information from multiple disciplines to assess the environmental, social, economic, and political aspects of sustainability [14,15]. IAMs are often used to evaluate different future scenarios by changing input parameters. This helps in assessing the potential outcomes of different climate scenarios, policy decisions, technological advancements, or changes in human behavior.

Several studies have tried to assess the global hydropower potential production under climate change scenarios [16,17]. However, there is still a high degree of uncertainty on how long-term societal options lead to a myriad of outcomes in water and land use, energy production, and emissions. Therefore, there is a need for a better understanding of the multi-sectoral interactions, trade-offs, and synergies between hydropower potential and other sectors such as agriculture, industry, and water supply.

This study seeks to significantly improve upon existing research by incorporating critical data from the Shared Socioeconomic Pathways (SSPs) in the new "Within Limits Integrated Assessment Model" (WILIAM) to analyze how varying levels of socioeconomic development, mitigation efforts, and adaptation strategies influence primary energy demand. SSPs scenarios represent population changes, economic growth, education, urbanization, and technical developments that will affect future emissions, also having a link with the previous "Representative Concentration Pathways" (RCPs) [18], which are only based on greenhouse gas concentrations. We used IAMs to understand the multi-sectoral interactions and trade-offs between hydropower potential and other sectors such as agriculture, industry, and water supply. This allowed us to assess the potential impacts of different climate scenarios, policy decisions, technological advancements, and changes in human behavior on future hydropower potential production.

The hydropower potential production of the future is influenced by a variety of factors, including climate change, demography, societal development, technological advancements, and governance [19–23]. The SSPs provide a framework for exploring different future scenarios based on varying levels of socioeconomic development, mitigation efforts, and adaptation strategies [24–26]. In this study, SSP scenarios were used as inputs for an IAM to evaluate how the various socioeconomic pathways may influence primary energy demand. This demand is then evaluated against the different choices associated with the

SSP scenarios, which influence the energy mix and in particular the ways in which future hydropower potential production could change.

Previously, a study using the WILIAM model to assess hydropower potential under future RCP scenarios disclosed a general decrease in hydropower potential in the future until 2050 [26]. This paper significantly improves upon this previous work by including SSP scenarios in the WILIAM model, with a focus on GDP, population, energy uses (including fossil and renewable options), temperature, and radiative forcing. The main objective of this paper is to assess the hydropower potential for future scenarios, with a focus on the narratives of the SSPs. With this purpose, we are also significantly improving the potential of the WILIAM model in researching future scenarios, increasing the range of possible results. This approach will provide insights into the complex relationships between hydropower potential, climate change, and socioeconomic factors, contributing to a more comprehensive understanding of sustainable energy planning.

2. Materials and Methods

The IAM used in this work is based on the "Within Limits Integrated Assessment Model" (WILIAM) and MEDEAS [27] modeling framework, which are open-source IAMs designed to support the transition towards a low-carbon and less resource-intensive economy [28].

The WILIAM model, which includes the submodules of Economy, Energy, Land and Water, Society, Demography, Materials, and Climate, runs in 9 regions, defined as European Union (EU27); United Kingdom (UK); China; India; Eastern Asia and Oceania (EASOC); United States, Mexico, and Canada (USMCA); Russia; Latin America (LATAM); and Rest of the World (LROW). Additionally, the economic data run in 62 sectors, divided into Agriculture, Industry, Transport, Energy, and Households sectors, and they are also linked with other submodules, such as Land and Water.

Data from the SSP scenarios were used as input for the IAM model. These variables are population, GDP, temperature, total radiative forcing, and precipitation (Figure 1). The main data sources for these variables are [17,18,25,28–31]. Additionally, we estimated potential evapotranspiration by the Hargreaves method [32], using countries' maximum, average, and minimum temperatures (derived from [33]) and the estimation of extraterrestrial radiation, which is a function of the day of the year, from the average countries' latitude. Regional and global values of precipitation and evapotranspiration were estimated from the average values weighed by the countries' areas.

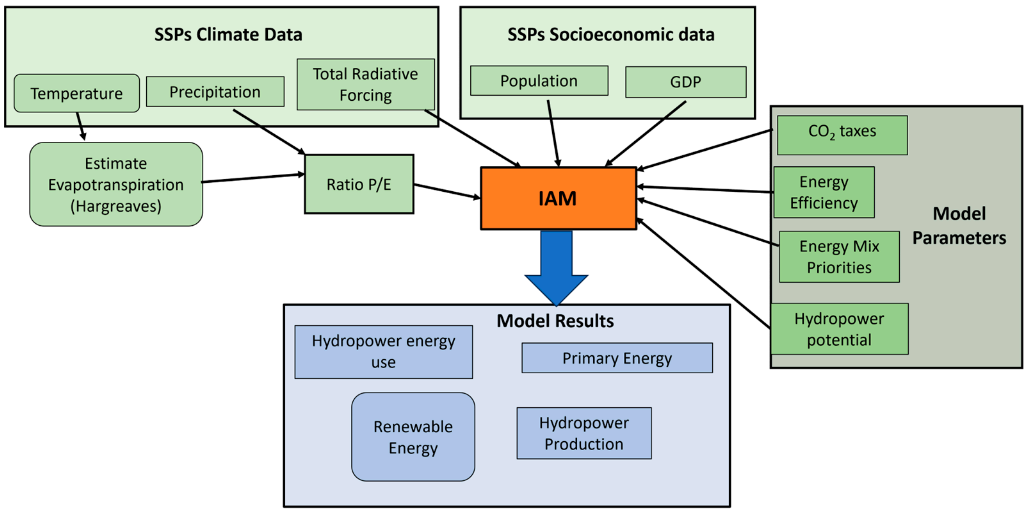


Figure 1. Scheme of the methodology used for the IAM discussed in this article.

The ratio of precipitation divided by evapotranspiration (ratio P/E), for each region, was computed for three future periods—2020–2039, 2040–2059, and 2060–2079—and compared with the present climate, the historical period 1995–2014. Values of ratio P/E > 1 indicate that future ratio P/E may increase and, consequently, the water availability may increase. On the contrary, values of ratio P/E < 1 indicate that the ratio can decrease in future years and that the water availability will be lower. The ratio P/E influences the hydropower capacity, which depends on biophysical limitations. In the case of hydropower, these limitations are ratio P/E changes, which are linked to water availability changes. These modifications affect hydropower production, which depends on both climate change and socioeconomic factors.

PySD [34] software v3.12.0 (Simulating System Dynamics Models in Python) was used to run the WILIAM model in a Python environment for five SSPs—SSP1, SSP2, SSP3, SSP4, and SSP5—in the baseline scenarios.

The SSPs consider a wide range of factors, including demographics, economic development, technology, and energy use. The SSPs consider different levels of mitigation and adaptation measures, resulting in different future trajectories [25]. Each SSP scenario represents a different narrative of societal development and is associated with different patterns of energy production and consumption.

The world in SSP1 ("Sustainability—Taking the green road") is characterized by a shift towards sustainability, with effective cooperation in all sectors of the economy and a rapid transition to low-carbon practices. In the economy, the emphasis changes from economic growth to human well-being, with a decrease in inequality and high levels of investment in education and health. The population will increase until the middle of this century and then decline. In the energy sector, there is an emphasis on energy efficiency and sustainable practices; thus, SSP1 is the scenario that has the highest share of renewable energy, with less energy demand and a significant reduction in fossil fuel use. The world will have low challenges in terms of mitigation and adaptation.

SSP2 ("Middle of the Road") illustrates a path similar to the one that the world is currently on in terms of its social, economic, and technological trends. Economic development is still differentiated between countries and regions, and the markets function imperfectly, with slow progress in reaching sustainable development goals. The world population is expected to grow in a moderate way, with stabilization after the middle of the century. In the energy sector, there is a moderate share of renewable sources, with a substantial yet slowly diminishing role for fossil fuels. The world will have moderate challenges in terms of mitigation and adaptation.

SSP3 ("Regional rivalry—A rocky road") portrays a world with many regional disparities and high competition, leading to policies increasingly oriented toward national and regional concerns, with uneven efforts to address global challenges. Education and technology will receive less investment, leading to high levels of inequality between and within countries and regions, together with strong environmental degradation in some regions. Population growth is expected to be highly differentiated, being low in industrialized countries and high in developing countries. In the energy sector, there is still a strong dependence on fossil fuels, with a slower adoption of low-carbon technologies, leading to higher GHG emissions compared to the other SSPs. The world will have high challenges to mitigation and adaptation.

SSP4 ("Inequality—A road divided") describes a future with high levels of inequality, as technological improvements and environmental conservation practices are uneven. Economic growth will be moderate in industrialized middle-income countries, with a higher contrast with low-income countries, characterized by several basic problems. Technology development is expected to be prominent in the high-tech sectors of the economy. The world population is expected to undergo a similar trend to the one in the SSP2 scenario. Energy is focused on traditional and less efficient energy sources. Globally, fossil fuels dominate the energy mix, and the share of renewable energy is thus limited. However, there will be some development of low-carbon supply options, leading to low challenges to mitigation. On the other hand, the challenges to adaptation are high.

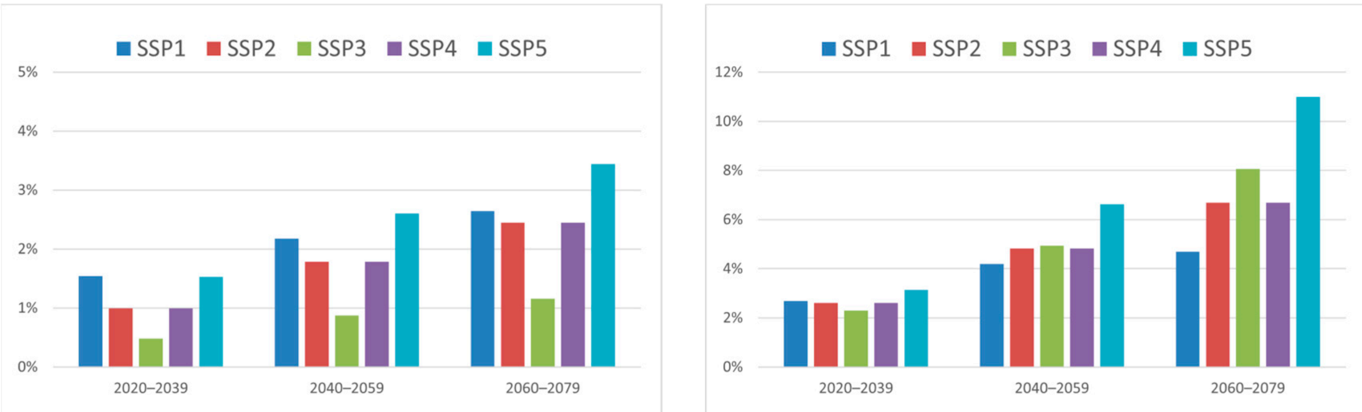
Finally, SSP5 ("Fossil-fueled development—Taking the highway") envisions a future where economic growth is prioritized over environmental concerns. There is a focus on innovation which produces rapid technological progress, with high levels of investment in education, health, and the enhancement of social and human capital. Economic and social development, combined with high energy demands, leads to rapid growth in the global economy. Environmental impacts are addressed using technological solutions. The world population is expected to experience a similar trend to the SSP1 scenario. Energy sources rely on the mass exploitation of fossil fuel resources and a relatively low share of alternative renewable sources. This world will have high challenges to mitigation and low challenges to adaptation.

The WILIAM model allows for users to input a set of variables that define future socioeconomic scenarios. Our purpose was to approximate these future scenarios to the SSPs. Furthermore, some scenario parameters, such as CO_2 taxes, energy efficiency, energy mix priorities, and hydropower pumped storage potential (Figure 1), were modified, which impacted our results significantly. The scenario parameters were different for each SSP; for example, the energy mix priorities in SSP1 are driven by an increased use of renewable energy. Oppositely, in the SSP5 scenario, the energy priorities center around fossil fuels, according to the SSP narratives. The main data sources for these variables are [17,18,25,28–31]. The model is run between the historical period and the future up to the year 2080.

3. Results

Climate Change

Precipitation and evapotranspiration values, at the global level, anticipate an increase of both variables,, with the increases being larger in SSP5, reaching more than 3% and 10%, respectively (Figure 2). Evapotranspiration's growth is higher than the precipitation, being more than double in almost all scenarios, except for SSP5. Additionally, the increases will be increasingly larger across the century. The SSP with the lowest expected growth in precipitation is SSP3 and, for evapotranspiration, the lowest predicted increase was found for SSP1, after 2040.



(**a**) (**b**)

Figure 2. Projections derived from the future SSPs (SSP1, SSP2, SSP3, SSP4, and SSP5) compared with the historical period for (**a**) precipitation and (**b**) evapotranspiration (both shown as percentage values).

The precipitation and evapotranspiration changes for the nine regions, SSP scenarios, and three future periods are detailed in Tables S1 and S2 in the Supplementary Materials.

The future scenarios indicate a decrease in the ratio P/E globally in the five SSPs (Figure 3). The expected decrease is more expressive in the 2060–2079 period of SSP5, with a 7% lower ratio P/E value. Effectively, the SSP5 scenario also shows the highest reduction in the period 2040–2059, with 4% less than the present climate. Upon closer analysis, it was found that the ratio P/E decreased by 1.7%, 3.8%, and 6.5% in the SSP3 scenario in the 2020–2039, 2040–2059, and 2060–2079 periods, respectively, with this scenario having the second-highest decreases. On the contrary, the most conservative scenario is SSP1, with expected reductions of 1%, 2%, and a little above 2% for the three periods, respectively. Additionally, SSP1 is the only scenario where the value projected for 2040–2059 is similar to the one projected for 2060–2079. In the other two scenarios (SSP2 and SSP4), the IAM anticipates a decreasing pattern throughout the three periods, with higher declines of around 4% in the 2060–2079 period.

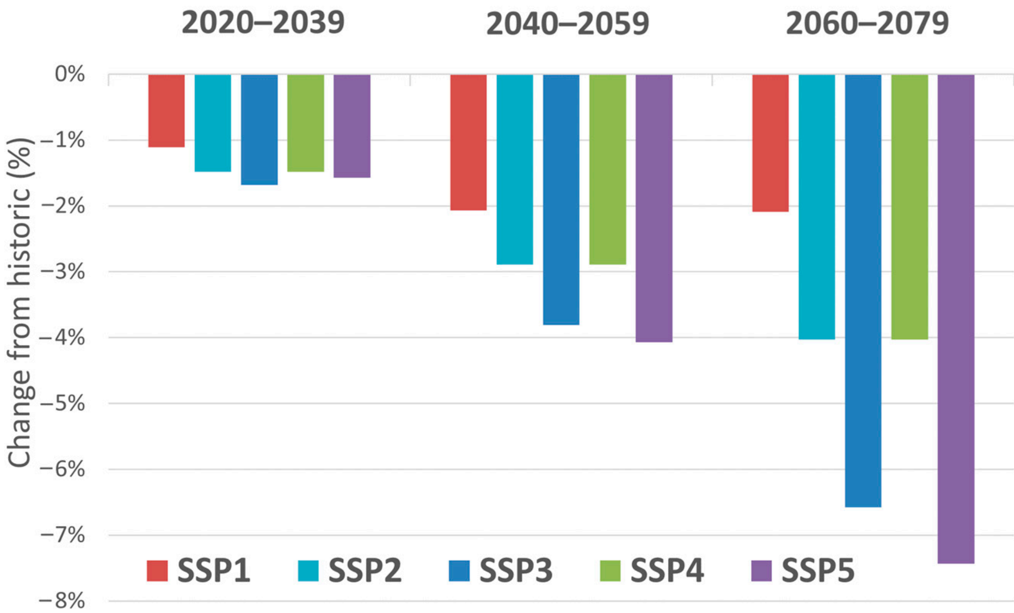


Figure 3. Change from historical ratio P/E (world average) to the three future periods—2020–2039, 2040–2059, and 2060–2079—for the five SSPs.

Global primary energy use was sectorized for twelve energy sources, and we found major changes in the different SSPs until 2080 (Figure 4), with an energy use peak near 2050 and a decline occurring afterwards. The most noteworthy contrast between the scenarios is the progressive decline in the use of coal energy, which becomes negligible after 2060 in SSP1 and after 2070 in SSP4. Additionally, the use of oil for energy also progressively declines to small values in SSP3 and SSP5, with increases in the use of coal and natural gas, especially after 2050 and 2070, respectively. Nuclear energy also has distinct paths in the future scenarios, with a progressive decrease to insignificant values in SSP1 (after 2050) and SSP2 (after 2070). A different trend is projected for SSP3 and SSP5, with both showing a small increase in the use of nuclear energy. The SSP4 scenario estimates a progressive decline in nuclear energy use and stabilization after 2060.

Analyzing the renewable energy sources, there is an increase in the use of forestry products and hydropower, along with a small increase in solar power use, in the SSP1 scenario. The largest increase in solar power use belongs to SSP2; on the other hand, in SSP3 and SSP5, it has negligible values after 2050. Wind power use is higher in the SSP1 and SSP2 scenarios, with larger values in SSP1 and growing values until 2060 before a small decline. For the other scenarios, a small increase is projected until 2030 and after a progressive decline (SSP3 and SSP5) or stabilization (SSP4) is expected. Hydropower use is more prominent in the SSP1 scenario, with a progressive increase until the end of the final period (2080). In SSP2, there is also a progressive increase, but only until 2040, with values remaining constant thereafter. For the other scenarios, an increase in hydropower use until 2035 is projected, with a small increase (SSP4) or a small decrease (SSP3 and SSP5) taking place thereafter. The share of each energy group (fossil, renewable, and bio and organic) (in percentage) of the total energy is detailed in Table S3 in the Supplementary Materials.

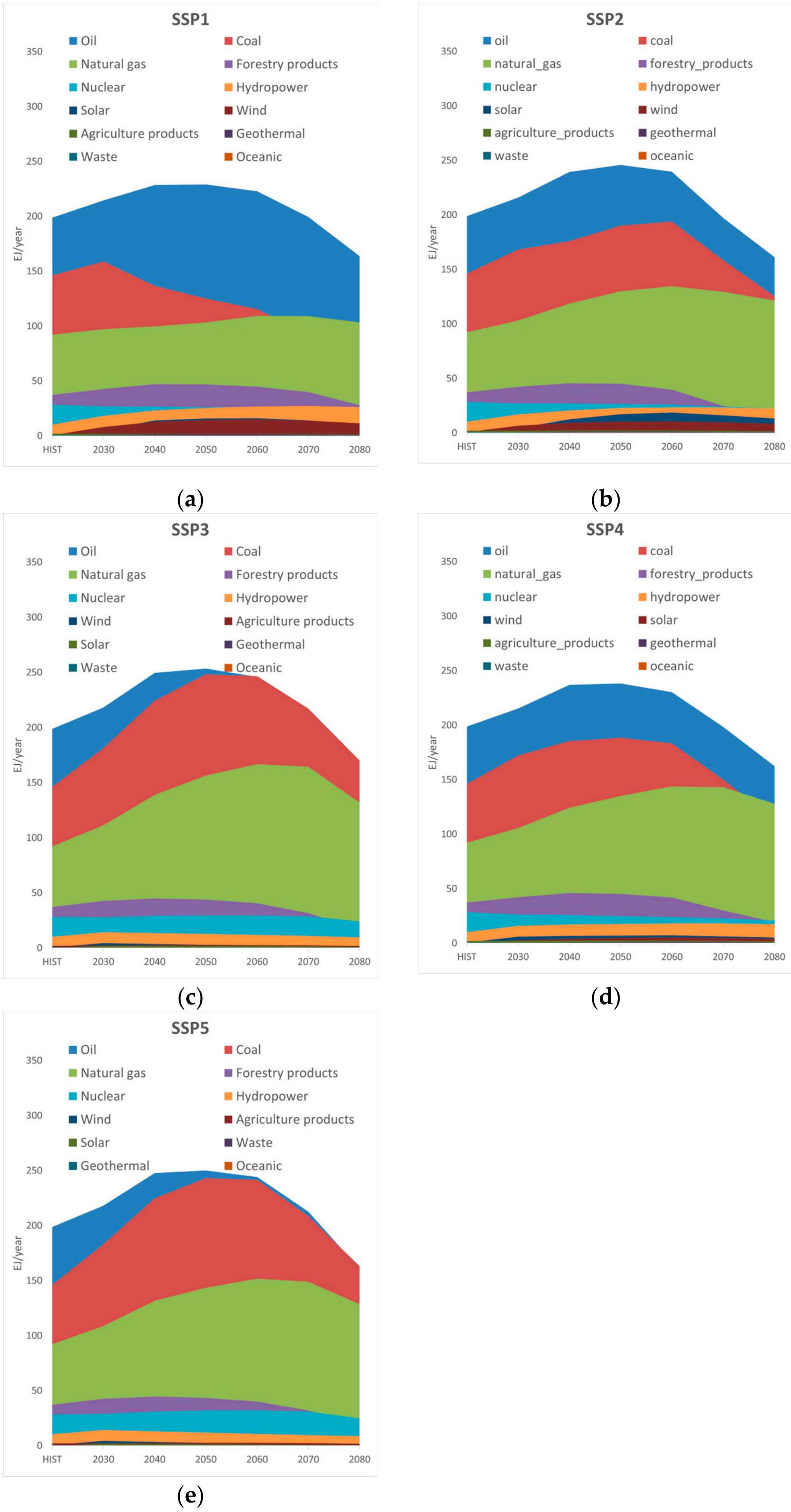


Figure 4. Global primary energy use according to historical data and data from the projections of the five SSPs—(**a**) SSP1; (**b**) SSP2; (**c**) SSP3; (**d**) SSP4, and (**e**) SSP5—(until 2080) sectorized by twelve energy sources: oil, natural gas, nuclear energy, wind power, solar power, geothermal energy, coal, forestry products, hydropower, agriculture products, waste, and oceanic energy.

Global renewable energy use shows a peak in 2060 for three SSPs (SSP1, SSP2, and SSP4) and a decline in 2080 (Figure 5). In the other two scenarios (SSP3 and SSP5), the projections indicate that the use of renewable energy will decline after 2030, with lower values anticipated for the SSP5 scenario. The expected path for future renewable energy use is similar in SSP1 and SSP2, with higher amounts in the SSP1 scenario, which shows a significant increase between the historical period and 2050. The increase is less dramatic in the SSP4, which has nearly half the value of SSP1. The modeled values suggest a gradual decrease in renewable energy use on a global scale in the SSP3 and SSP5 scenarios, which show lower values when compared with the other three scenarios.

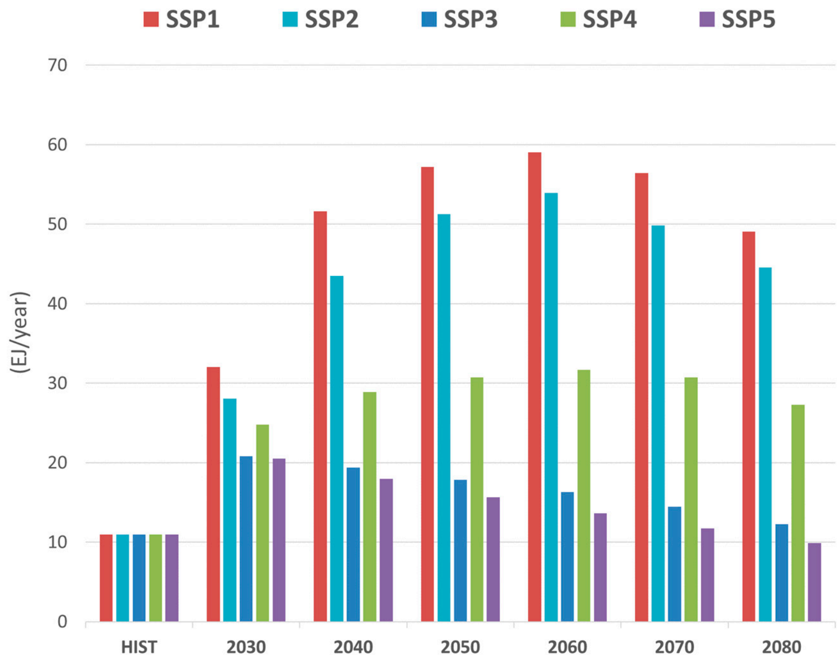


Figure 5. Global renewable energy use (world average) based on historical data and data modeled for 2030, 2040, 2050, 2060, 2070, and 2080 for the five SSPs.

Upon analyzing the change from the historical share of renewable energy, it is evident that an increase is projected in three scenarios, especially in the SSP1 and SSP2, reaching amounts above 400% and almost 300%, respectively, in the last period (Figure 6). The paths for the future show similar values with respect to global renewable energy use (Figure 5), with increasing values across the century in SSP1, SSP2, and SSP4 and an expected decrease (below 100%) in SSP3 and SSP5. Effectively, the IAM modeled very low percentages for renewable energy use in both scenarios, reaching only 5% in SSP3 for the 2060–2079 period.

The modeled hydropower energy use projections are aligned with an expected increase in the future, except for the SSP5 scenario, where a decrease of 10% in the 2060–2079 period is estimated (Figure 7). The scenario with the highest projected increase is SSP1, reaching more than 160% in 2060–2079 and around 155% in 2040–2059. In the SSP2 scenario, the projected increases are around 55%, 65%, and 50%, respectively, for the three periods: 2020–2039, 2040–2059, and 2060–2079. Contrasting with these strongly increasing amounts across the century, the projections of SSP3 show an increase in the three periods but are almost stable in the final period (35%, 20%, and 2%, respectively). SSP4 presents a high increase in hydropower energy use, similar to SSP1, but with more modest values, reaching almost 85%, 130%, and 140%, respectively. Finally, SSP5 also shows relatively small increases in the first two periods, with hydropower energy use increasing by around 35% in 2020–2039 and 10% in 2040–2059.

The hydropower production projections for the nine regions are dissimilar to the global hydropower energy use data. Effectively, there are several regions with an expected decrease in hydropower production due to both lower water availability and socioeconomic paths (Table 1). Exploring each region, an increase in hydropower production is expected in the EU27 region in most scenarios, except for SSP3 and SSP5, reaching less than 46% in SSP5 and 2060–2079. In the UK, a small decrease is anticipated in most of the projections. Oppositely, in China, the expectation is that hydropower production will substantially increase in all modeled scenarios and periods. Diverse outcomes are modeled for the EASOC region, with substantial growth in SSP1 and SSP4 and a decrease after 2040 for the other scenarios. In India, the projections suggest an increase in hydropower production, except for very small declines in three scenarios in the 2060–2079 period. The LATAM results are similar to China's, with relatively lower increases, except in the 2060–2079 period of the SSP5 scenario, where a decrease is expected. Russia has distinct consequences resulting from future climate change and the socioeconomic scenarios, with an increase in SSP1 and SSP4 and mostly decreases in the other projections. Similar results are anticipated for the USMCA region, but growth is expected for SSP1, SSP2, and SSP4, and a decline is forecasted in the other scenarios. Finally, for the LROW results, the results anticipate large growth in hydropower production for SSP1 and SSP4, an increase for SSP2, and a decrease for SSP3 and SSP5 after 2040. The results presented in Table 1 are also displayed in graphic form in Figure S1 in the Supplementary Materials.

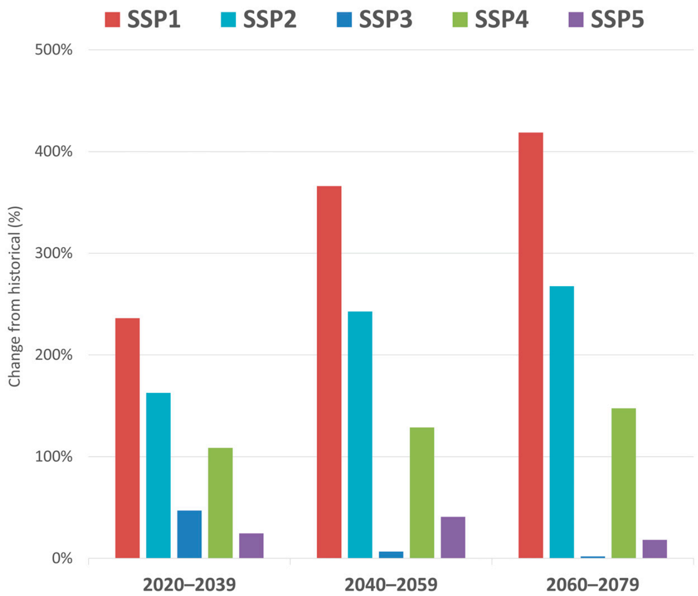


Figure 6. Change from share of renewable energy (world average) to the three future periods—2020–2039, 2040–2059, and 2060–2079—regarding the five SSPs.

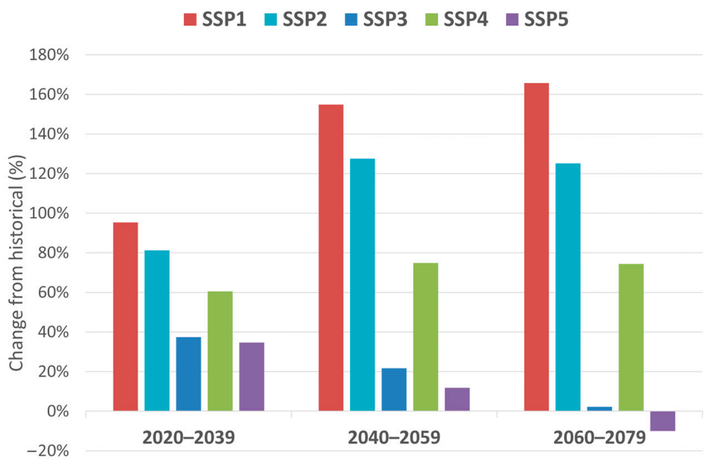


Figure 7. Change from historical hydropower energy use (world average) to the three future periods—2020–2039, 2040–2059, and 2060–2079—regarding the five SSPs.

Table 1. Hydropower production changes compared with the historical period for SSP1, SSP2, SSP3, SSP4, and SSP5; for 2020–2039, 2040–2059, and 2060–2079; and for the following nine regions: EU27, UK, China, EASOC, India, LATAM, Russia, USMCA, and LROW.

	SSP1			SSP2			SSP3			SSP4			SSP5		
	2020–2039	**2040–2059**	**2060–2079**	**2020–2039**	**2040–2059**	**2060–2079**	**2020–2039**	**2040–2059**	**2060–2079**	**2020–2039**	**2040–2059**	**2060–2079**	**2020–2039**	**2040–2059**	**2060–2079**
EU27	58%	47%	43%	40%	41%	34%	−8%	−26%	−42%	55%	45%	39%	−10%	−29%	−46%
UK	11%	−12%	−17%	11%	−11%	−19%	11%	−11%	−22%	11%	−12%	−18%	11%	−12%	−29%
CHINA	188%	193%	175%	179%	175%	163%	168%	157%	123%	182%	184%	176%	163%	130%	91%
EASOC	65%	292%	272%	18%	−3%	−20%	17%	−4%	−24%	42%	98%	101%	18%	−5%	−24%
INDIA	40%	47%	24%	36%	16%	−2%	36%	15%	−5%	37%	26%	6%	38%	17%	−2%
LATAM	63%	143%	254%	55%	89%	111%	43%	41%	29%	63%	127%	194%	31%	8%	−13%
RUSSIA	51%	46%	42%	5%	−9%	−17%	2%	−17%	−34%	47%	43%	38%	2%	−18%	−37%
USMCA	64%	64%	62%	19%	41%	35%	−2%	−20%	−37%	64%	63%	59%	−2%	−21%	−38%
LROW	133%	301%	307%	29%	41%	41%	14%	−8%	−26%	93%	258%	271%	13%	−9%	−28%

4. Discussion

Global projections for precipitation and evapotranspiration anticipate an increase in both variables in the five SSPs; however, the increase in evapotranspiration will be higher than the localized increase in precipitation, leading to less water being available in most parts of the world [35]. Consequently, the global ratio P/E, which reflects the future water availability path, is expected to gradually decline until 2080, with larger reductions being forecasted in the SSP5 and SSP3 scenarios.

Derived from exploring the sectorized global primary energy use across the five SSPs, our analysis results reveal distinctive trends, as well as shifts in energy sources, which have significant implications for the future global energy landscape. A crucial observation is the progressive decline in coal's energy contribution, which becomes negligible after 2060 in SSP1 and later in SSP4. Furthermore, the diversified trajectories of oil energy share are a result of the combined effect of the coal share reductions, particularly in SSP1 and SSP4, and the increased share of natural gas in all SSP scenarios. The fact that coal's share is higher in the SSP3 and SSP5 scenarios is related to the fact that in these scenarios, there are no incentives for the use of less carbon-intensive energy sources; thus, carbon taxes are lower, and when the price of coal is lower than that of oil, the former is preferred in the model and replaces oil use. In all SSP scenarios, natural gas becomes the dominant energy source, which reflects the combined effect of the lower price of this commodity and a preference for lower carbon emissions, a general premise of the IAM used in this study.

The share of renewable energy sources, despite remaining lower in absolute value when compared to fossil sources, does evidence a significant increase when compared to the historical values. Particularly the SSP1 and SSP2 scenarios, generally show higher usage of renewable energy with an increasing share, which reaches above 400% and almost 300%, respectively, in 2080. SSP4 shows a moderate increase in renewable energy use, with values around half of those of SSP1. SSP3 and SSP5 indicate a very limited share in renewable energy use, decreasing slightly over time. In these two scenarios, nuclear power remains almost constant throughout time and continues to provide more energy than renewables, which contrasts with the other scenarios, particularly in SSP1 and SSP2, in which renewables are more relevant.

The hydropower energy use projections indicate a general expected increase for the future across most scenarios. The only exception is the SSP5 scenario, which estimates a decrease of 10% in the 2060-2079 period, thus deviating from the other scenarios general increase trend. SSP1 stands out with the highest projected increase, exceeding 150% after 2040. In SSP2, the projected increases are above 120% after 2040. SSP4 presents a moderate increase in hydropower use, reaching values between 60% and 75%. SSP3 and SSP5 share a similar change from the historical period and a tendency to decrease as time advances which is somewhat aligned with the general trend in renewable energy sources. Effectively, hydropower is often considered fundamental in the transition towards renewable energy sources, contributing significantly to greenhouse gas emissions reduction and energy supply security [36,37].

Hydropower production will be influenced by climate change due to water availability changes and also differences in socioeconomic pathways. The results regarding hydropower production in the five SSPs for the nine regions across the century are dissimilar. In SSP1 and SSP4, the model shows an increase in hydropower production in almost all parts of the world, except for the UK. However, in the other SSP scenarios, the results are divergent, with large increases in some regions and important decreases in others. The most relevant result is the expected decline in hydropower production in almost all parts of the world in SSP3 and SSP5 for the 2060–2079 period, which is mostly associated with the higher fossil fuel use in these scenarios. These results are similar to those obtained by other authors, such as the authors of [16], who used a multi-model ensemble in their study and concluded that the largest increases will be found in high-latitude regions such as India and Central Africa, reaching 33% by 2080. Additionally, the same authors [16] anticipate the largest decline, more than 20%, for the United States, Europe, and Eastern Asia.

The projected changes in precipitation and temperature regimes can affect hydropower production across the world [2,38,39]. Moreover, due to climate change impacts, hydropower will have competition from other renewable energy sources (mainly solar PV and wind power) [2,40].

Several studies on the impact of meteorological changes on hydropower production in small countries like Ecuador and Portugal have estimated substantial decreases in hydropower production of 18% and 41%, respectively [40,41]. Other findings suggest that a decrease in precipitation, independent of temperature changes, has the potential to compromise the operational efficiency of hydroelectric plants [42]. This highlights the vulnerability of hydropower to meteorological variations, emphasizing the importance of understanding both precipitation and temperature patterns for effective energy planning.

These findings provide a nuanced understanding of the future trajectory of renewable energy share and hydropower use across different socioeconomic scenarios. SSP1 and SSP2 appear to be more optimistic scenarios with more expressive increases in renewable energy, while SSP3 and SSP5 depict a less encouraging outlook, particularly for renewable energy use. These results are in line with other published articles on SSPs [28,29,31], especially when comparing the future trends; however, the primary energy values for the future are not similar. Another study on forecasting socioeconomic paths also projects very low coal and oil use in the most optimistic scenarios but also lower natural gas values [43].

Global final energy demand is linked to the main socioeconomic drivers of economic development, population changes, technological innovations, and societal choices [18,25,30]. Historically, population changes and economic growth are the most important factors influencing energy demand [30,44]; however, hydropower's future potential is dependent on additional factors, such as energy demand, climate change, and reservoir management, among many others. In particular, reservoir management strategies can be used to optimize the balance between water supply reliability for irrigation and human consumption [45,46] and the water available for hydropower production [41,47].

While the results of this study align with certain aspects of published articles on SSPs, the energy values found in this study differ, underscoring the complexity of predicting future energy landscapes accurately. The five main SSP narratives loaded in the IAM were also used by the IPCC in their reports. The decision was made to use only the baseline scenario in each of the SSP's narratives to study the IAM outcomes in the absence of new climate policies beyond those already in place today. Nevertheless, the objective of this article is not to fully represent the future world but instead to model the future differing trends in energy use while acknowledging that the IAM has some limitations.

This work emphasizes the importance of using the SSPs scenarios in combination with an IAM, providing insights for future climate research. The scenarios cover a broad range of dimensions; however, the SSPs baseline scenarios have limitations in the way they incorporate climate policies focused on reducing emissions and also in the accounting of feedback mechanisms associated with the impacts of climate change on the economy, energy, and land management.

5. Conclusions

The narratives of the SSPs considered in this study provide a framework for the various dimensions that determine the challenges to mitigation and adaptation. In this work, they are used to generate potential scenarios for the evolution of the global energy system, particularly for the share of renewable sources in the energy mix and, even more specifically, for hydropower production.

The SSPs scenarios vary significantly in terms of the energy futures they depict, encompassing different demand trends and supply systems. The factors influencing these differences include assumptions about technological innovations, socioeconomic development, energy demand, and the balance between the availability and costs of fossil fuels and renewable alternatives.

The energy demand projections across the different SSPs scenarios vary widely, impacting mitigation and adaptation challenges. The SSP3 and SSP5 scenarios rely heavily on fossil fuels, particularly coal, posing high mitigation challenges. In contrast, SSP1 and SSP4 foresee an increasing share of renewable sources, associated with successful energy efficiency measures, thus depicting a future with fewer mitigation challenges. The SSP2 scenario, characterized as a "middle-of-the-road" narrative, envisions a balanced evolution of the energy landscape that entails a sustained reliance on the current fossil fuel-dominated energy mix, presenting challenges of intermediate magnitude in terms of both mitigation and adaptation.

The projections for hydropower energy use present a dynamic landscape, displaying varied trajectories across the different SSP scenarios. Most scenarios indicate that a general increase is probable. SSP1 and SSP2 project the highest increase, especially after 2040, while the SSP5 scenario stands out with a notable deviation in the form of a decrease in the 2060–2079 period. The influence of climate change, particularly alterations in water availability, adds another layer of complexity to hydropower production projections. The dissimilar results across the five SSPs and nine regions highlight the nuanced interplay of socioeconomic factors and climatic influences and their impacts on the future of hydropower.

These findings highlight the importance of considering a range of potential future scenarios in energy planning and policy development. The varied outcomes across the scenarios emphasize the need for flexibility in strategies to accommodate for uncertainties and address the challenges posed by divergent trajectories in hydropower use and renewable energy shares.

Suggestions for future work include the integration of feedback mechanisms into the SSP scenarios, which would improve the understanding of the way climate change impacts might influence socioeconomic development. Another approach that can be adopted is to explore cross-sectoral interactions in more detail, examining how changes in one sector (e.g., energy) might impact others (e.g., agriculture, water resources). This can provide insights into potential synergies or conflicts between different development pathways.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16041548/s1, Figure S1. Hydropower production changes, in percentage, compared with the historical period, for the SSP1, SSP2, SSP3, SSP4 and SSP5; for 2020-2039, 2040-2059 and 2060-2079; and for the 9 regions: EU27, UK, China, EASOC, India, LATAM, Russia, USMCA and LROW. Table S1. Precipitation changes for the nine regions. Table S2. Evapotranspiration changes for the nine regions. Table S3. Share of each energy source group in % of the total energy. Fossil includes Oil, Coal, Natural gas, and Nuclear; Renewable includes Hydropower, Solar, Wind, Geothermal, and Oceanic; and Bio & Organic, which includes Forestry products, Agriculture products, and Waste

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