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Energy planning in the Eastern Nile Basin countries: the role of floating solar photovoltaics on hydropower reservoirs

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Abstract

The Eastern Nile Basin is a highly populated region dealing with inadequate energy systems and water scarcity issues. Moreover, its population is expected to increase in the following decades, leading to even higher electricity and water demands. In order to sustainably meet this demands and guarantee access to electricity and water for all, new technologies and careful energy planning can play an important role. In this context, floating solar power is a relatively new technology with promising advantages, such as the synergies between solar and hydropower resources, the exploitation of already existing infrastructures, and the reduction of evaporation rates and land use. These become even more relevant if seen in the context of the Eastern Nile Basin countries, where the need for efficient energy sources and solutions to the water scarcity issues are vital.

In this work, the role of floating solar power in the sustainable fulfillment of the increasing energy demand of the region is explored. The novelty of this study consist in the introduction of floating solar power in a long term regional energy system cost-optimization model (OSeMOSYS-TEMBA) at a single plant resolution. To do so, the single hydropower plants are also explicitly modelled, allowing both the spatial disaggregation of floating solar power plants and the connectivity between the countries via the Nile river. The regional approach is further enhanced by the presence of electricity trade links between countries, which connect the energy systems of the single countries directly. Finally, the role of floating solar power on the energy system's footprints is evaluated in terms of CO2 emissions, land use and water savings. To this extent, a new methodology for land use accounting and pricing is proposed, and findings from previous studies are brought together to assess the evaporation reduction rates caused by the floating solar power plants. This extended modelling framework is then used to analyse different scenarios, exploring hydrological regimes under different climate change projections and policy decisions such as the introduction of taxes for carbon emissions and land use change.

The results show that floating solar photovoltaics are a cost-optimal technology since early stages in the modelling horizon, and their full assumed potential is developed under every scenario. Their role in satisfying the energy demand of the whole region reaches 3% of the generation mix in the reference scenario, but it increases to 4.3% with the introduction of taxes on carbon emissions and land use. Moreover, the introduction of such policies cause an anticipation of floating solar power's capacity expansion. On the other hand, the tested climate change projections do not affect the results relevantly. The sensitivity analyses, however, prove that the obtained results are very sensitive to the assumptions behind capacity constraints and costs of these technologies, which need more dedicated research. As far as the energy system's footprints are concerned, the results show that the implementation of floating solar power can help reduce the total emissions and land use slightly, and cause evaporation reduction rates up to 376 million m^3/y (approximately 2% of the total evaporation from hydropower reservoirs). The optimal locations to invest in this technology are identified to be the largest hydropower plants in the system (Lake Nasser, the Grand Ethiopian Renaissance Dam and Merowe reservoir), but the reason of this choice relies in the very large size of these plants, which emerge for highest FPV capacity deployment and water evaporation savings at the large scales considered. Future research is still needed to reduce the uncertainty behind the key parameters (costs, capacity constraints), improve the representation of hydropower production, improve the evaporation assessments and investigate the effects of implementing floating solar power at smaller spatial and temporal scales.

Contents

List of Figures

List of Tables

List of symbols and acronyms

Symbol	Meaning
ENB	Eastern Nile Basin
FPV	Floating photovoltaics
GERD	Grand Ethiopian Renaissance Dam
RCP	Representative Concentration Pathway
SSP	Shared Socioceonomic Pathway
PJ	Petajoule
M$	Million USA dollar
Mt	Megatonne
mcm	Million cubic meter

1 Introduction

With the current global energy crisis, it becomes more and more important to accelerate the development of clean energy sources and increase the self-sufficiency of countries in terms of energy production. At the same time, the ongoing climate change is posing a threat to water resources, with prolonged droughts and changed rainfall patterns that are decreasing water systems' reliability. Therefore, there is the danger that traditional large scale hydropower plants fail to provide the energy they were built for, and having to respect minimal flow conditions in times of droughts can result in energy shortages. This is especially true in those area of the world that are particularly impacted by climate change and economic instability, such as North-Eastern Africa. Here, the strong reliance of energy systems on hydropower production is making the already harsh competition over water resources very fierce. In particular, the Eastern Nile Basin is experiencing very tense relationships between its riparian countries, with the most recent object of dispute being the recently built Grand Ethiopian Renaissance Dam (GERD). In this context, new renewable technologies like floating solar power may help a sustainable and peaceful development of these countries. This technology in particular has a series of advantages, among others exploiting the synergy between hydropower and solar power resources and helping reducing evaporation from reservoirs.
This chapter analyses the status of the Eastern Nile Basin countries in terms of demographic and socio-economic development, together with the status of its water resources and energy system. This analysis is carried out in order to identify the current and future challenges of this region. Subsequently, the state of the art of the floating photovoltaic technology is analysed, as well as the results of a literature scan aimed at individuating research gaps in this field. Finally, the research questions of this work are identified.

1.1 Demographic and socio-economic development

Demographic context
The Nile basin (Figure 1) is home to around 10% of the population of Africa. The size of the population living within the basin has grown from 238 million in 2012 to 272 million in 2018 (Nile Basin Initiative, 2021). Most of this large population is found in the central and northern part of the basin, with Egypt, Ethiopia, Sudan, and Uganda alone accounting for over 75% of the total Basin population (Nile Basin Initiative, 2021).
In this study, we focus on the north-eastern part of the basin, which includes Ethiopia, Sudan, South Sudan and Egypt, from now on referred to as the Eastern Nile Basin (ENB) countries. As far as these countries are concerned, most recent data show a total population of almost 286 million people, the most of them living in Ethiopia (120M) and Egypt (109M), followed by Sudan (45,6M) and South Sudan (10,7M) (World Bank, a). Moreover, in Egypt, South Sudan and Sudan more than 80% of the total population lives within the Nile Basin area (Nile Basin Initiative, 2021).
In terms of demographic dynamics, population growth rates have been generally declining in the last decade in Egypt, Ethiopia and Sudan, while in South Sudan they have been very irregular due to political upheaval. However, these countries still have pretty high rate value: Sudan is the fastest growing with 2.7%, closely followed by Ethiopia (2.6%), Egypt (1.7%) and South Sudan (1.3%) (World Bank, a). Therefore, the Eastern Nile Basin countries' population is expected to continue its growth in the next decades, reaching 411 million by 2040 and 477 million by 2050 (World Bank, b). Even though in all of the four countries the rural population still constitutes the largest share (57% in Egypt, 64% in Sudan, 78% in Ethiopia and 79% in South Sudan), the urban population is increasing fast, with annual growing rates of 4.8% in Ethiopia, 3.7% in Sudan, 2.9% in South Sudan and 1.8% in Egypt (World Bank, a). This growth will lead to almost 225 million urban inhabitants in the ENB countries by 2050, around 46% of the total population (World Bank, b). According to the Nile Basin Initiative (2021), the urban expansion is occurring mostly in the Delta in Egypt and in the greater Addis Ababa region.

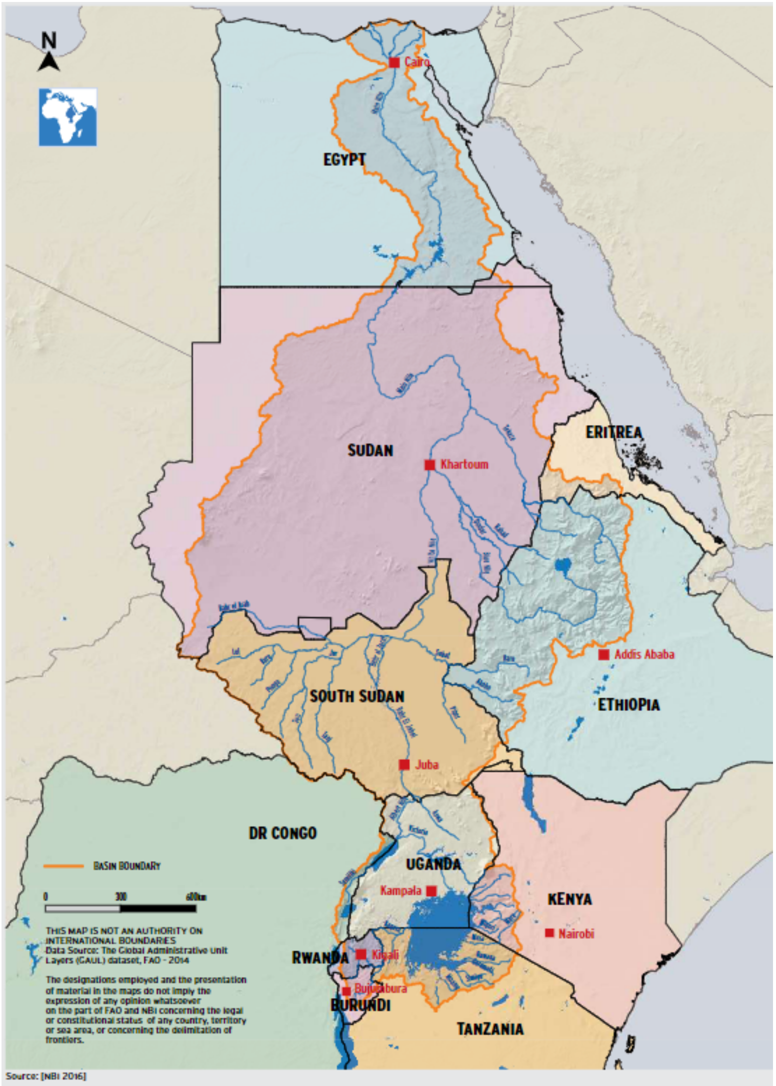


Figure 1: Map of the Nile basin (Nile Basin Initiative, 2021)

Socio-economic context
The Eastern Nile Basin countries, despite signs of economic growth in the last decades, remain among the poorest in the world. Apart from Egypt, the other three countries lie within the last 20 countries in the world for human development index (UNDP, 2022). In particular, reducing poverty, inequality, malnutrition and providing access to basic services remains a major challenge (Nile Basin Initiative, 2021). The latest values from the World Bank (World Bank, a) for the percentage of people living under the extreme poverty threshold of 2.15$ per day are 1.5% for Egypt (2019), 15.3% for Sudan (2014), 27% for Ethiopia (2015) and 67.3% for South Sudan (2014). Moreover, the COVID19 pandemic has hit most economies and is likely to reverse some of the gains recorded over the recent years (Nile Basin Initiative, 2021). In fact, the GDP growth rate sank in the period 2016-2021 years for all four countries: Egypt went from 2.2 to 1.6%, Ethiopia from 6.5 to 2.9% and Sudan from 0.3 to -4.5%. South Sudan does not have available data after 2015 (-10.6%) (World Bank, a). An important factor that explains the persistence of poverty in the Basin is the slow structural change of the economies. In the Nile Basin, the sectoral make-up of GDP has remained roughly constant since 2000 (Nile Basin Initiative, 2021).
Therefore, in order to fulfill their aspiration to become middle-income countries in the next future, these countries need careful infrastructure planning in order to undertake a sustainable industrialization.

1.2 Water resources in the Eastern Nile Basin countries

Hydrological characteristics
The Nile is the longest river on the planet, crossing 10 countries and diverse climate, topographic, environmental and socio-economic landscapes. Its basin extends from the big equatorial lakes in Tanzania until the Nile Delta in Egypt, covering an area spanning 36 degrees of latitude and 5 climate zones. Despite its length and its huge drainage area (3.2 milions of squared km), the mean annual runoff is estimated to be between 84 and 91 billion cubic meters only (Nile Basin Initiative, 2021). This number, combined with the amount of people that live in the basin, is relatively low, making the water a very precious and valuable resource in the region. The main reason behind this small discharge is the fact that a huge part of the basin lies in an arid area which generates no runoff and is characterised by high evaporation rates (up to 3000 mm/year in northern Sudan, (Nile Basin Initiative, 2021)). In fact, rainfall over the basin is highly uneven, with peaks in Ethiopia (1184 mm/yr) and lowest values in Sudan (260 mm/yr) and Egypt (20mm/yr). Additionally, the runoff coefficient is very low (less than 5%) in large parts of the basin, with exception of Ethiopia where it reaches 20%. This very low value translates into the fact that most of the water that rains over the basin never reaches the river (Nile Basin Initiative, 2021). As far as flow distributions and seasonality are concerned, the biggest share (85%) of the annual flow comes from Ethiopian tributaries, and 70 to 80% of this runoff is generated in a single season of four months. This can be seen in the hydrograph depicted in Figure 2, where the intra-annual variability and distribution of flows between the main tributaries is reported. Moreover, there is a very strong inter-annual variability in discharge, a condition that is intensifying with the ongoing climate change (Nile Basin Initiative, 2021).

Water use and future trends
As the above presented data suggest, water is a very precious resource in such a huge and densely populated basin. According to the Nile Basin Initiative (2021), the Nile waters are currently fully utilized, with the demand being dominated by irrigation and evaporation losses from reservoirs, which is estimated to be around 18 billion cubic meter per year. Moreover, the water demand is expected to rise in the upcoming years. The key components of the water demand show an upward trend, but with different projected increases. Specifically, water use for municipal and industrial purposes is subject to exponential growth due to population dynamics and economic development, but the actual increase in terms of volume of extra surface water required is relatively modest, since most of these water can be recycled provided that a proper infrastructure system is developed. As far as the agricultural sector is concerned, supplementary irrigation to extend rainfall productivity in the large

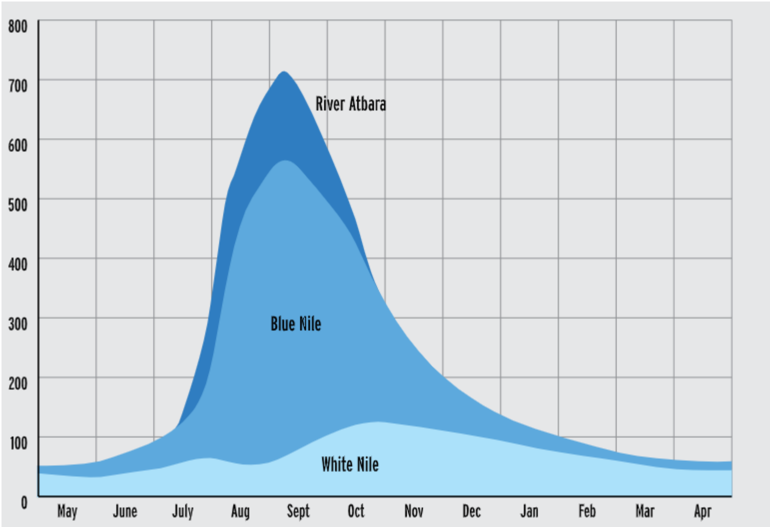


Figure 2: Intra-annual variability and distribution of flows $[10^6 m^3/day]$ (Nile Basin Initiative, 2021)

rainfed agricultural sector will only marginally impact the renewable Nile water resources. Finally, if the remaining potential hydropower capacity will be developed, the water demand from evaporation losses will increase (Nile Basin Initiative, 2021). This highlights the necessity of developing other energy sources than hydropower that do not affect or rely on the already precious water resources of the region.
Next to this increasing demand, the ongoing climate change and environmental degradation are adversely impacting the long term water availability of the basin. Recent climate projections predict that the Nile region is subject to a warmer and more variable climate, with the main impacts being increased aridity, higher temperatures, more frequent and more intense droughts and higher variability of rainfall and associated streamflow. However, the extent of future climate change in the Nile region is yet unclear, and different part of the Basin will be affected in different ways (Nile Basin Initiative, 2021). In details, in the period 1990-2018 compared to 1960-1989 the average annual temperatures have risen in every part of the Nile basin, with increases ranging from 0.5 to 1.1 °C. The rainfall patterns, instead, don't show any uniform signal, with rainfall decreasing in some areas and increasing in others (Nile Basin Initiative, 2021).

1.3 Energy system in the Eastern Nile Basin countries

Current status
Electricity consumption in the Eastern Nile Basin riparian countries is still among the lowest in the world. The highest value per capita is found in Egypt, with 1.54 MWh, followed by Sudan (0.3042 MWh), Ethiopia (0.0911 MWh), and South Sudan (0.0479 MWh) (IEA, 2020). There are three main reasons behind such small consumption: the power supply is unreliable and inadequate, the price of electricity is too high for most of the consumers, and many of them don't even have access to the grid. In fact, apart from Egypt where the percentage of the population with access to electricity is 100%, Ethiopia, Sudan and South Sudan have values as low as 51%, 55% and 7% respectively World Bank (a). This values fall even lower if the rural population only is considered, since urban areas have significantly better electrification than rural areas. Therefore, the rural population is still heavily dependent on biomass and charcoal for their energy needs (Nile Basin Initiative, 2021). The sources of electricity production are quite different among the Nile Basin countries. According to recent data from IEA (2020), Egypt is strongly dependent on natural gas (83,9% of the mix), while Ethiopia relies almost entirely on hydropower (95.8% of the mix). Sudan has two main sources of energy, producing 59.4% of their energy from hydropower and 40.6% from oil, and South Sudan production is dominated by oil (98%) (IEA, 2020). Combining the data from the four countries together, it can be noticed

that the total energy mix is dominated by natural gas (71.5%) and hydropower (17.8%), while solar and wind only constitute around 2% of the mix each. The Nile Basin region is the only in Africa without a functional regional power grid (Nile Basin Initiative, 2021). Therefore, a very small fraction of the generated power is traded amongst Nile countries, making their energy system very fragile and unreliable (Nile Basin Initiative, 2021). However, this is expected to change with the forthcoming completion of several transmission lines between Kenya and neighbouring countries, and as a result of the GERD coming into service (Nile Basin Initiative, 2021).

Future trends
Given the demographic and socio-economic trends described earlier, the long term demand for electricity in the Nile is set to increase rapidly. Specifically, the increasing rates of electricity access, urbanisation, industrialization and automation will boost the electricity demand significantly (Nile Basin Initiative, 2021). For the Eastern African Power Pool, the energy demand is expected to increase from 363 TWh in 2020 to 903TWh in 2040. In particular, Egypt and Ethiopia have the highest forecasted increases, reaching respectively 592 and 161 TW in 2040 (IRENA, 2021). In order to ensure energy access and security, significant additional power generation capacity is required to satisfy this future energy demand.

The Nile countries have a large availability of energy resources: hydropower potential, natural gas, oil, geothermal energy, coal, peat, biomass (including biogas and waste-to-energy), solar, and wind (Nile Basin Initiative, 2021). Between all those, the hydropower production is the most attractive to the policy makers, due to its long economic life and low levelised cost of energy. The hydropower potential in the Nile basin is estimated at 31 GW, and in 2018 about 19% of it had been developed. This figure will likely rise to 42% when new hydropower plants (mainly the GERD) become fully operational (Nile Basin Initiative, 2021).

However, this huge potential is not enough in the longer term to achieve regional energy security, also taking into account the threat posed to the water resource by climate change. For this reason, and given the decreasing costs of other renewable energy sources, countries have committed to increasing their share of non-hydro renewable energies in their production mixes. Between 2010 and 2019, the global weighted average capital cost of solar PV has reduced by 78%, while that of onshore wind has decreased by 24%. Following this trend, the capital costs of solar PV and wind projects are expected to continue to fall (IRENA, 2021). Moreover, Eastern Africa is known for its massive solar and wind potential. A study from IRENA (2021) found that the total potential reaches 6.97 TW for solar and 2 TW for wind, with current deployed capacities (8.96 GW) being approximately 0.1% of the total potential. The potentials for Sudan, Egypt and Ethiopia can be seen in Table 1.

Country	**Solar**	**Wind**
Egypt	63 806	58 775
Ethiopia	16 491	5929
Sudan	2160	5778

Table 1: Solar and wind potentials for ENB countries (MW)

Developing this vast potential would at the same time help to increase generation capacity, reduce the costs of electricity and improve the reliability of the power supply, with wind and solar power helping to compensate shortages of hydropower production during droughts and reducing the dependency on fossil fuels. Moreover, the Eastern Nile basin countries have already adopted ambitious plans for their energy systems. Ethiopia with its Ten Years Developement Plan 2021-2030 (Federal Democratic Republic of Ethiopia, 2021a) aims to achieve several goals by 2030, like raising power generation to 19.9 GW, increase power transmission lines to 29900km, increase electricity export to 7184 GWh, increase electricity customers to 24.3 million, increase coverage of grid based electricity to 96% and reduce power wastage. Egypt, according to the adopted Integrated and Sustainable Energy Strategy to 2035 (NEEAP, 2018), planned that renewable energy shall comprise 42% of the total electricity generated by 2035. The strategy is also targeting to achieve 18% reduction in the energy consumption.

Environmental footprints

In this context of fast demographic, economic and electrification expansion, pressures on the environment have to be taken into account if a sustainable development is to be guaranteed. First of all, in the recent years a lot of attention has been posed on the greenhous gas (GHG) emission footprints of energy systems. According to 2020 data (Climate Watch (WRI), 2022), the energy sector's GHG emission contribution is relatively low in Sudan and South Sudan (6 and 4% of the total countries' emissions respectively) and even close to zero in Ethiopia. However, this figure rises enormously in Egypt, where the energy sector is the first sector for GHG emissions, responsible for 38% of the country's total emissions. Moreover, given the projected electricity demand increase, this numbers are likely to increase in the following decades if the emissions are not taken into account in the electrification expansion plans. To this end, all of the four countries have submitted and updated their Nationally Determined Contributions (NDC), in which they present their strategies to cut the GHG emissions in every sector. Insights from such documents (Arab Republic of Egypt (2022), Federal Democratic Republic of Ethiopia (2021b), The Higher Council for the Environment and Natural Resources (2021), South Sudan's Ministry of Environment and Forestry (2021)) are presented in the following paragraph. In Egypt, the mitigation target by 2030 is to reduce the energy sector's emissions by 33%. To this extent, the main suggested actions are to installing new renewable capacity up to 40% of the mix by 2030, improve the energy efficiency, increase large and small scale decentralised renewable energy systems and improve the transmission and distribution grids. Additionally, the mitigation target from oil and gas includes a reduction of emissions from this sector by 65% by 2030. In Ethiopia, the energy sector's contribution to the total emissions is forecasted to reach 5% in 2030 in a business as usual scenario. To avoid this increase, the country aims at reducing the sectoral emissions by 25.5% if no international support is recieved and by 52.5% otherwise. This goals are supposed to be achieved by increasing energy efficiency and by increasing the electrification of the transport and industrial sectors. Sudan, instead, aims at a reduction of 38% of energy related emissions (excluding biomass supply which is accounted for in the forestry sector), by investing in utility scale solar and wind power plants, stand alone and mini-grid energy systems, rehabilitation of hydropower plants and increase of energy efficiency. Finally, according to South Sudan's NDC, emissions from the energy sector are supposed to increase from the current 0.2 MtCO2 to 6.7 MtCO2 in 2030 in the baseline scenario. However, developing strategies such as investing exclusively in renewable energy (hydropower plants, solar power, wind, biogas) would reduce the increase of emissions by 92%, reaching 0.53 MtCO2 in 2030. From the above insights, it is quite clear how each country has ambitions in reducing the emissions connected to the energy sector. Therefore, this aspect is something that can't be neglected in the energy system expansion planning processes.

Moving from the international to regional scale, another environmental footprint that involves the energy system is relative to its land use. In fact, literature studies (Kaza and Curtis (2014), Lovering et al. (2022)) have brought this topic to attention in the recent years, showing how energy systems are strongly connected to land use issues. Kaza and Curtis (2014) in particular highlights the fact that most of these issues are rarely considered in the planning studies that precede the building of new infrastructures. Even though it might be argued that the Eastern Nile Basin countries have vast parts of land with low value (e.g. deserts and shrublands), it has to be kept in mind that energy production sites are often located close to urban areas or key infrastructures, in order to abate the transmission and distribution costs. For this reason, energy generation sites might compete with other sectors over land resources, especially agriculture and urban development. The competition with agriculture is particularly important for the studied region, being this area faced with recurrent food scarcity issues (Nile Basin Initiative, 2021). Moreover, land use concerns are especially intense for the most promising renewable energy technologies (solar and wind) that are supposed to play a large role in satisfying the increasing energy demand of these countries and at the same time decarbonising their energy systems. However, even technologies with relatively small direct land use necessity (e.g. gas and coal fired thermal plants) show high land use intensities due to the mining of the necessary fuels, as also shown by (Lovering et al., 2022). Given all of the above, it is important to also include the land use footprints in the planning of future energy systems, in order to make sure that other social and environmental necessities are satisfied as well.

1.4 Relevance of the floating photovoltaic technology

Given the analysis presented in the previous paragraphs, there is rising need of developing non-hydro, carbon-neutral and land-use-neutral renewable energy sources in the Eastern Nile Basin countries. Moreover, seen the huge solar potential of this region, photovoltaic production seems a very promising technology.
Specifically, a new type of installation has been raising the interest of researchers in the last years: floating photovoltaics (FPVs). This technology has emerged as potential solution to meet growing future energy demands while reducing pressure on land and water resources. Gadzanku et al. (2021) gathered and checked from the existing literature all the potential combined advantages of these systems compared to ground mounted solar panels, dividing them into their area of benefit (social, economic, energy, water, food or land). Besides, the authors distinguished between empirically confirmed, theoretically confirmed and unclear, unconfirmed or understudied benefits. The table summarizing these results can be seen in Figure 2. The letters in brackets stand for stand-alone systems (S) and hybrid hydro-floating solar systems (H).

Summary of FPV Co-Benefits	**Social**	**Economic**	**Energy**	**Water**	**Food or land**
Empirically Confirmed	• Reduces land use (S) • Repurposes otherwise unusable land (S)	• Increases ease of installation (S; H) • Reduces site preparation (S,H) • Modular (S,H)	• Increases panel efficiency (S) • Increases panel packing density (S,H) • Reduces shading (S,H)		• Reduces land use (S) • Repurposes oterwise unusable land (S)
Theoretically Confirmed	• Preserves valuable land and water for other uses (S; H)	• Uses existing electrical transmission infrastructure • Reduces curtailment • Improves power quality	• Increases panel efficiency (H) • Improves power quality (H)	• Reduces evaporation (S,H) • Reduces algae growth and/or improves water quality (S)	• Reduces land use (H) • Increases energy sources near demand or population centers (S,H)
Unclear, Unconfirmed or Understudied	• Avoids or reduces conflicts over land and water use (S,H) • Avoids or reduces power generation related air pollution (S,H) • Reduces displacement of local communities for energy developement (S,H) • Improves power sector resilience (S,H)	• Extends system life (S,H)		• Reduces algae growth and/or improves water quality (S) • Reduces water temperature (S,H) • Provides power during drought • Reduces wave formation (S,H)	

Table 2: Summary of FPV co-benefits divided by category and level of knowledge (adapted from Gadzanku et al. (2021))

The most promising benefits of the hybrid plants for the ENB countries are the reduction of evaporation losses, the increased panel efficiency, the improved power quality and the reduction of land use.
The first advantage, given the scarcity of water resources in the region and the fact that the second sector for water consumption is evaporation losses from reservoirs (Nile Basin Initiative, 2021), is crucial for the study area. The potential magnitude of water savings were quantified for the East African Power Pool by a study from Sanchez et al. (2021). This study investigated two types of floater types and three area coverage scenarios: 1% of the reservoir area, 10% and the necessary percentage to match the capacity of the hydropower plant. Only considering the 1% scenario, the evaporation savings could be as high as 334.37 million cubic meters per year for one floater type and 106.75 for the other. In the same study the electricity benefits were assessed. In the 1% coverage scenario, the annual electricity output from floating solar power would be 17296 GWh for the EAPP, of which 86%

in the Eastern Nile Basin countries (6801.4 GWh in Egypt, 4239.2 GWh in Ethiopia and 3840.7 in Sudan). As far as these two main advantages are concerned, the relevance for the Eastern Nile Basin countries is evident.
Moreover, given the current underdevelopment of the region's electricity grid, another significant advantage of hybrid hydro-FPV system in this region is the possibility to use the existing infrastructure of the hydropower plants to distribute on the grid the additional capacity generated by the floating panel arrays (Cazzaniga et al., 2019), (Lee et al., 2020). Additionally, connecting FPV to the existing transmission infrastructure may increase the utilization rates of transmission lines where additional transfer capacity exists. In this way, potentially underused transmission lines could be fully exploited, leading to a reduction of electricity unit costs.
Finally, the combination of the two systems could stabilize the oscillating PV output (Silvério et al., 2018), which is one of the main downsides of solar technology that is preventing its deployment at large scales. Alternatively, hybrid systems can take advantage of the complementary nature of solar and hydropower generation patterns. According to Lee et al. (2020), this is true at different time scales. At the seasonal scale, dry and wet seasons show opposite benefits for both technologies, with more solar resources available in the dry season and more water resources available in the wet season. This could be of particular interest for ENB countries, in order to improve the resilience of their energy sector to prolonged droughts due to climate change. At the daily scale, hydropower can compensate for the intermittent output of solar PV due to the daily cycles of solar resources. Finally, at the hourly scale, hydropower can compensate for the random fluctuations of solar resources and power demand.
Table 3 summarizes the most relevant advantages of FPV technologies for the Eastern Nile Basin countries, assigning them to specific problems or challenges identified in the previous sections.

Challenge	**FPV advantage**
Increase electric capacity	Exploitation of huge solar potential
Reduce costs	Use of already existing electric infrastructures
Reduce pressure on water resources	Reduction of evaporation rates
Increase resilience of energy production	Complementarity of HP and FPV resources

Table 3: Advantages of FPV in the ENB countries

1.5 State of the art

The first commmercial FPV installation started operations in 2007, in a winery in California, with a capacity of 175 kW. Later on, the worldwide capacity experienced an important growth, reaching 2.6 GWp of capacity in August 2020, 73% of it being in China and the rest by Japan, Korea and Europe (Sanchez et al., 2021). The two largest plants are installed in China, with a capacity of 150 MWp each (World Bank, 2019).
In the last few years, the use of FPV in hybrid systems with hydropower plants started to emerge, but this technology is still at its very early stages. The first operational project was a small system of 220 kWp installed in Portugal. More recently, other plants became operational in Brazil, Albania, Russia, and Japan, but the largest one came online in 2021 in Thailand, with 45MW of floating solar capacity (Sirindhorn dam). The details of this projects can be seen in Table 4.
In Africa, the Bui Power Authority (2020) started a large project of hybrid hydro-solar system on the Bui reservoir in the Volta basin. The final expected capacity will be 250MW of solar capacity, with an addition of 5MWp of floating panels on the reservoir of which 1MWp is already operational. Some other small plants are operational in Tunisia (200 kW), Kenya (69kW) and South Africa (60kW).

1.6 Literature review and research gaps

Apart from the previously mentioned studies that focus on the technical advantages of the FPV technology, many studies analyse their possible deployment and usage through tecno-economic assessments

Project Name/Country	Floating Capacity	Developer/Owner	Investment/Revenue	Status
Sirindhorn, Thailand	45 MW	EGAT, 2020	THB 842 million	Under construction
Magat, Philippines	200 KW (360 MW hydro)	Ocean Sun, GCL-SI and SN Aboitiz Power (SNAP), 2019	0.4 million dollar	Pilot testing
Alto Rabagao, Portugal	220 KWp (68 MW hydro)	Ciel & Terre International, 2017	Not available (N/A)	Operational
Bahia, Brazil	1 MWp (175 MW hydro)	Ciel & Terre International, 2019	N/A	Operational
Banja, Albania	2 MWp (73 MW hydro)	Ocean Sun, Statkraf	2.61 million dollars	Under construction
Kutani Dam, Japan	4.99 MWp	Japanese public enterprise agencies	5.4 million dollars	Operational
Nizhne-Bureyskaya, Russia	1.2 MW	Hevel Group and RusHydro, 2019	N/A	Operational

Table 4: Status of hybrid FPV plants worldwide (Solomin et al., 2021)

and operational optimizations. The most relevant findings from literature are discussed in this section. A first scan was conduced on Scopus and Google Scholar, giving as input terms as "Floating solar panels", "Floating photovoltaics" and "FPV". From this scan, the information about the technical advantages presented in section 1.4 was taken. Given the amount of available literature, the scan was then restricted to only identify the studies that took hybrid hydro-FPV systems into account. This was done by adding the terms "Hydropower" and "Hybrid FPV-hydropower" to the previous keywords. This scan gave interesting results, mainly finding studies concerning (1) techno-economic assessment of one or few plants, (2) optimization of operations one plant and (3) multiple plants techno-economic assessments.
As far as the first category is concerned, Ghasempour et al. (2022) studied a potential FPV-hydro hybrid system on the Karun-3 dam in Khuzestan (Iran). The FPV capacity is calculated aiming at cover 5% of the electrical demand of Khuzestan during peak hours. The results shows that the required reservoir coverage for this goal would be 1.16 km2, with a consequent reduction of evaporation by 1.97% annually. Additionally, the saved GHG emissions would be around 5 million tons of GHG per year. Another study by Snehith and Kulkarni (2021) on the technical performance of a 10MW plant in India focuses on the comparison between FPVs and ground mounted panels (GPV). The authors find that the floating solar panels could generate 3.18% more electricity yearly than the ground mounted ones, and show better operating performances. Also in this case, the system would cause an important reduction of CO2 emissions, amounting to 301 kilo tonnes annually. A similar study was conducted by Thoresen and Skogheim (2021), who investigated the role of FPV in Ghana's solar increase plans. To do so, the author compared the floating technology with the ground based one, analysing two possible hybrid systems on two reservoirs (Bui and Akosombo). Besides, an assessment of the possibility of combining FPV with pumped hydro storage (PHS) is carried out, in order to see if this solution could improve the flexibility of the system. Again, the results show that the FPV increases the energy yield over the ground mounted panels. The combination with PHS, however, is not chosen by the optimization software used due to its high total system cost, even if the author suggests it might be still a good option to increase the system's flexibility.
The operational optimization of hybrid FPV-hydro plants was studied by Zhou et al. (2020). In his paper, the author tries to give a solution to the difficulty of complementary operations between floating solar and hydropower generation due to high hydro-meteorological uncertainties. To do so, a Grasshopper genetic optimization algorithm is used, in order to maximise three objectives: the total power output, the ratio of storage to reservoir capacity and the ratio of water supply to demand from the irrigation districts. The Shimen reservoir watershed (Taiwan) and its water-energy-food system are taken as a case study. The results, apart from finding the optimal tilt of panels, reported an increase in power output, water storage and food production compared to the non-optimization case.
A study that considered multiple reservoirs for possible FPV hybrid systems within a basin was conducted by Silvério et al. (2018). Here, the authors outline a procedure for technically and economically

sizing floating PV plants, and analyse their techno-economic benefits. The study area is the Sao Francisco River basin in Brazil. The results find an optimal panel tilt of 3% to minimise costs, an average energy gain of 76% and an average capacity factor increase of 17.3% considering all the reservoirs. Besides, the PV source has a seasonal profile that compliments the natural inflow of the river. The conclusion is that the proposed system design could replace much of the thermoelectric generation in Brazil.

Finally, two studies were found that developed frameworks to aid the inclusion of FPV in energy systems planing. Prinsloo et al. (2023) developed a geo-sensitive dynamics framework to systemically integrate the energy, environmental and economic object functions in characterising the behaviour and sustainability of floating photovoltaic systems. When tested, this geospatial digital twin showed significant advantages of floating compared to ground mounted (19.3% energy gain, reduction of 5168t of CO2e emissions, and evaporation benefits of 983kL). Puppala et al. (2022), instead, carried out an analysis of the potential for FPV for all major reservoirs in India. On top of this, the author developed a multi criteria framework to detect the hierarchy of hydropower for FPV installation, considering available area, harnessable power, capacity factor, elevation and wind speed.

In order to find the literature available for the area of interest, a third scan was performed including the keyword "Nile". Three studies were found, two based in Egypt and one in Ethiopia. Getie and Jember (2022) assessed the potential of the deployment of FPV on the Grand Ethiopian Renaissance Dam (GERD), in terms of power generation potential, performance ratio, capacity utilization factor, GHG emissions and water conservation. The proposed floating capacity (1MW) was designed to meet the demand of neighbouring communities, even though the studies found a total FPV potential of 18740 MW for a 10% reservoir coverage. The results showed that 7.81 tCO2 emissions are saved, as well as 54.4 million liters of water yearly. Elshafei et al. (2021), instead, studied the utilization of Lake Nasser's surface for massive production of solar energy, and found that with a 20% of area coverage, the electricity production could meet 16% of the European demand, and reduce water loss by evaporation by 3 billion liters of freshwater. Finally, Ravichandran et al. (2021) studied the addition of two 5MW of FPV for the High Aswan Dam comparing the system's performances with and without floating panels. The results showed better performance in terms of carbon dioxide reduction, water saving from reducing evaporation and increasing hydropower generation in the FPV implementation case.

As can be noticed, the most of the existing literature focuses on assessing the effects of implementing FPV on single reservoirs in terms of annual electricity gain and evaporation savings (Ghasempour et al. (2022), Snehith and Kulkarni (2021)). The comparison between ground mounted and floating installation is also widely studied (Thoresen and Skogheim (2021),Snehith and Kulkarni (2021)). Furthermore, optimization of design and operations of the hybrid system are also addressed (Zhou et al., 2020). Some other studies include multi-reservoir systems (Silvério et al., 2018) or create planning frameworks to aid decision makers (Prinsloo et al. (2023) Puppala et al. (2022)). Besides, the only available literature for the area of interest focuses on techno-economic assessments of single reservoirs (Getie and Jember (2022), Elshafei et al. (2021), Ravichandran et al. (2021)). However, no study was found that assessed the effects of integrating this relatively new technology in the long term energy plans of a country or basin. Moreover, in the area of the Eastern Nile Basin the available literature on this technology is very minimal.

1.7 Research questions

Given the findings highlighted in the previous sections, there is a need for studies that comprehend the energy system of the entire Eastern Nile Basin region, and assess the role of this promising technology in the long term future. Besides, these projections need to be tested under different scenarios, in order to see how this technology behaves under different climate and economic hypotheses. Moreover, it is important to assess the role of this technology on the energy system's footprints to guarantee the sustainability of the electrification process. Finally, an identification of the most promising locations for the installation of floating photovoltaics power plants is needed to help directing investments efficiently.

All these considerations led to the formulation of the research questions of this studied, outlined as follows:

1. What are the effects of implementing floating solar power on hydropower reservoirs on the long-term energy plans of the Eastern Nile Basin countries?
    (a) How does the impact of this technology change under different climate change and policies scenarios?
    (b) How does the implementation of this technology affect the energy system's footprints?
2. What are the best locations for this technology in the Eastern Nile Basin countries?

2 Methodology

The current section presents the proposed methods aimed at answering the research questions. First of all, the adopted long term energy planning modelling framework is described, together with the steps followed to add the floating solar power technologies. Then, the definition and modelling of the different simulation sets is presented. Subsequently, the procedure and modelling tools used to estimate the water savings due to evaporation reduction is outlined. Finally, the performed sensitivity analyses are explained. Other adaptations that had to be applied to the main modelling framework and further procedures are reported in Appendix A.

2.1 Long term energy planning

In order to answer the main research question (RQ1), a long-term energy planning modelling framework is needed. In the literature, there are many modelling frameworks available, as can be seen in a review from Musonye et al. (2020) who analysed 30 of them for South Saharan Africa only. The most interesting ones for the proposed work, since they have been developed for African countries in particular, are SPLAT (used in IRENA (2021)), PyPSA (Kirli et al., 2021) and OSeMOSYS-TEMBA (Taliotis et al., 2016). Between the three of them, OSeMOSYS-TEMBA was chosen for convenience reasons, since it provides a full open source framework (including all the necessary data to model the energy system) and is backed up by a solid free access documentation and tutorials. In particular, the 2.1 version of TEMBA (Pappis et al., 2022) was adopted in this work, since it constitutes the most recent, updated and improved version of this model. Its details and assumptions will be discussed in the following section.

2.1.1 OSeMOSYS-TEMBA 2.1

The first OSeMOSYS (Open Source Energy Modelling System) version was developed by Howells et al. (2011). This consists of a long term energy planning model designed as a tool to inform the development of energy system at various spatial scales, from local to continental. In order to give possible solutions on how energy systems can transition from one state to another, the model minimises an objective function which expresses the cost of operating and expanding the energy system as a linear function of the discounted sum of the generation capacity and activity over time. To do so, the model takes as input the projected electricity demand over the study period, the existing and planned generation technologies and the economic parameters related to them. After calculating the least cost solution, it outputs the projected capacity mixes, energy supply and consumption mixes and related emissions.

Due to its open-source nature and internet community, OSeMOSYS was used as a base to develop multiple other models, specific to country or regions. One of them is The Energy Model Base for Africa (TEMBA), developed by Taliotis et al. (2016) with the UN Economic Commission for Africa (UNECA). This model consists of final energy demands for forty-seven African countries. Each production, import, export, domestic transmission and transport option per country is included. In particular, the energy trading scheme is taken into account by implementing cross border electricity trade links and gas pipelines. The main addition to the base OSeMOSYS is the multi-country nature of this model, which allows to calculate electricity trades between countries in the African continent, as well as assessing the benefits of interconnecting the single States in order to reach a greater efficiency with less costs. Moreover, the inclusion of extensive data for each country makes this model a valuable resource for future energy planning work in Africa.

The TEMBA model was further developed and updated by Pappis et al. (2019), who created the TEMBA 2.0 version. Here, the model was extended to include non-electricity demands for oil products together with their (simplified) supply system, new power plant options to include Carbon Capture and Storage (CCS), and water footprint of technologies (implemented as water factors) depending on the cooling type. Additionally, the data were extended and updated, including operational production data for solar and wind at a finer granularity, and new data for capacity, cost, performance, fuel price

and energy demand projections.
The same author further developed the model, creating the TEMBA 2.1 version (Pappis et al., 2022). Here, the fuel system was extended to simulate country specific fuel export possibilities, and the nexus with water consumption was enhanced by including the water losses due to evaporation in hydropower plants, and the water consumption and withdrawal factors were refined by collecting more data.

2.1.2 Time modelling

In long term energy planning models, a quite important role is played by the lenght of the time horizon and the amount of time steps within each year of simulation.
In fact, electricity demand can vary drastically from winter to summer and from day to night. Additionally, some technologies like solar and wind also have very different capacity factors depending on the season and on the time of the day. Therefore, in order to simulate a realistic behaviour of the energy system and make sure the demand is satisfied in every time step, these variations have to be explicitly modelled through different time steps within the single year.
The original TEMBA model was implemented with a modelling period of 55 years (2015-2070), each one containing 8 time steps. These were representative of two day parts (h 9-18 and h 18-9) for four seasons of three months (March-May, June-August, September-November, December-February). This time modelling scheme was considered adequate for the purposes of this study and therefore adopted for the simulations.
However, in order to avoid so called "edge effects" that may arise in the first and last years of simulation, the results are analysed in a restricted time horizon that spans from 2023 to 2065.

2.1.3 Adapting TEMBA 2.1

In order to use TEMBA 2.1 to answer some of the research questions, the model needed to be adapted to the technologies and area studied. Since the study area was the Eastern Nile Basin region only, the model also needed to be restricted to Egypt, Ethiopia, Sudan and South Sudan only. This also helped reducing the computational time and efforts. To achieve this, the data of the above mentioned countries only were extracted from the full TEMBA 2.1 dataset with the aid of a python script.
Furthermore, some data had to be changed since they were considered outdated, or they were the source of unrealistic results. This had to do with mainly two sets of parameters: those relative to the electricity trade links and the ones relative to the costs of renewable technologies. The steps needed to modify this parameters are presented in Appendix A.1.

2.1.4 Implementing floating solar power technologies

After having adapted the model, the floating solar panel were implemented as a new technology. The existing version of TEMBA provides data for concentrated solar power (with and without storage) and solar PV (utility, rooftop and with storage). Therefore, a new technology for floating solar power had to be defined in the model. The following subsection presents the step that were followed to achieve this, together with the relative assumptions.

Spatial disaggregation of hydropower technologies

In the adopted version of TEMBA, given the original size of the domain (the whole African continent), all the production technologies are spatially disaggregated at a country resolution only. Once restricted to the Nile basin, however, the spatial resolution of some technology could be increased without compromising the computational efforts. Since this study aims at investigating the role of FPV technologies on hydropower reservoirs, both these two production technologies were spatially disaggregated to a single plant resolution.
In order to achieve this, a list of the existing and planned reservoirs in the ENB countries was obtained from the RePP database (Peters et al., 2023). Apart from the geospatial data of the reservoirs, this dataset included the reservoir size (for existing plants), the nominal capacity in MW and the first

year of operations. Data from this source were then merged with the African Hydropower Atlas (Sterl et al., 2021), which also included the capacity factor of each plant under different hydrological scenarios (more details are presented in the scenarios description section). The final list of hydropower plants contains 48 locations, 37 of which are reservoirs and the remaining 11 run-of-river plants. Egypt has 5 locations, Ethiopia 24, Sudan 12 and South Sudan 7. Afterwards, the selected hydropower plants were implemented in the model. The full list of plants and the assumed parameters can be seen in Appendix A.

FPV technologies

After the hydropower plants had been spatially disaggregated, the FPV technologies could be implemented. This required more research on the parameters, since the technology was not originally present in the model. To obtain the list of possible locations for FPV, the list of hydropower plants previously shown was used, considering only those with a reservoir. Eleven hydropower plants were excluded from this list, being run-of-river plants and therefore lacking a suitable reservoir for floating installations.

Capacity factors

One of the most important parameters to retrieve was the capacity factor. This is defined as the ratio between the amount of power produced by a plant over a certain period and its nominal capacity. For solar power, the capacity factor can vary significantly over different seasons and time of the day, due to its heavy reliance on sun radiation which is not always present. In particular, given the definition of the timeslices in TEMBA with 2 day parts (h 9-18 and h 18-9) per four seasons (March-May, June-August, September-November, December-February), eight different capacity factor values had to be calculated for each single FPV plant.

Data of solar power production were calculated throught the PVGIS onine tool of the Joint Research Center (JRC) of the European Commission (`https://re.jrc.ec.europa.eu/pvg_tools/en/#HR`). Here, the coordinates of the selected locations were given as input, together with the following assumptions:

- Installed capacity: 1kWp
- Radiation database: PVGIS-SARAH2
- Analysed year: 2019
- Tilt and azimuth angle: optimised from the tool based on the coordinates
- System losses: 14%
- PV-technology: crystalline silicon

From these, the tool calculated the hourly production of the power plants over the selected year. This was then used to calculate the hourly capacity factor by dividing it by the selected nominal capacity (1KWp). Then, the hourly capacity factor was aggregated over the day parts and the seasons in order to obtain the desired values for each time slices.

Costs

The costs for FPV technologies are still very uncertain, and there is a high discrepancy between different studies in the literature. After a detailed screening (details for CAPEX in Appendix A), it was decided to take the values from the Floating Solar Market Report 2019 (World Bank, 2019). Here the CAPEX of FPV are considered to be 8% higher than ground mounted PV system, while the OPEX are considered to be 2.5% of the CAPEX. This results in a capex of 2851.2 $/kWp for the first year (2015), which means a value of 1963 $/kWp for CAPEX in 2023 and 49 $/kWp for OPEX.

This choice is motivated by the fact that the source of these values is considered the most reliable (World Bank), and being given as a percentage it allows to derive the values from the values for solar already present in TEMBA, guaranteeing coherence with the rest of the cost data.

Capacity constraints
In order to realistically simulate the possible deployment of floating solar power technologies, constraints on their total and maximum yearly installable capacity were set:

- Total annual maximum capacity: the upper constraint for the total annual capacity of each plant was assumed as the nominal capacity of the respective hydropower plant, following the approach of Sanchez et al. (2021). This can be a loose constraint (especially for very large hydropower plants), but the actual capacity expansion is more strictly constrained by the total annual maximum capacity investment parameter.

- Total annual maximum capacity investment (TMCI): This parameter was set according to the following equation:

$$TMCI = min(MaxFeasibleCapacity, NominalCapacity) \tag{1}$$

  with:

  - $MaxFeasibleCapacity$: maximum feasible capacity for an FPV plant. This value is projected to increase during the horizon due to technology improvements, similarly to traditional solar power plants (table 5). The starting value is taken from the currently largest existing plant (Dezhou Dingzhuang, China, 300MW), and the increase follows the learning curve of traditional solar present in the TEMBA database.
  - $NominalCapacity$: nominal capacity of the corresponding hydropower plant.

  For the planned reservoirs, the value of the TMCI parameter was set to 0 for all the years before the year of creation of the reservoir.

Period	MaxFeasibleCapacity
2024-2040	300 MW
2040-2050	600 MW
2050-2070	1000 MW

Table 5: Maximum annual capacity investments assumptions for FPV technologies

Linking hydropower and FPV plants
Apart from the parametrisation, an additional constraint needed to be implemented in the model code in order to realistically model the implementation of floating solar power plants. In fact, with the original version of the model it could happen that floating solar power was built before the respective hydropower plant was built. This came from the fact that the technologies were modelled separately, each one with its own parameter and without any equation that linked the two.
In order to solve this issue, additional constraints had to be implemented to make sure that no new capacity of FPVs were built if the total capacity of the respective hydropower plant in that year was 0 (e.g. the hydropower plant was not present in that year). Expressing this in a pseudo-code form:
if

$$TotCapacity[t_{HYD}, y] = 0 \tag{2}$$

then:

$$NewCapacity[t_{FPV}, y] = 0 \tag{3}$$

with t_{HYD} being the hydropower plant technology, t_{FPV} being the respective floating solar panel technology and y being the year considered.
However, the model uses mixed linear programming to solve the capacity allocation problem and it does not allow for explicit if-else conditons, thus everything has to be express in terms of equalities

and inequalities. Therefore, new binary variables had to be implemented, and the so-called "big M" and "small epsilon" strategies were used to mimic the behaviour of an if-else condition.
Firstly, a binary variable z was introduced, so that if $TotCapacity[t_{HYD}, y] = 0$ then $z[r, t_{HYD}, y] = 0$, else $z[r, t_{HYD}, y] = 1$. Expressing this with inequalities means:

$$\begin{cases} TotalCapacityAnnual[t_{HYD}, y] \leq z[t_{HYD}, y] \cdot M \\ TotalCapacityAnnual[t_{HYD}, y] \geq z[t_{HYD}, y] - 1 + eps \end{cases} . \tag{4}$$

With M = 7 GW and eps = 0.005 GW being the upper and lower values for capacities in the hydropower plants list.
At this point, the variable z had to be multiplied by the $NewCapacity[t_{FPV}, y]$ to make sure that this assumes a value of 0 in case the $TotCapacity[t_{HYD}, y]$ is 0. However, implementing a product between decision variables would make the problem non-linear, making it more complex and not guaranteeing the individuation of the global optimum. This problem was overcome by linearising this product through another binary variable v:

$$\begin{cases} v[t_{FPV}, y] <= M * z[t_{HYD}, y] \\ v[t_{FPV}, y] <= NewCapacity[t_{FPV}, y] \\ v[t_{FPV}, y] >= NewCapacity[t_{FPV}, y] - M * (1 - z[t_{HYD}, y]) \\ v[t_{FPV}, y] <= M \\ NewCapacity[t_{FPV}, y] = v[t_{FPV}, y] \end{cases} . \tag{5}$$

This constraints were applied to all hydropower and floating solar power technologies, for all years (y) of simulation.

2.2 Defining the simulation sets

In the evolution of an energy system, many factors that are external to the energy system's cost-optimization process itself play an important role in influencing the infrastructure and generation mix. This is even more relevant if the time horizon under study is very long as it is in this work (42 years). Therefore, it is very important to develop the planning projections under different assumptions, to be able to understand how the changes in the external factors affect the system's evolution.
In this study, three types of external factors are taken into account: the introduction of a new technology (FPVs), climate change, and the introduction of taxation policies on the footprints caused by the electricity generation. Nevertheless, it is important to distinguish between external factors that are dependent or independent from the energy planning authority's decisions. In fact, the introduction of new technologies or taxation policies is external to the energy cost-optimization process itself, but it still lies within the energy planning framework. The presence of climate change, instead, is something that is external to this framework, and does not depend on the energy authority's decisions. A visualization of these differences can be seen in Figure 3.
The reference set and these three simulation sets are described in details in the following paragraphs.

2.2.1 Reference

The reference simulation is aimed at analysing the energy system's optimal expansion in the business as usual scenario. Here, floating solar power is not present among the possible technologies, and no taxation policies are applied. As far as the hydropower capacity factors as concerned, they are calculated from the monthly median flow estimates based on historical climate data (1975-2005) (Sterl et al., 2021). A deeper explanation on these parameters is presented in section 2.2.3

2.2.2 Introduction of FPVs

The first simulation set is aimed to answer the main research question: what is the role of implementing floating solar power in the energy mix?

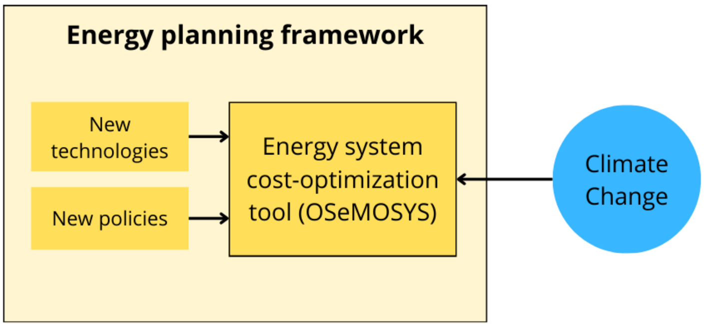


Figure 3: Different factors defining the simulation sets

To do so, different simulations are run with and without the addition of FPVs in the list of possible technologies for the optimization problem. In this way, the effects of the introduction of FPVs can be assessed comparing the model results of the different simulations. Apart from the introduction of this new technology, all the other assumptions of this simulation set are the same as in the reference set.

2.2.3 Climate change scenarios

The second simulation set is aimed at answering the first research sub-question: **how does the role of FPVs change under different scenarios?**.
In particular, this set is developed to simulate the influence of climate change on the energy system's long term expansion, which is a topic getting more and more attention in recent years. In fact, in order to make sure that the electrification plans of developing countries are effective and viable in the long term, climate change dynamics have to be taken into account in the planning stages. Possible impacts of climate change on energy systems are the alteration of natural renewable resources availabilities (water, wind and solar radiation) and the alteration of energy demand for cooling and heating. These dynamics were considered by Seljom et al. (2011) in a study on the impact of climate change on the Norwegian's energy system. In the current study, however, this approach would require a large amount of work in terms of searching for meteorological data, feeding them to a climate model and obtaining the capacity factors variations, especially given the dimensions of the region under study. Moreover, modelling the single countries' cooling energy demand and developing different projections would also require an additional research that would fall outside of the scope of this work. As far as other literature studies are concerned, Carlino et al. (2023) conducted a similar research on the energy system of the African continent, and modelled climate change effects by altering the capacity factors of hydropower plants only. The same approach was followed in this work, since the capacity factor alterations data had been already modelled and made easily accessible by Sterl et al. (2021). In this study, the author calculated these parameters based on the flows obtained forcing a hydrological model with different combinations of representative concentration pathways (RCPs) and shared socio-economic pathways (SSP) projections. In particular, these combinations are: SSP1-RCP2.6 and SSP4-RCP6.0. Moreover, each of these scenarios provides the capacity factor values for the lower and higher uncertainty ranges of the flows, that is to say for the "dry" and "wet" cases, corresponding to the 5th and 95th percentile of average annual flow respectively. The capacity factors were calculated by Sterl et al. (2021) at a monthly resolution, and had therefore to be aggregated to the seasonal resolution used in the OSeMOSYS model. The average of the three months composing every season was used as aggregation method.
Following this procedure, four scenarios have been obtained: the two flow uncertainty estimates (dry and wet) for the two SSP-RCP combinations. In order to have an idea of how the capacity factor changes in each country across these scenarios, the weighted average capacity factor for each season

has been calculated and plotted in Figure 4, using the nominal capacities of the plants as weights.

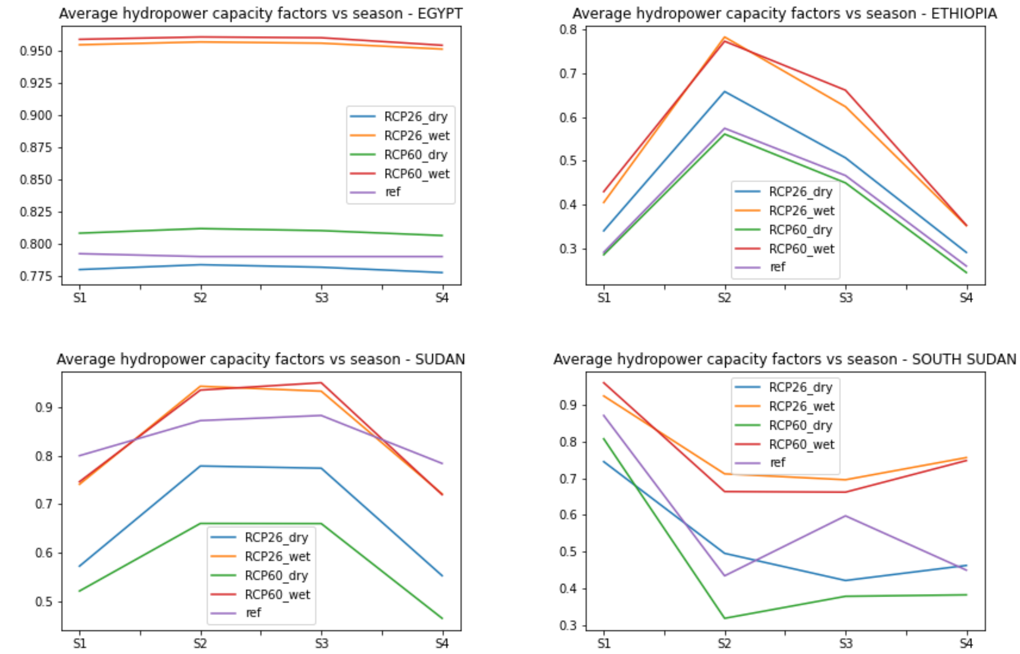


Figure 4: Seasonal variability of average hydropower capacity factors in each country for each climate change scenario

It is interesting to see how each climate change scenario has different impact on the different countries. In all four countries we notice that wet regimes have higher capacity factors than the reference for both climate change projections, while the opposite is not always true for dry regimes. In particular, RCP6.0 dry has a higher capacity factor than the reference in Egypt, while in Ethiopia this happens for RCP2.6 dry. Sudan has the most predictable behaviour, with dry regimes of both projections causing lower capacity factors than the reference. Finally, South Sudan exhibits the most peculiar behaviour, with capacity factors for RCP2.6 dry that have a different trend across the seasons compared to the other scenarios. It is also interesting to notice how the wet regimes of both climate change projections cause very similar capacity factors, while the dry regimes show a higher difference between RCP projections.

2.2.4 New policies

The last set of simulations has to do with the introduction of taxes to include the energy systems' footprints in the cost-optimization process. In the previous simulation sets, in fact, negative environmental effects of the power technologies are not taken into account in their cost parameters, even though most of these technologies apply a pressure on the environment, for example in terms of carbon dioxide emissions and land use. In the introduction it was highlighted why it is important to include specifically these two footprints in the planning of an energy system, both for their global and regional effects. Moreover, as also presented in the introduction, a possible advantage of floating solar power is that it can help reduce this footprints significantly, since it does not produce emissions while operating and do not consume land directly (being installed on water surfaces).
Therefore, two scenarios were developed to represent the cases in which the energy systems' footprints are taken into account by taxing carbon emissions and land use. The first scenario ("TAX_Low") implies a relatively mild taxation, starting with a smaller value and a less steep yearly increase; while the "TAX_High" scenario imposes a higher value and a steeper yearly increase. The details and assumptions behind each tax are presented in the following paragraphs.

Carbon pricing

Choosing a realistic price for carbon emissions is a very debated topic, which many organisation have studied in the last years (Carbon pricing leadership coalition (2017), World Bank (2023)).
In the current study, the carbon prices for the "TAX_High" scenario (the most ambitious in terms of carbon emissions reduction) were taken from the World Energy Outlook (IEA, 2022), and start with 80$/tCO2 in 2023, rising up to 140$/tCO2 in 2030 and 200$/tCO2 in 2050. These three values were then linearly interpolated (and extrapolated) to cover the whole modeling period (2015 to 2070).
For the "TAX_Low" scenario, instead, prices from a similar Msc. Thesis that focused on Ethiopia were adopted (De Vries, 2023). Here, the slow scenario starts with a price of 25$/tCO2, with an increase rate of 1% annually.

Land use pricing

As far as land use pricing is concerned, estimating a value can be very hard, especially in such a large and heterogeneous area as the Eastern Nile Basin countries. In order to get an idea of the value of land typically used for power plants, the following procedure was conducted.
First of all, a spatial dataset of existing and planned power plants in the region was downloaded from data portals of the European union (EU Joint Research Center, 2022) and the World Resources Institute (2021). These two datasets were merged in a QGIS environment, removing the duplicate entries. A map of this dataset can be seen in Appendix A.
Then, in order to estimate the value of land at each power plant location, the actual agricultural yield was used as a proxy. Following this approach, the land value is assumed to be the value of agricultural crops that could be yielded if a certain area was not used by a power plant.
Such values were obtained from the GAEZ data portal of the FAO (FAO, 2021). This portal offers raster maps showing the spatial distribution of agricultural yield valued at year 2010 international prices (k$/ha). The obtained map, visible in Figure 5, was then used to sample the land value at each power plant location of the list presented previously.
These values were then analysed with the aid of a python script by aggregating them into the main power technologies categories. However, as can be seen from the map in Figure 5, there is a clear difference between crop values in Egypt and in the other countries, due to the presence of high value agricultural districts in the Nile Delta. For this reason, in order to better represent the variability of land value, it was decided to disaggregate the land values between different countries. However, due to the lack of power plants data for some generation categories in Sudan and South Sudan, it was decided to keep the aggregation between these two countries and Ethiopia, and only disaggregate Egypt. Moreover, the difference in crop value between these three countries is not as sharp as the one with Egypt, therefore this aggregation influences the model precision less.
Still, the data had some gaps to be filled after separating Egypt from the three other countries. In fact, there were no data available of geothermal power plants in Egypt nor nuclear power plants in the other three countries. In order to fill this gaps, the geothermal values for Egypt were assumed to be the same as for the other three countries, and vice versa for the nuclear values.

Aggregate crop production value in the ENB

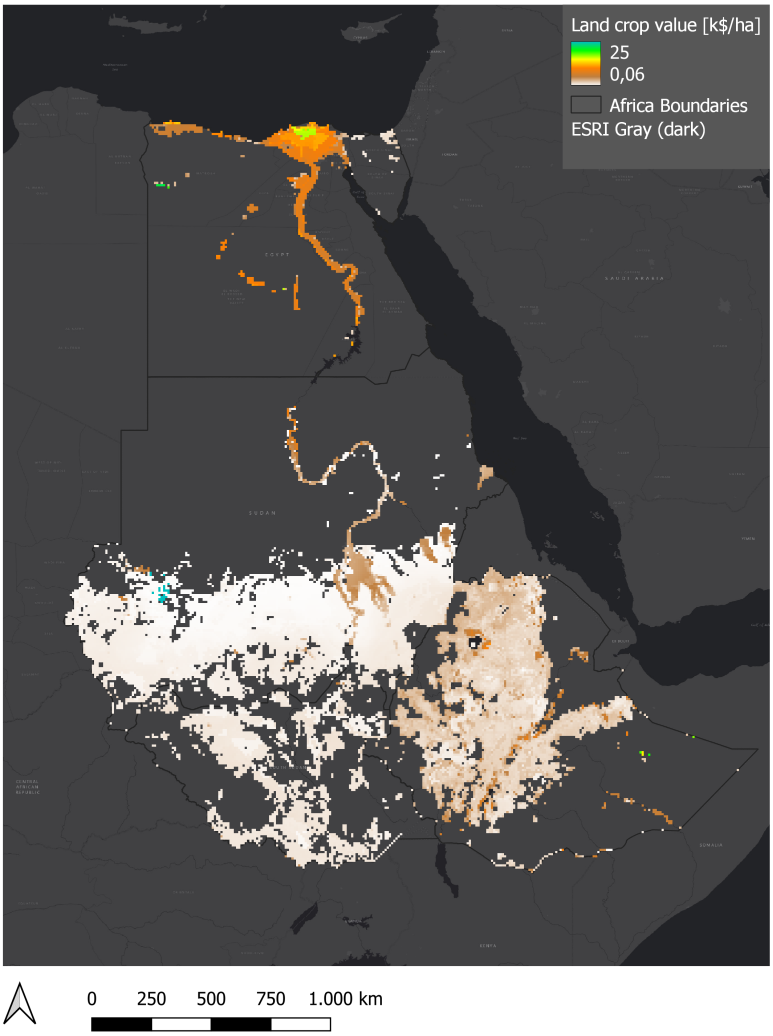
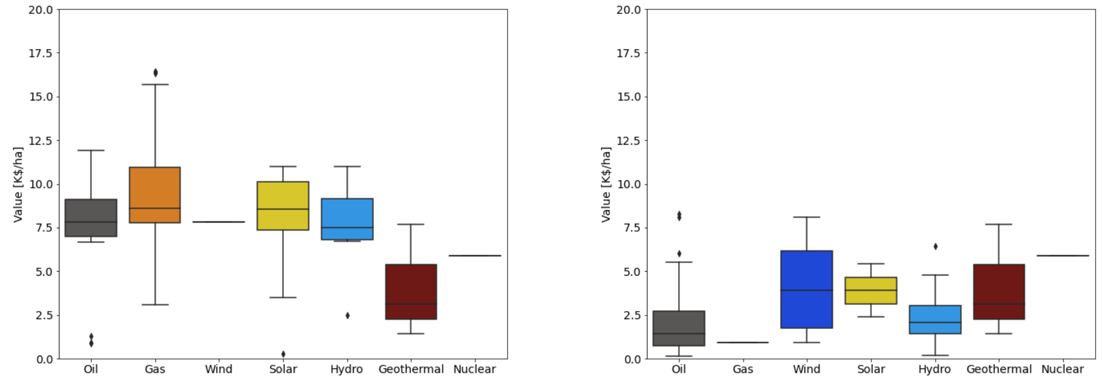


Figure 5: Spatial distribution of agricultural yields

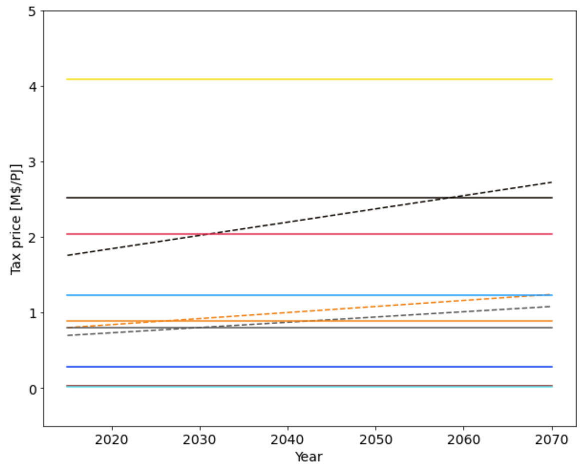
The statistical properties of the land values for each power generation category and for each area can be seen in the boxplots in Figure 6.
From Figure 6, the difference in values between Egypt and the other three countries is evident, with higher average values for each technology in Egypt.
Moreover, there is a quite large uncertainty for most of the technologies. This is expectable, since the power plant dataset is very large and the spatial land value is very heterogeneous across the locations. Based on this analysis, a different land tax for each technology type had to be implemented into OSeMOSYS. Due to the large uncertainty, the values adopted for the "TAX_Low" and "TAX_High" scenarios were arbitrarily taken as the 25th and 75th percentile of the land value respectively. Moreover, differently from the carbon tax, this tax was assumed to be constant over the whole modelling horizon. It has to be noticed that no land values for coal plants were available in the datasets. Therefore, its value was assumed to be the same as the value for oil power plants.



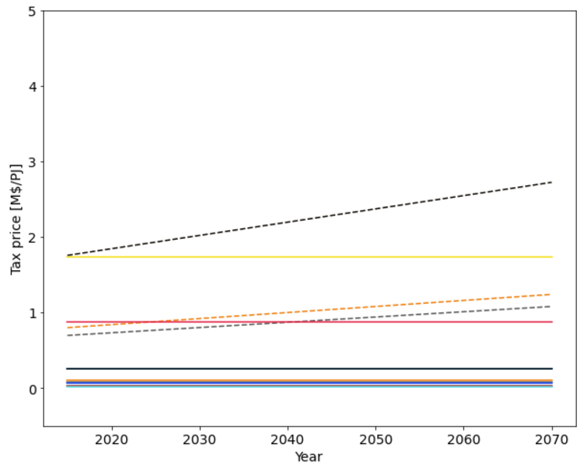
(a) Egypt (b) Other countries

Figure 6: Land values for different generation technologies

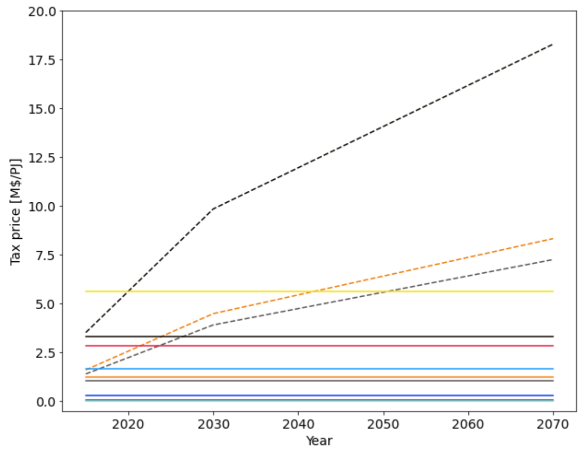
(a) Egypt - TAX_Low scenario



(b) Other countries - TAX_Low scenario



(c) Egypt - TAX_High scenario



(d) Other countries - TAX_High scenario

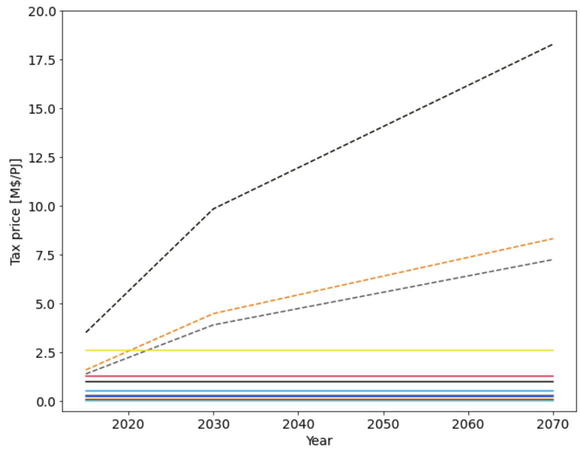


Figure 7: Generation mix of the single countries for the Reference scenario

Technology	LUIE [ha/TWh]
Nuclear	7.1
Geothermal	45
Wind	130
Gas	410
Hydroelectric	650
Coal	1000
Solar CSP	1300
Ground-mounted solar PV	2000

Table 6: Land use intensity per electricity production technology

Once the tax values were set, they were implemented in the model as "penalties". However, another step was needed to convert the tax values from price per externality unit ($/tCO2 and $/ha) to price per activity (i.e. energy generation, $/PJ) unit.
In the case of carbon dioxide, this was done using the "emission activity ratio" data already present in the TEMBA dataset, while in the case of land use the values were researched in the literature.
In particular, a study from Lovering et al. (2022) calculated the land use intensities of electricity production (LUIE) for each technology type using real world power plants data and including the indirect land use linked to the fuel production (e.g. coal and gas extraction). Their results were used in this study, and they are reported in Table 6. These data did not report values for oil power plants, therefore the land use intensity of this technology was assumed to be the same as the one of gas power plants.
In order to have a better idea of how the different penalties affect each technology, they were plotted together over the modelling horizon. The results can be seen in Figure 7.
From these figures, it can be seen how for Ethiopia, Sudan and South Sudan, the carbon tax on coal is the highest in both scenarios. In Egypt, instead, the land tax on solar is the highest in the "TAX_Low" scenario, and the carbon tax on coal is the highest in the "TAX_High" scenario. It is also worth to notice how the land tax on coal is high in Egypt (even higher than the carbon tax on coal in the slow scenario), while it is quite low in the other countries. Finally, it has to be remarked that fossil fuels technologies are affected by both the penalties, and in particular coal technologies have high penalties values in both scenarios for both penalty types. For these reasons, it is expected that fossil fuel technologies will be the most penalised in both the scenarios, followed by solar technologies.

2.3 Estimating the water savings

As highlighted in the introduction, water is a very precious resource in the Eastern Nile Basin countries. Therefore, energy planning should take this resource into account when studying the possible evolutions of the energy system.
In the introduction it was also reported that floating solar panels could theoretically play a role in reducing evaporation from water reservoirs. However, it can be very hard to estimate evaporation ratios in such big water surfaces. Moreover, it is still empirically uncertain if covering small percentages of the reservoir could play any relevant role in reducing evaporation (Gadzanku et al., 2021).
In this study, in order to have an idea of the magnitude of saved water and of the potential extra electricity generation that follows, the procedure described in the next paragraphs was adopted. Its schematic overview can be found in Figure 8.

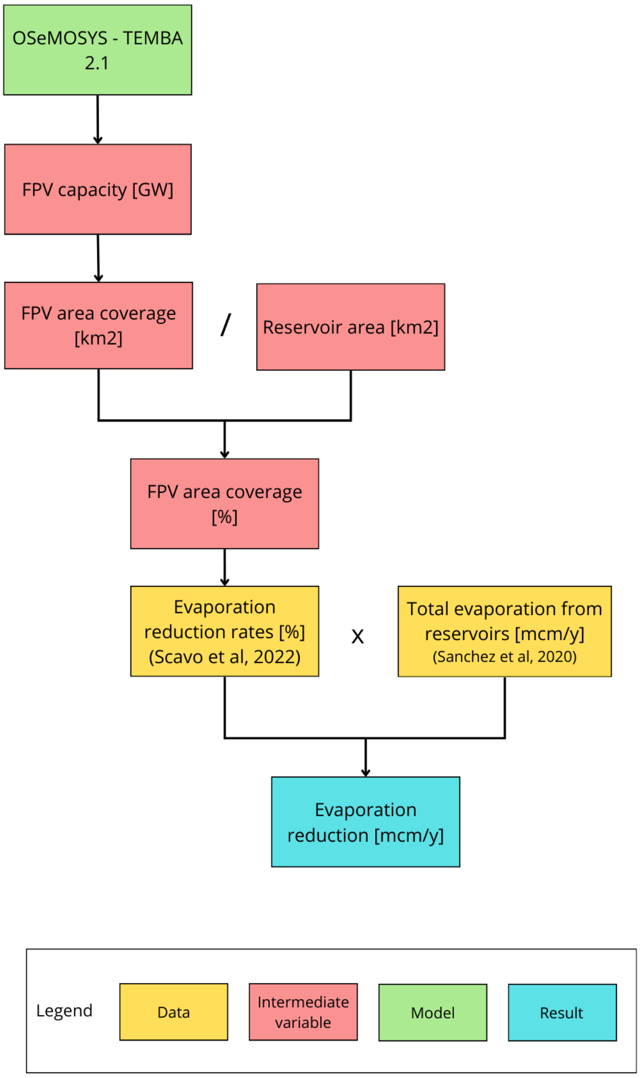


Figure 8: Evaporation assessment procedure

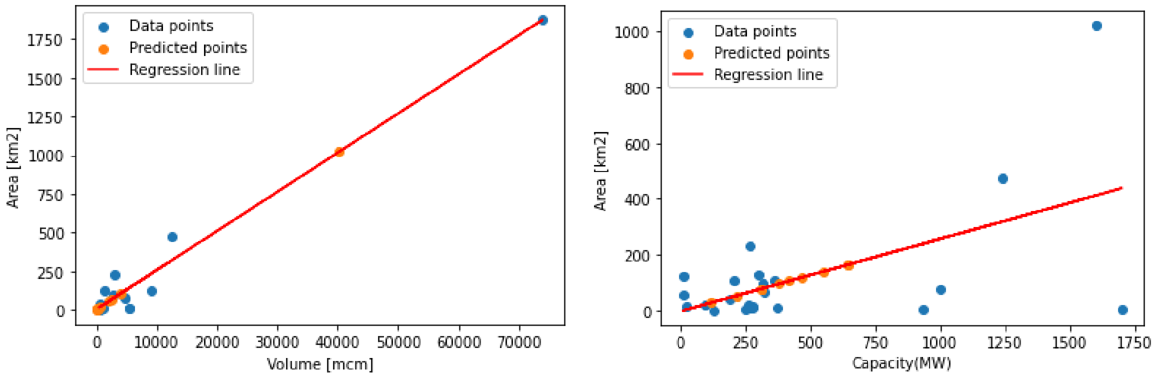
Estimating the FPV coverage percentage

In order to estimate the percentage of FPV coverages for these calculations, the FPV capacity obtained from the OSeMOSYS simulations was used. This value was then converted into an area using the capacity to area ratio for floating solar panels from Sanchez et al. (2021) (0.1 kW/m^2). Finally, the area covered by the floating solar panels was divided by the total reservoir areas to get the covering percentage.

However, the used hydropower plants dabases (Sterl et al., 2021) and (Peters et al., 2023) did not include the areas of all the reservoirs, especially the planned ones. For this reason, a way of estimating such areas was needed. To this end, the first step was to try to fill the gaps searching for values of either area or volume for each reservoir. This search was conducted online using various grey literature sources and Google Earth measuring tools. After this step, there were still many gaps in the data, with some reservoirs having volume values but not area values and others missing both the values. For the first category, a linear regression was used to estimate the volume-area relationship using the known data from the other reservoirs. For the second group, instead, the linear regression was performed to estimate the capacity-area relationship using the known data from the other reservoirs. Both the regression lines are visible in Figure 9.

Percentage of covering [%]	0	10	30	50	70	100
Evaporation reduction [mm/year]	0	18	49	73	89	100

Table 7: Evaporation reduction ratios for different FPV covering percentages (Scavo et al., 2021)



(a) Volume - Area regression

(b) Other countries

Figure 9: Capacity - Area regression

The final values of surface areas for each reservoir are reported in Appendix A, together with the source used to estimate them.

Estimating the evaporation reduction

For a similar study, Sanchez et al. (2021) used evaporation rates from Scavo et al. (2021) that relate the percentage of FPV coverages to evaporation reduction percentages. These rates were obtained by modifying the radiation balance at the water surface due to the covering, and the resulting reduced heat flux was then used to calculate the reduced evaporation with the Penman-Monteith equation. For floating solar panels in direct contact with water, the ratios obtained are reported in Table 7 and plotted in Figure 10. In order to have values for each FPV coverage percentage, these values were interpolated with a cubic interpolation function.

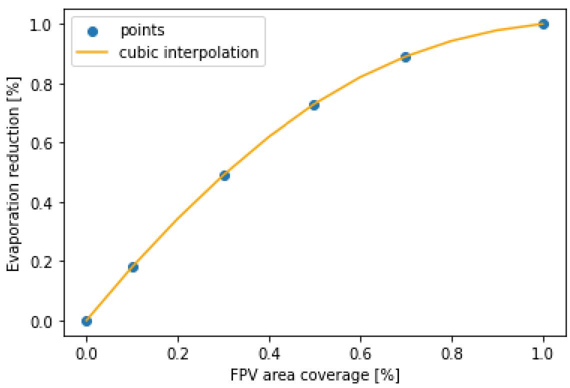


Figure 10: Evaporation reductions vs FPV coverage percentages

Estimating the total water savings

In order calculate the total water savings linked to each evaporation reduction percentage, the total evaporation from each reservoir had to be estimated. To this end, the data obtained in a study by Sanchez et al. (2020) were adopted. In this study, the water losses to evaporation from all the existing reservoirs of each country were estimated, as well as the total reservoir surface areas. Sanchez et al. (2020) calculated the evaporation rates using the FAO methodology for open water surfaces and

the reference evapotranspiration calculated using the LISVAP model (based on the Penman-Monteith equation).
These variables were then used to obtain a reference evaporation value for each country, by dividing the total water losses by the total reservoir area. For the countries under study, the values can be seen in Table 8. South Sudan does not have any existing reservoir and is therefore not present in the table.

Country	Total reservoir area [km2]	Total water losses [MCM/y]	Total water losses [mm/year]
Egypt	5248.37	5757.43	1097
Ethiopia	1966.5	923.27	469
Sudan	796.06	2718.96	3416

Table 8: Total reservoir areas and yearly water losses by country (Sanchez et al., 2020)

The reference evaporation value in mm/year of each country was then used to obtain the water losses from each single reservoir, multiplying it by the area of each reservoir. Finally, this value was multiplied by the evaporation reduction in percentage obtained through the floating solar panels deployment, to finally estimate the total water savings.

Estimating the extra hydropower generation

Once the evaporation reduction was obtained, it was used to calculate the potential increase in hydroelectricity generation, which can be calculated with:

$$\Delta E_g = \Delta P_g \cdot \frac{V_s}{Q} \tag{6}$$

With ΔE_g the difference in electricity generation [W s], ΔP_g the difference in hydropower generation [W], V_s the saved water volume $[m_3]$ and Q the nominal water discharge through the turbines. The assumption behind this equation is that with an extra volume of water V_s, the turbine can operate an additional amount of time equal to $\frac{V_s}{Q}$, assuming the nominal discharge could be fully utilised.
In order to calculate the difference in hydropower generation needed for equation 6, the following formula was used:

$$\Delta P_g = \Delta H \cdot \eta \cdot \rho \cdot g \cdot Q \tag{7}$$

With ΔH the evaporation reduction [mm], η the system efficiency (assumed to be 0.85 from Sanchez et al. (2021)), ρ the density of water (1000 kg/m^3), g the gravity acceleration (9.81 m/s^2) and Q the nominal water discharge through the turbines.
Combining equations 6 and 7 and having $\Delta H = \frac{V_s}{A}$, the following relation can be obtained:

$$\Delta E_g = \frac{V_s^2}{A} \cdot \eta \cdot \rho \cdot g \tag{8}$$

With A being the reservoir area.

2.4 Sensitivity analyses of projected pathways to main parameters

Since many assumptions were taken during the implementation of FPV technologies, sensitivity analyses had to be conducted.
The main objective function to be minimised within the optimization tool is the total costs, hence the model results are quite sensible to changes in technology costs. Therefore, the first sensitivity analysis focuses on the costs of FPV technologies. However, since these are closely related to the traditional solar technologies, all the solar technology costs were altered in this sensitivity analysis. Hence, one run with lower capital costs for solar and one run with higher capital costs were performed, altering the cost values by -20% and +20% respectively.
Apart from the costs, another crucial parameter that affects the results are the maximum and minimum capacity bounds that constrain the capacity expansion of each technology. In order to check the role of

such constraints for FPV technologies, a simulation was performed increasing the maximum installable capacity of each FPV technology by an arbitrary factor of 10.

To summarize this whole subsection, the simulations list is reported in Table 9, and the sensitivity analyses in Table 10.

Simulation set	**Simulation name**	**Simulation code**
Reference	Reference	REF
Introduction of FPVs	Reference FPV	REF_FPV
Climate change	RCP 2.6 dry	RCP26_dry
Climate change	RCP 6.0 dry	RCP60_dry
Climate change	RCP 2.6 wet	RCP26_wet
Climate change	RCP 6.0 wet	RCP60_wet
Taxes	Low taxes	TAX_low
Taxes	High taxes	TAX_high

Table 9: Summary of simulation sets

Sensitivity analysis	**Code**
Lower solar capital costs	Costs_low
Higher solar capital costs	Costs_high
Looser constraints for FPVs	Loose_constr

Table 10: Summary of sensitivity analyses sets

Finally, a schematical overview of the methodology of this work is pictured in Figure 11. Here, we can see the main data sources (yellow boxes) used to create model extensions (orange boxes) and build scenarios sets (blue boxes). The results of all these processes are then fed to the main modelling tool (green box) used to obtain four sets of results (violet boxes). These will be presented in the following section, and focus on the overall energy system's evolution, on the role of floating solar power, and on the environmental footprints of the energy system.

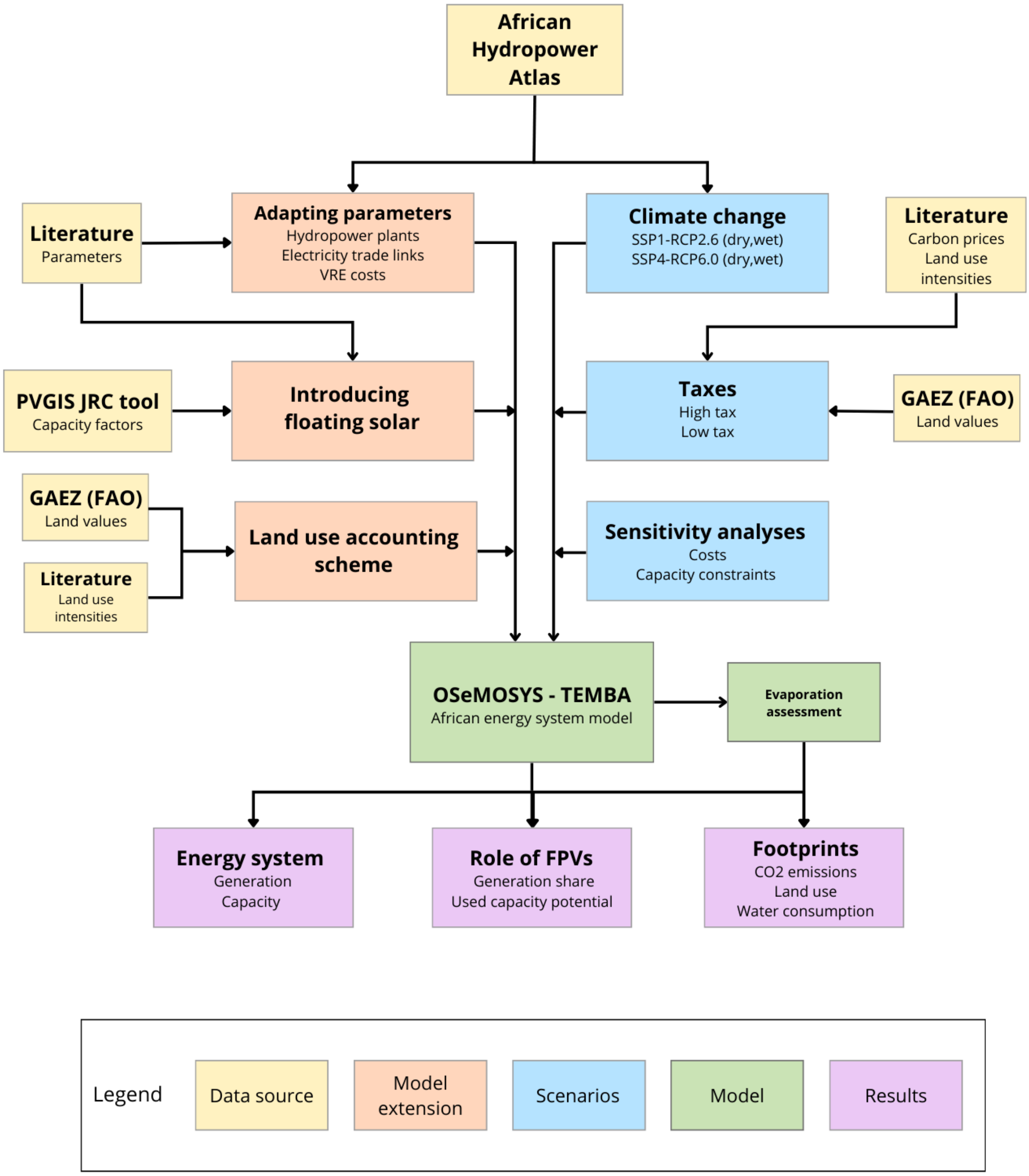


Figure 11: Study structure overview

3 Results

In this chapter the results from each scenario are reported, followed by the sensitivity analyses. Firstly, the reference scenario (REF) results are presented, in order to have a general idea of the behaviour of the model in the baseline case. Then, the introduction of floating solar power is assessed through the first scenario (REF_FPV). Afterwards, climate change (RCP) and the taxation (TAX) scenarios are presented, focusing on the differences with the reference FPV scenario. The analysis focusing on the role of floating solar power is then carried out. Finally, the findings of the sensitivity analyses are reported.
Since the model contains a very large number of variables, the results presented here only focus on those variables that are crucial in order to answer the research questions. Such variables are mainly the yearly electricity generation mixes, the capacity expansion of floating solar power and the system costs, emissions, land use and evaporation reductions. The behaviours of these variables are reported for the whole system as well as for each single country. Further results are included in the appendixes.

3.1 Reference scenario

The reference scenario explores the electricity generation expansion of the system without the introduction of floating solar panel technologies. Moreover, no climate change is assumed to be affecting the capacity factors of hydropower generation, which are calculated from the monthly median flow estimates based on historical data. Finally, no taxes are applied for land use or CO2 emissions.
The yearly energy generation mix over the modelling horizon is reported in the bar chart of Figure 12. Additionally, a pie chart showing the energy generation percentages is also reported, in order to have a clearer overview of the role of each technology in the mix.

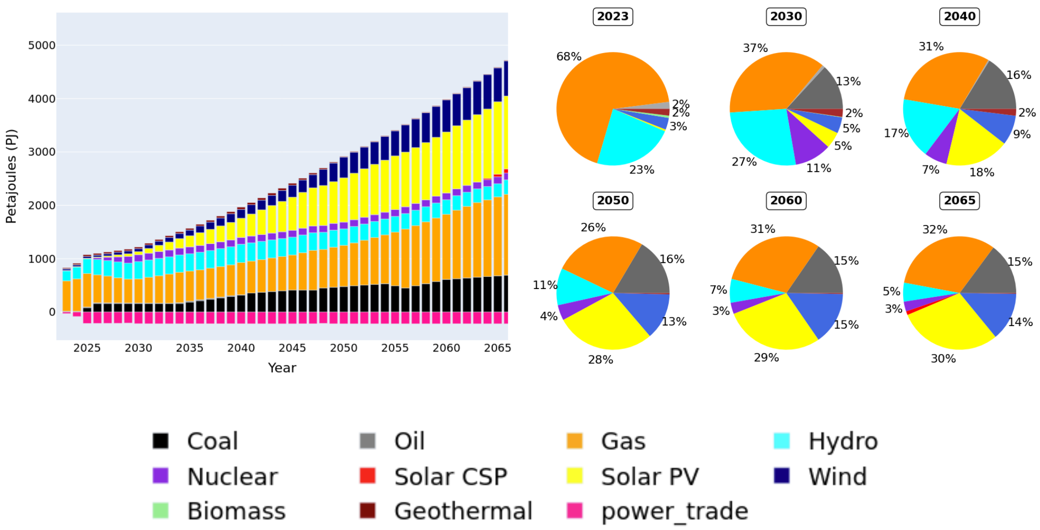


Figure 12: Generation mix of the whole region for the Reference scenario

In this figure, the generation technologies are aggregated by technology type. As it can be seen from the figure, in this scenario the largest share of the mix is still composed by fossil fuel technologies (gas and coal) over the whole modelling period. However, the role of variable renewables technologies (wind and solar) becomes more important towards the end of the horizon, as a result of their projected decreasing costs included in the optimization. Furthermore, the role of hydropower generation in the basin remains mostly constant apart from a slightly decrease in the long term. The nuclear generation share in the chart is only composed by the Egyptian power plant that had been explicitly modelled as described in section 2. Finally, it is also interesting to notice that from 2025 onward, there is a relatively important amount of energy exported outside of the modelling area, as it can be seen from

the negative pink bars in the bar chart. This is mainly composed by exports from Egypt to Saudi Arabia and from Ethiopia to Kenya, as it is shown in the following paragraphs and in Figure 41.
Another important fact to remark is that these charts refer to the aggregated electricity generation from the four countries together. However, the electricity generation is very different between countries in absolute numbers: Egypt dominates the region with up to 3100 PJ/y, Ethiopia and Sudan follow with 900 PJ/y and 650 PJ/y respectively, while South Sudan only reaches 70 PJ/y. Therefore, it is also important to analyse the results of the different countries singularly, which is done in the following paragraphs.
In Figure 13, the mix for each single country is reported. As it can be seen, the energy generation mix is very different from country to country. In fact, Egypt's mix is highly dominated by fossil fuels over the whole horizon, while the other three countries develop mainly renewable resources (solar over all). Additionally, Ethiopia (and Sudan in the last 25 years) develop a substantial amount of wind power.

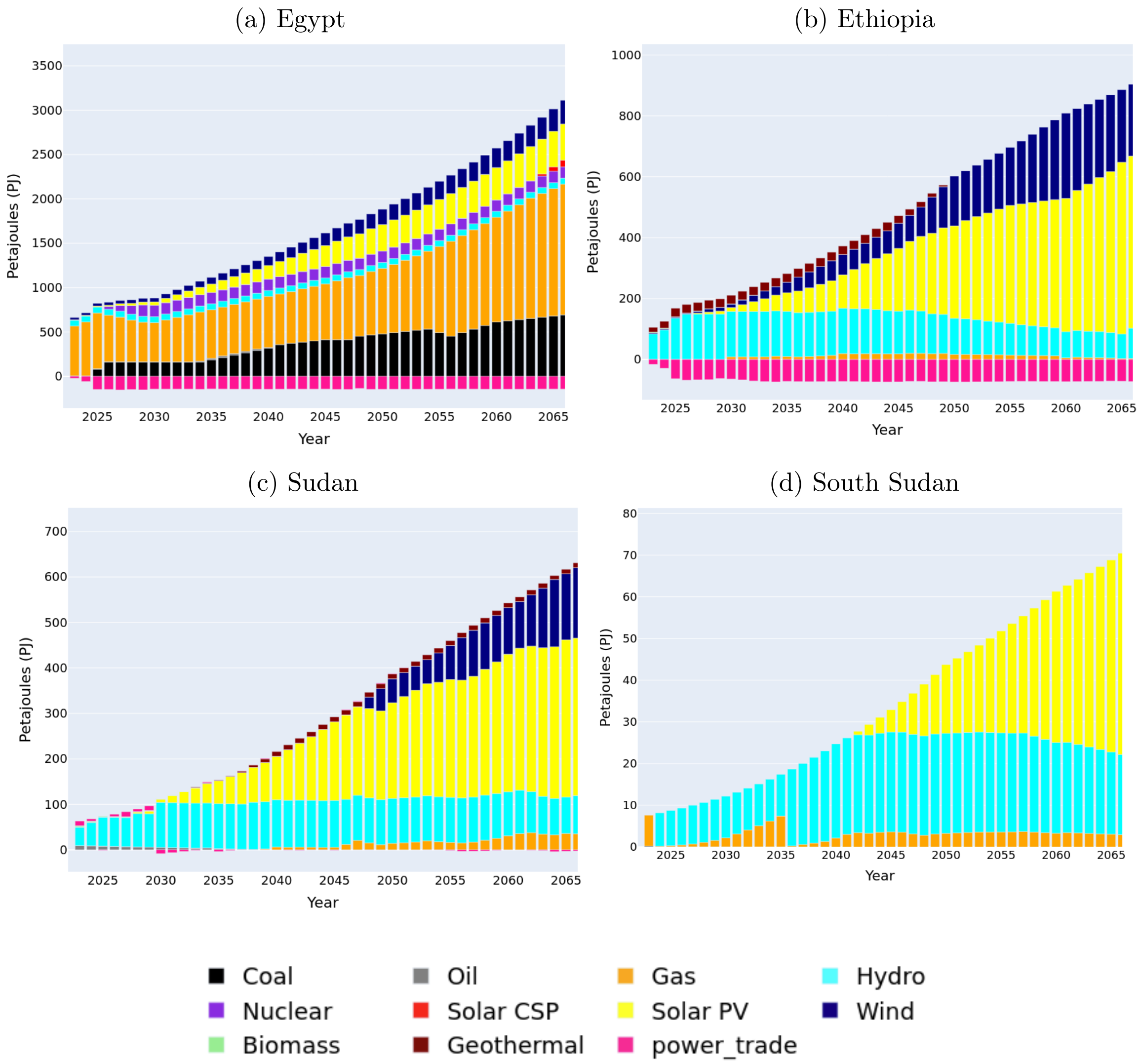


Figure 13: Generation mix of the single countries for the Reference scenario

Ethiopia and Egypt export a relatively important amount of electricity, mainly to Kenya and Saudi Arabia respectively, while Sudan is an intermediate trader from Ethiopia to Egypt, therefore its net traded electricity does not occupy a relevant part of its generation bar chart. South Sudan does not develop any trade links and therefore does not trade electricity with the neighbouring countries. Details about trades in the single countries can be seen Appendix B.

3.2 Introduction of FPVs

In this scenario, the introduction of floating solar power is explored. Apart from the introduction of these technologies, the other assumptions are the same as in the reference scenario: no climate change and no externality penalties are applied in this scenario.
The graphs of the energy generation of the whole system for this scenario can be seen in Figure 14. Here, the mix is very similar to what observed before the introduction of floating solar technologies, however, it can be noticed how this new technology is cost-optimal already from the late 2020s, and reaches around 2% of the generation mix in 2040.

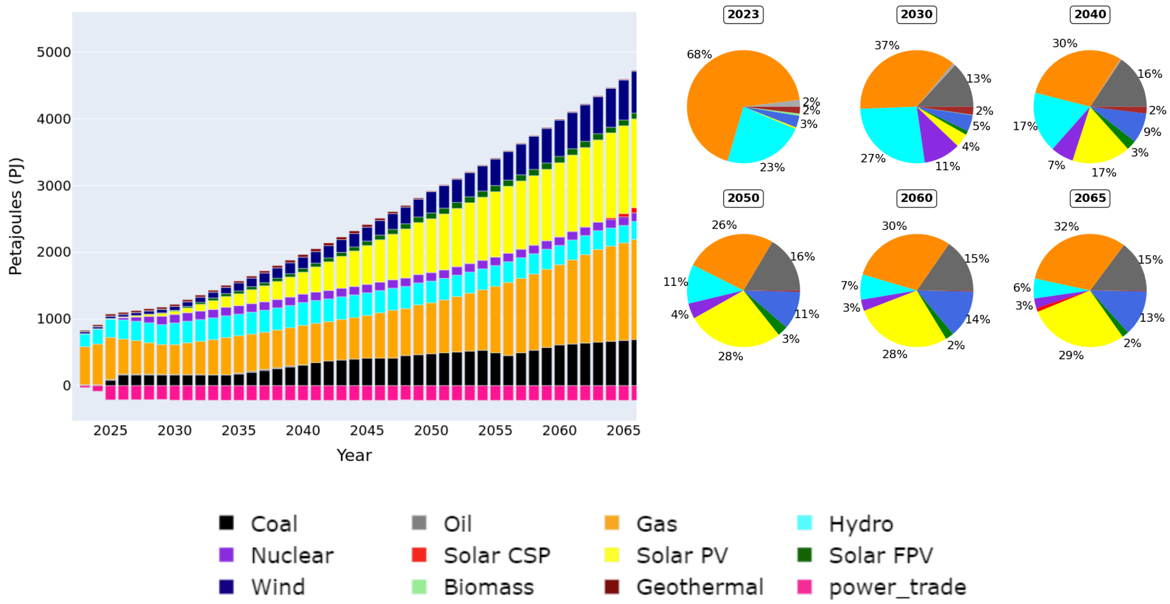


Figure 14: Generation mix of the whole region for the Reference FPV scenario

In order to better analyse the changes from the reference scenario after the addition of FPVs, the difference between the generation mix of the REF scenario and the REF_FPV scenario were plotted and reported in Figure 15. In these plots, the positive bars represent the generation that is added in the scenario with FPVs, and the negative bars represent the generation that is removed. In this way, it is easy to visualise what the floating solar panel technologies replace in terms of generation. To guarantee a better comparison between the regions and favour a better understanding of how drastic the changes are on the scales of a certain region, the differences were scaled on the maximum annual generation of the region.
For the whole system, it can be observed that floating solar power mainly substitutes other renewable technologies (wind and solar), but also some gas and coal generation. It is also interesting to see that the addition of floating solar power causes an extra amount of hydropower generation in the second half of the modelling period.
Going into the detail of the single countries, different behaviours can be observed. In Egypt, floating solar power replaces natural gas generation only, while in Ethiopia they replace mostly wind and solar, and imply a higher hydropower generation. In Sudan, instead, they mostly replace traditional solar power, along with some wind power generation. Finally, in South Sudan, no floating solar power is developed because the country does not develop any reservoir, and the difference in the mix between the two scenarios is irrelevant. Possible reasons and implications of these behaviours will be presented in the discussion session.

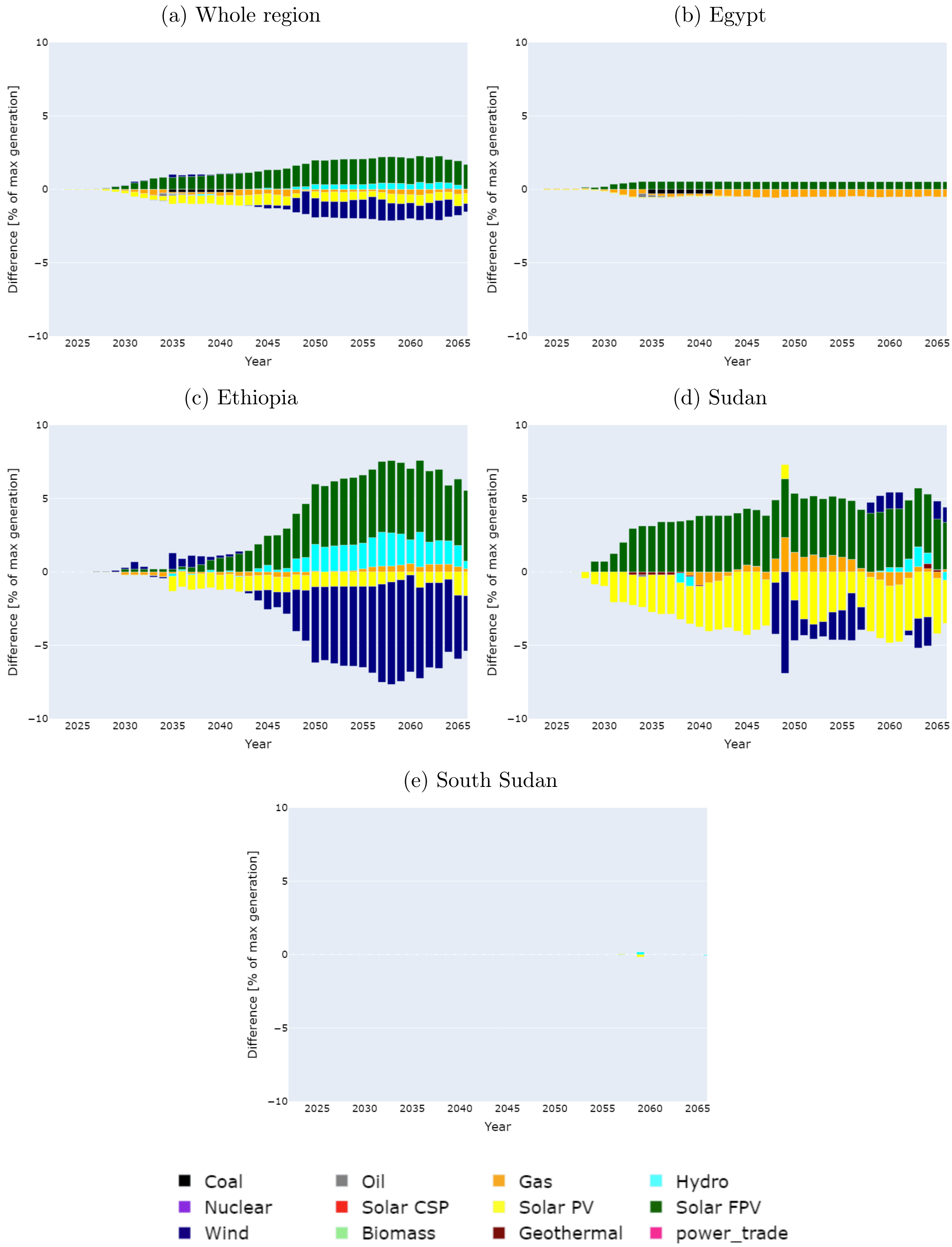


Figure 15: Difference between generation mix in the FPV scenario and reference scenario

3.3 Climate change scenarios

In this section, the results of the four climate change scenarios are presented. Since the addition of floating solar power has been already analysed in the previous paragraph, the scenarios reported here all feature the FPVs technologies. Moreover, since the relevance of these scenarios is to analyse how the role of floating solar power changes under different climate change projections, climate change

scenarios without FPV technologies were considered superfluous.
In Figure 16 the generation difference between the climate change scenarios and the reference scenario is reported for the whole modelling area. Here we can see that three scenario out of four produce expectable results, with a deficit in hydropower generation in the dry case (RCP6.0 dry) and an increase in hydropower generation in the wet case (RCP2.6 wet and RCP6.0 wet). Instead, the RCP2.6 dry scenario shows an initial reduction followed by an increase of hydropower generation. Besides, the wet scenarios affect the generation mix more than the dry scenarios, as it is shown by the magnitude of the bars in the plots. Finally, the difference between the two climate change projections is clear in the dry case (RCP6.0 causing a decrease in hydropower generation unlike RCP2.6), while it is not really relevant in the wet case.
A more detailed analysis of the effect of the climate change scenarios on each country's generation mix is reported in Appendix B.

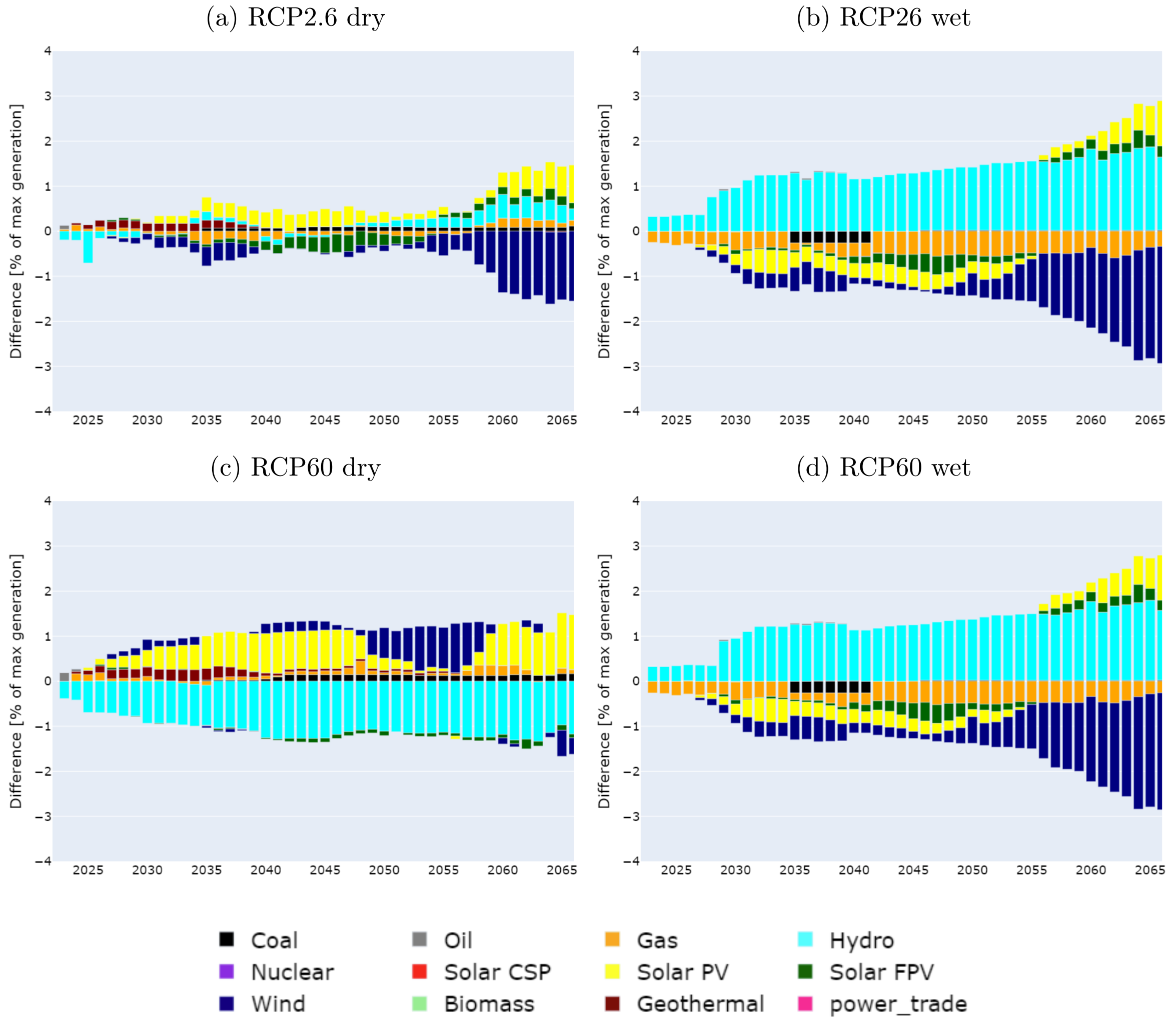


Figure 16: Difference between generation mix in the RCP2.6 dry scenario and reference FPV scenario

3.4 Taxation of environmental footprints scenarios

In this section, the results of the taxation of environmental footprints scenarios are presented. First, the differences in the generation mix from the reference scenario is reported for both the high and low tax scenario for the whole region (Figure 17). Here, we see that in the low scenario, coal and solar are replaced by gas, wind power, hydropower and concentrated solar power (CSP). Something similar happens in the high taxes scenario, but this time CSP and wind power technologies occupy a way larger part of the mix, reducing the role of gas in replacing coal generation. This has to do with the fact that in the high taxes scenario, the carbon price is even higher, making fossil fuels technology more expensive than high-cost renewables. The results from the single countries are analysed in Appendix B.

(a) Low taxes scenario (b) High taxes scenario

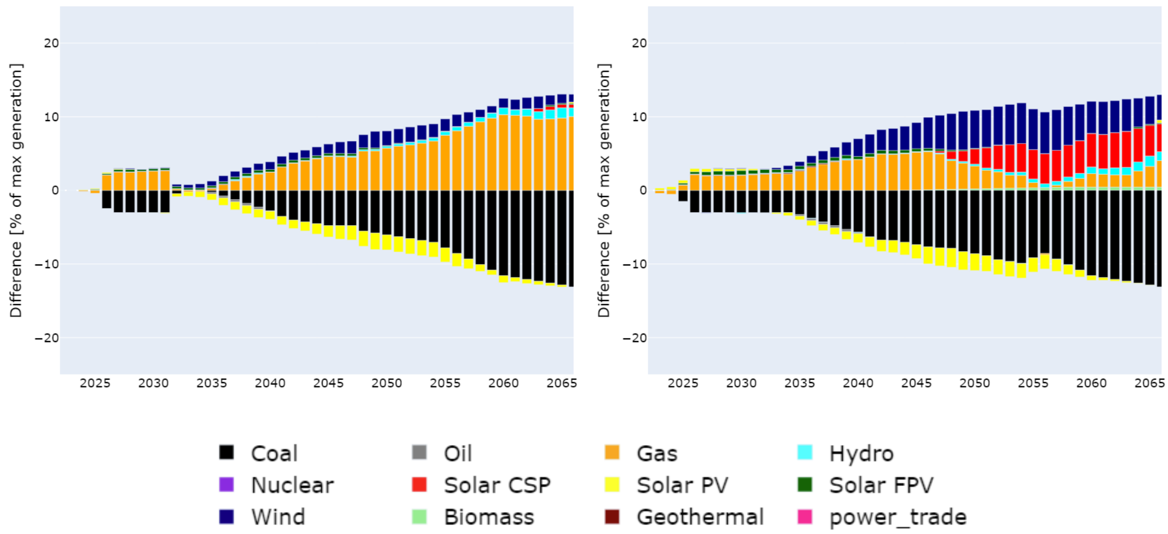


Figure 17: Difference between generation mix in the taxes scenarios and reference FPV scenario for the whole region

3.5 Analising the role of floating solar power

In the previous sections, the differences in the energy generation mix between the different scenarios and the reference scenario were analysed. However, in order to have a more precise idea about the role of floating solar technologies, a more detailed analysis had to be carried out.
First of all, a sensible way of assessing the importance of such technologies in the mix had to be defined. Two important variables providing such information are the percentage of the generation mix FPV plants occupy and their onset year (i.e. when they appear in the mix for the first time). Besides, the total generation of FPVs over the whole horizon can also shed some light on their importance in the electricity system.
In Tables 11 - 12, these variables are compared for all the countries across the different scenarios. The onset year tables are not reported since this variable can be easily seen from the capacity expansion graphs in Figure 19, topic of the next paragraph.

Scenario	[%]
TAX_High	4.31
TAX_Low	3.76
REF	2.98
RCP60_dry	2.91
RCP60_wet	2.82
RCP26_dry	2.80
RCP26_wet	2.79

(a) Whole region

Scenario	[%]
TAX_High	2.15
TAX_Low	2.00
RCP60_dry	1.74
REF	1.73
RCP26_dry	1.73
RCP26_wet	1.73
RCP60_wet	1.73

(b) Egypt

Scenario	[%]
TAX_High	8.79
TAX_Low	8.25
RCP60_wet	7.67
RCP26_dry	7.58
RCP26_wet	7.52
RCP60_dry	6.93
REF	6.74

(c) Ethiopia

Scenario	[%]
TAX_High	17.96
TAX_Low	16.70
RCP60_dry	15.17
RCP60_wet	14.88
REF	14.76
RCP26_wet	14.40
RCP26_dry	14.03

(d) Sudan

Table 11: Maximum generation share of floating solar power

(a) Whole region

Scenario	[10^3 PJ]	$\Delta_{(sc-ref)/ref}$[%]
TAX_High	3.57	21.79
TAX_Low	3.43	17.16
REF	2.93	0.00
RCP26_wet	2.88	-1.55
RCP60_wet	2.87	-2.03
RCP26_dry	2.84	-3.16
RCP60_dry	2.81	-3.96

(b) Egypt

Scenario	[10^3 PJ]	$\Delta_{(sc-ref)/ref}$[%]
TAX_High	0.84	13.02
TAX_Low	0.81	9.06
RCP26_dry	0.74	0.00
RCP26_wet	0.74	0.00
RCP60_dry	0.74	0.00
RCP60_wet	0.74	0.00
REF	0.74	0.00

Scenario	[10^3 PJ]	$\Delta_{(sc-ref)/ref}$[%]
TAX_High	1.56	36.32
TAX_Low	1.50	31.04
REF	1.14	0.00
RCP60_dry	1.11	-2.99
RCP26_wet	1.09	-4.46
RCP26_dry	1.09	-4.88
RCP60_wet	1.08	-6.02

(c) Ethiopia

Scenario	[10^3 PJ]	$\Delta_{(sc-ref)/ref}$[%]
TAX_High	1.17	12.08
TAX_Low	1.12	7.68
RCP60_wet	1.05	0.90
RCP26_wet	1.05	0.53
REF	1.04	0.00
RCP26_dry	1.00	-3.52
RCP60_dry	0.96	-7.86

(d) Sudan

Table 12: Total model period FPV generation

Maximum FPVs electricity generation share

As far as the maximum generation share of floating solar panel technologies is concerned, it can be seen from the tables of Table 11 that there are some differences and similarities between the countries. First of all, in terms of absolute magnitudes, the maximum share varies from around 3-4% for the whole system, to around 2% for Egypt, 6-9% for Ethiopia and 14-18% for Sudan. Besides, the ranking of scenarios changes from area to area: even though taxation scenarios show the highest generation shares for FPVs in all the countries, the ranking of the other scenarios vary.

If the whole area is considered, the maximum FPV share is not relevanlty affected by climate change scenarios (0.1 % difference with the reference). Something very similar happens in Egypt, but here the effect of climate change scenarios are negligible. In Ethiopia, instead, all scenarios cause an increase compared to the reference, with wet scenario causing a higher maximum share than dry scenarios, even though with less than 1% difference. In Sudan, finally, the RCP2.6 climate change scenarios cause a very slight reduction in FPV generation share compared to the reference, while the RCP6.0 scenarios cause a very slight increase.

Total FPVs electricity generation

Analysing the total FPV generation also shows different results from country to country. In Table 12 the total generation for each scenario and for each country is reported, together with the difference in percentage between each scenario and the reference. If we consider the total system (Table 12 a), we see the highest total generation for the taxation scenarios and the lowest for the dry climate change scenarios. In Egypt something similar happens, but here the climate change scenarios don't sort any effect on the total FPV generation. In Ethiopia, instead, all climate change scenarios cause a reduction in FPV total generation, especially the wet cases. Finally, for Sudan taxation and wet scenarios cause an increase in FPV total generation, while dry scenarios cause a reduction. Possible reasons for these behaviours will be presented in the Discussion section.

Capacity expansion of FPVs

Another interesting way of assessing the relevance of floating solar panel technologies is to observe how much of their total capacity potential they develop. To this end, the FPVs capacity expansion for each

country and in each scenario was analysed. This analysis can give a better idea about how necessary a technology is for the mix: the higher the utilised potential, the more cost-optimal the technology is for a country in a certain scenario. On the other hand, it is also important to bear in mind that every country has a different floating solar panel potential, which depends on the hydropower reservoirs expansion potential. For example, since Egypt has limited hydropower development potential, its floating solar panel potential is limited compared to Ethiopia, which has the possibility to build many more reservoirs. To further analyse this limitation, a scenario with looser constraints for FPVs is run, and its results are presented in the sensitivity analyses paragraph (3.9). Additionally, the capacity expansion pathways for FPVs also give information on when and how the development of this technology takes place.
The graphs with the FPV capacity expansion are reported in Figure 19, and the maximum potentials for each country in each scenario are reported in Figure 18. These maximum potentials are restricted to the hydropower capacity built according to the optimization, and do not represent the total theoretical potential that could be implemented if all the reservoirs were built. In this way, we can analyse the potential of floating solar power independently from the potential of hydropower reservoirs, allowing us to see their actual importance as single technology. The hydropower capacity expansion results for each scenario are included in the Appendix.
Analysing the whole system, we can see that the full potential of FPVs is exploited in every scenario. This is also true for every country under analysis.
In all the regions, the overall effect of the scenarios is similar: the taxation scenarios cause an earlier development of the FPV potential, the dry scenarios cause a lower total development (due to lower hydropower capacity expansion) and the the wet scenarios cause a higher but later development (due to higher hydropower capacity expansion and generation). It is also interesting to notice that in Ethiopia the wet climate change assumptions delay the onset of FPV technologies more significantly (almost 20 years), due to the increased hydropower generation.

(a) Whole region

Scenario	**Max potential [GW]**
RCP26_dry	16.8
RCP26_wet	16.8
RCP60_wet	16.8
EXT_High	15.2
EXT_Low	15.2
REF	15.2
RCP60_dry	14.89

(b) Egypt

Scenario	**Max potential [GW]**
RCP26_dry	2.65
RCP26_wet	2.65
RCP60_wet	2.65
RCP60_dry	2.65
EXT_High	2.65
EXT_Low	2.65
REF	2.65

Scenario	**Max potential [GW]**
RCP26_dry	10.01
RCP26_wet	10.01
RCP60_wet	10.01
EXT_High	8.41
EXT_Low	8.41
RCP60_dry	8.41
REF	8.41

(c) Ethiopia

Scenario	**Max potential [GW]**
EXT_High	4.14
EXT_Low	4.14
RCP26_dry	4.14
RCP26_wet	4.14
RCP60_wet	4.14
REF	4.14
RCP60_dry	3.83

(d) Sudan

Figure 18: Maximum FPV capacity potential across scenarios

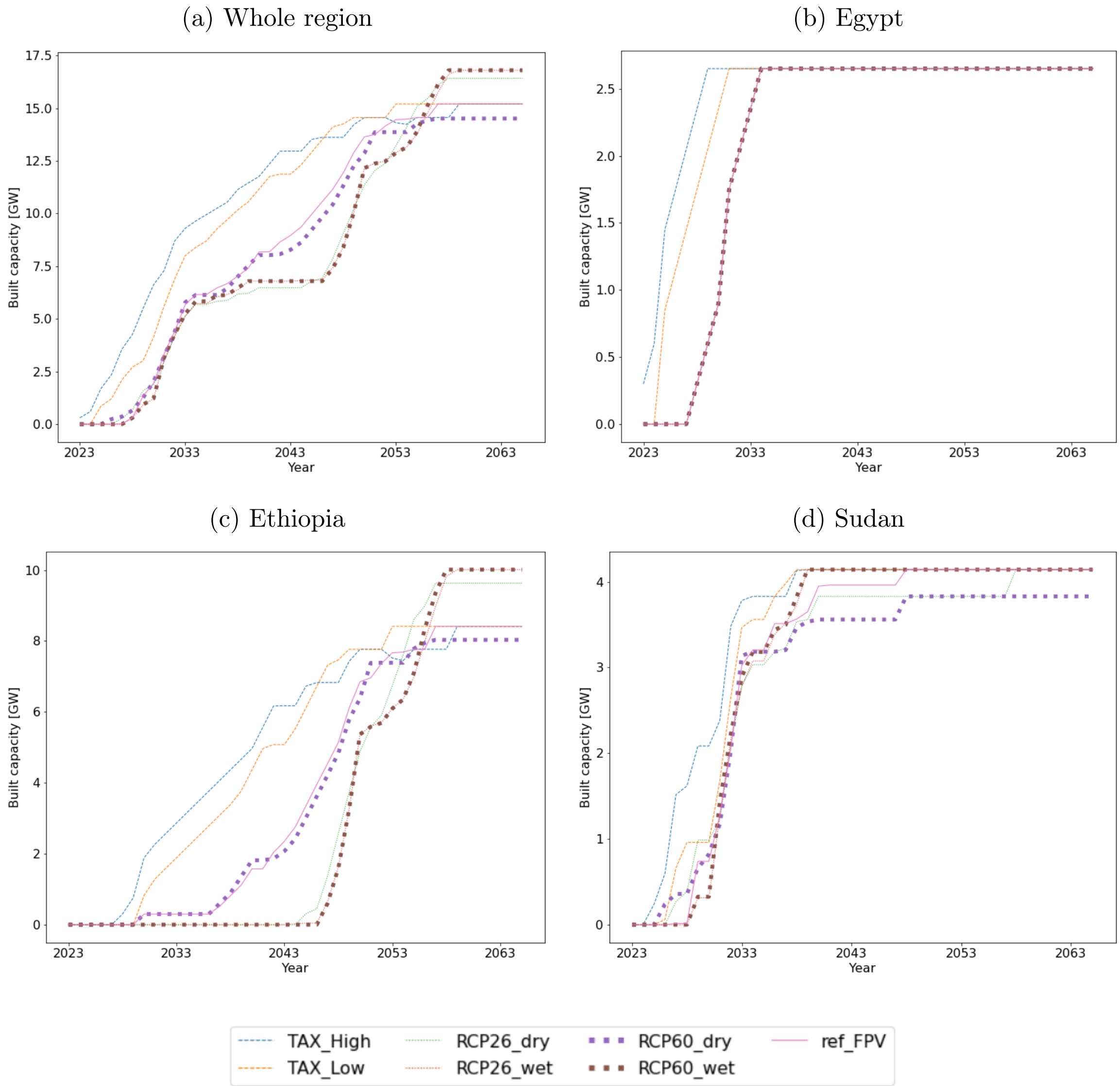


Figure 19: FPV capacity potentials across scenarios

3.6 Water savings and extra hydropower electricity generation

In Section 2.3, the procedure followed to obtain the water savings due to the implementation of floating solar power was presented, together with the steps followed to calculate the consequent extra hydropower generation obtainable from this saved volume of water. In this section, the results relative to this analysis are reported.

The water savings and extra hydropower generations have been calculated for each location and for each year, based on the existing FPV capacity in a certain reservoir in a certain year (data available in the Appendix). This data was then aggregated in four regions (the three single countries that develop FPVs and the whole area). Afterwards, in order to have an idea of the maximum yearly water savings that are feasible according to this analysis, the year with the maximum FPV capacity was selected for each region. The relevant values of this analysis for the REF_FPV scenario are visible in Table 13.

The values in the table show that the addition of floating solar panels can reduce evaporation up to 1.93% yearly in the whole region, with a peak of 2.61% yearly in Ethiopia and Sudan. The consequent increase in hydropower generation, however, is not as relevant if compared to the scales of electricity generation of the hydropower plants, showing increases of 0.37% for the four countries combined, with the highest increase being in Sudan (0.81%).

	ENB	EG	ET	SD
Installed FPV capacity [GW]	15.11	2.65	8.31	4.14
FPV coverage area [%]	0.02	0.01	0.03	0.03
Reservoir evaporation [mcm/y]	19 536	7 149	2 765	9 622
Water savings [mcm/y]	376	53	72	251
Evaporation reduction [%]	1.93	0.74	2.61	2.61
Extra hp generation [PJ/y]	0.49	0.05	0.02	0.42
Extra hp generation [% of HP]	0.37	0.16	0.04	0.81

Table 13: Yearly values relative to evaporation reduction and extra hydropower generations analysis

	ENB	EG	ET	SD
Reservoir evaporation [mcm]	799 705	307 387	118 632	373 685
Water savings [mcm]	11 449	1 855	1 422	8 172
Water savings [%]	1.43	0.60	1.20	2.19
Extra hp generation [PJ]	15.75	1.74	0.30	13.71
Extra hp generation [% of HP]	0.15	0.07	0.01	0.34

Table 14: Total evaporation reduction and extra hydropower generations

To have an idea of the effect of these maximum yearly rates over the whole modelling horizon, the total values for the variables under study were reported in Table 14 for each region (REF_FPV scenario). Here, we see that the total evaporation reduction reaches up to 1.43% in the three countries combined, with a peak of 2.19% in Sudan. The total increase in hydropower generation, instead, doesn't exceed 0.81% in Sudan and 0.37% in the whole region.
Finally, the total values were calculated for each scenario, in order to assess how the total water savings and extra electricity generation changes between the different simulations and are reported in Table 15 and 16.
Here, we see that the difference between each scenario is almost negligible, reaching maximum 0.21% increase in the EXT_High scenario for the water savings and -0.03% in the RCP_26 wet scenario for the extra electricity generation. This has to do with the fact that the variations in capacity expansion of FPVs between the scenarios are relatively small, causing therefore quite small variations in area coverage percentages and even smaller variations in evaporation savings and extra electricity generation.

Scenario	Tot reduction [mcm]	Tot reduction [%]	$\Delta_{(sc-ref)}$[%]
TAX_High	13 110	1.64	0.21
TAX_Low	12 508	1.56	0.13
REF	11 449	1.43	0.00
RCP60_wet	11 283	1.38	-0.06
RCP60_dry	10 844	1.37	-0.06
RCP26_wet	11 232	1.37	-0.06
RCP26_dry	10 954	1.35	-0.08

Table 15: Total water savings across scenarios

3.7 Total costs, CO2 emissions and land use

Another assessment that can give some information on the role of floating solar power and on the dynamics in the different scenarios is about the energy system's total costs, total emissions and total land use.

Scenario	Tot extra generation [PJ]	Tot extra generation [%]	$\Delta_{(sc-ref)}$[%]
RCP60_dry	14.72	0.17	0.02
TAX_High	17.46	0.16	0.01
TAX_Low	16.81	0.16	0.00
REF	15.75	0.15	0.00
RCP26_dry	15.04	0.14	-0.01
RCP60_wet	15.83	0.12	-0.03
RCP26_wet	15.77	0.12	-0.03

Table 16: Total extra hydropower electricity generation across scenarios

Total costs

In Table 17 an overview of the total system costs (e.g. cumulative costs over the whole modelling horizon) across the different scenarios is reported. Besides, the difference between each scenario and the reference scenario is calculated and shown as a percentage.

Scenario	Total Costs [10^6 M$]	$\Delta_{(sc-ref)/ref}$[%]
TAX_High	0.822	55.98
TAX_Low	0.616	16.89
RCP60_dry	0.532	0.95
RCP26_dry	0.529	0.38
REF	0.527	0.00
REF_FPV	0.526	-0.19
RCP60_wet	0.522	-0.95
RCP26_wet	0.522	-0.95

Table 17: Total costs across the scenarios

From here, we see that taxation scenarios have the highest total costs (due to the taxes), dry scenarios have higher costs compared to the reference scenario (due to reduced hydropower generation) and wet scenarios have lower costs for the opposite reason. Besides, the addition of floating solar power reduces the total system costs, even though by very small amounts (maximum 0.26% reduction) in the TAX_high scenario.
Another insightful variable as far as costs are concerned is the capital expenses needed to reach the maximum floating solar power capacity. This amounts to 8.6 B$ for the whole region, 1.3 B$ of which in Egypt, 5.4 B$ in Ethiopia and 1.9 B$ in Sudan.

Total CO2 emissions

In terms of total system emissions, in Table 18 we can observe a similar behaviour: the total system

Scenario	Total Emissions [10^5 MtCO2]	$\Delta_{(sc-ref)/ref}$[%]
REF	0.181	0.00
RCP60_dry	0.180	-0.03
RCP26_dry	0.180	-0.19
REF_FPV	0.180	-0.37
RCP60_wet	0.179	-0.83
RCP26_wet	0.179	-0.87
TAX_Low	0.158	-12.47
TAX_High	0.139	-22.89

Table 18: Total CO2 emissions across the scenarios

emissions decrease very slightly with the addition of floating solar power (reduction of 0.37%). Besides, the taxation scenarios present the lowest total emissions, followed by the wet scenarios. The dry scenarios, instead, show slightly higher emissions than the reference, due to a slight increase in gas generation.
In Figure 20, the emission pathways are represented. From the plot we can see that the REF, REF_FPV and RCP scenarios are all very close together, while the taxation scenarios clearly show a decrease in emissions, especially in the TAX_High scenario.

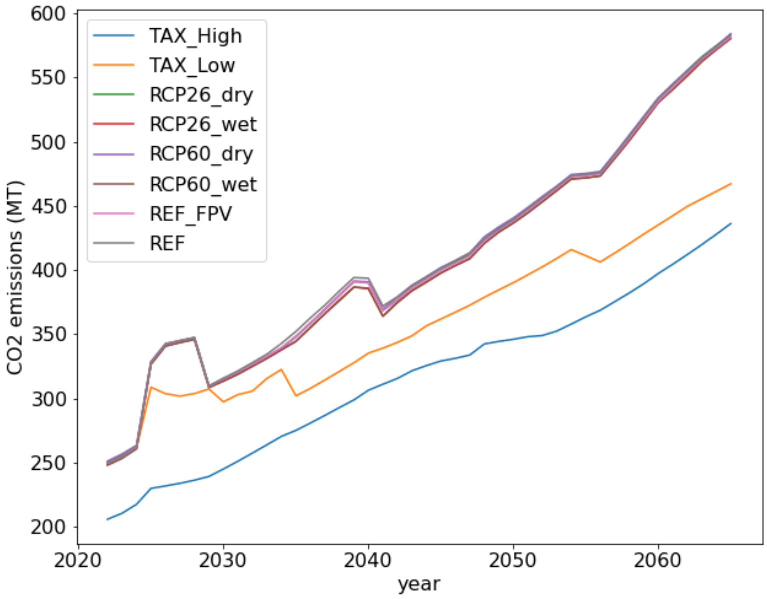


Figure 20: CO2 emissions evolution across scenarios

Total land use

As far as the land use is concerned, the total land use over the whole horizon across scenarios is reported in Table 19. Here, we see that the introduction of floating solar power reduce the total land use by 1.19%. Besides, the introduction of a land tax in the taxation scenarios help reducing the total land use up tp -22%, while the effects of climate change projections are milder, with the wet scenarios slightly reducing land use and the dry scenarios slightly increasing it.
In Figure 21 the land use pathways are reported. Similarly to what seen in Figure 20 for the CO2 emissions, the reference scenarios and the RCPs scenarios all follow a similar pathways, while the taxation scenarios show a lower land use. However, in this case the TAX_High scenario crosses the TAX_Low scenario in the early 2050s, reaching a higher total land use. This has to do with the fact that in this scenario the carbon tax is very high, and gas generation is replaced with concentrated solar power, which in turn has a higher land use intensity and causes a higher total land use.

Scenario	Total Land Use [10^7 ha]	$\Delta_{(sc-ref)/ref}$[%]
RCP60_dry	1.83	0.63
RCP26_dry	1.82	0.09
REF	1.81	0.00
REF_FPV	1.79	-1.19
RCP60_wet	1.78	-1.64
RCP26_wet	1.78	-1.77
TAX_Low	1.44	-20.56
TAX_High	1.40	-22.92

Table 19: Total land use across the scenarios

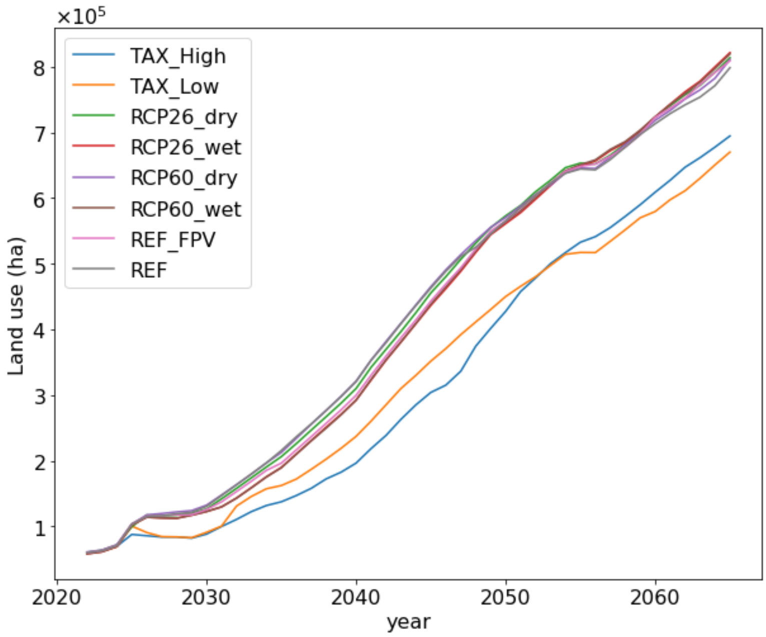


Figure 21: Land use evolution across scenarios

Analysing the role of each tax

In the process of decision making of these taxation policies, it is important to know how each tax (land or carbon) contributes to each goal (emissions and land use reduction). This is especially relevant given the fact that it is more realistic for a policy maker to decide to apply only one tax at a time, instead of the two of them simultaneously. In fact, it can be the case that one of the two footprints (emissions and land use) is reduced indirectly only by applying a penalty on the other one.

Therefore, to better clarify the role of each tax, other four simulations were developed, applying either the carbon or the land tax in both their high and low cases (Land_Low, Land_High, Carb_Low, Carb_High). The results of this analysis were compared with the scenarios where both taxes are applied, and are reported in Figure 22 and Figure 23. Besides, the total CO2 emissions and land use are reported in Tables 20 and 21.

From Table 20, it is very interesting to see how the land tax both in the high and low case contributes very marginally to the reduction of CO2 emissions (less than 1%), which are then to attribute fully to the carbon tax, as it can also be seen by the irrelevant difference in CO2 emissions reduction between the Carb_High and Tax_High cases.

As far as land use is concerned, the results show that the carbon tax is also more efficient than the land tax in reducing the total land use, both in the high and low cases, and it contributes to more than half of the reduction if both penalties are applied. This comes from the fact that the carbon tax is significantly higher than the land tax, and it indirectly significantly reduces the land use caused by the extraction of coal and natural gas.

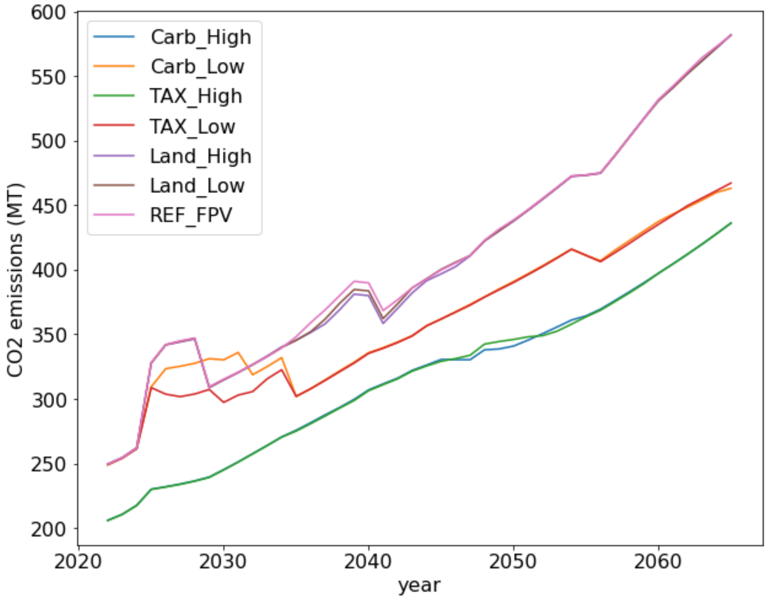


Figure 22: CO2 emissions evolution in the single and combined tax cases

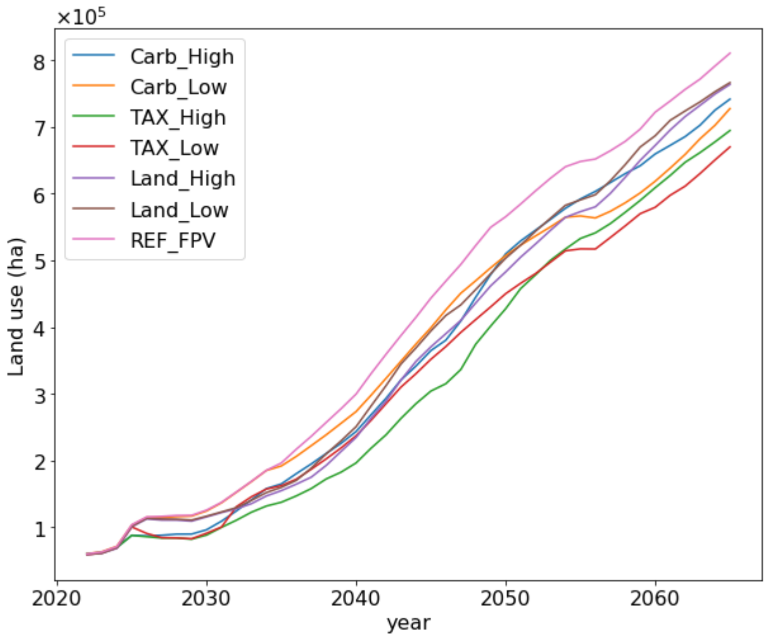


Figure 23: Land use evolution in the single and combined tax cases

Scenario	Total Land Use [10^7 ha]	$\Delta_{(sc-ref)/ref}$[%]
REF_FPV	1.79	0.00
Land_Low	1.63	-9.05
Carb_Low	1.61	-10.27
Land_High	1.58	-12.00
Carb_High	1.58	-12.02
TAX_Low	1.44	-19.63
TAX_High	1.40	-22.02

Table 21: Total land use in the single and combined tax cases

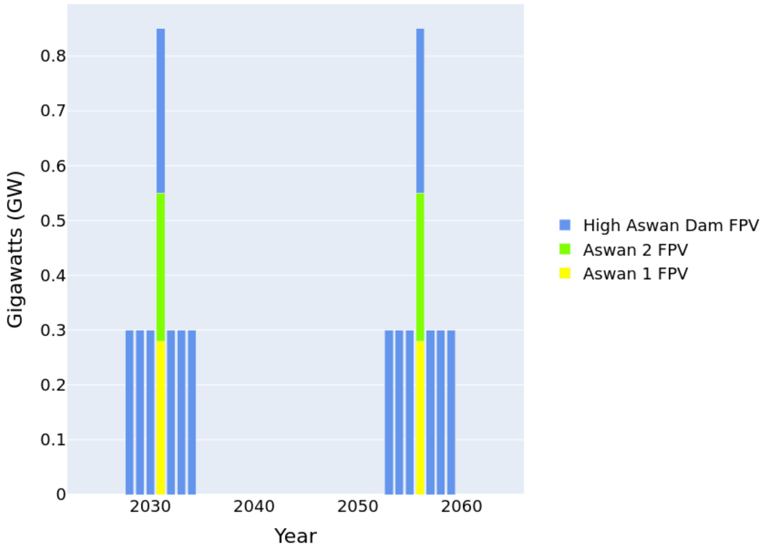
Scenario	Total Emissions [10^5 MtCO2]	$\Delta_{(sc-ref)/ref}$[%]
REF_FPV	0.180	0.0
Land_Low	0.179	-0.3
Land_High	0.179	-0.5
Carb_Low	0.160	-11.0
TAX_Low	0.158	-12.1
Carb_High	0.139	-22.6
TAX_High	0.139	-22.6

Table 20: Total CO2 emissions in the single and combined tax cases

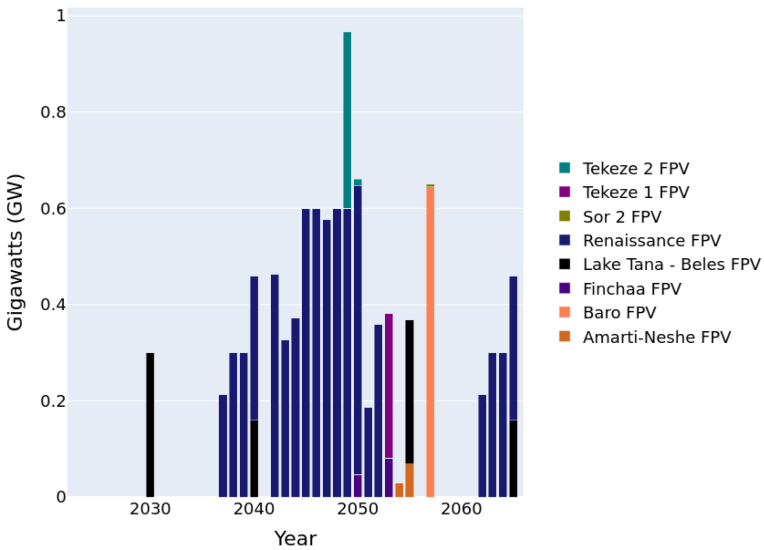
3.8 Best locations for floating solar power

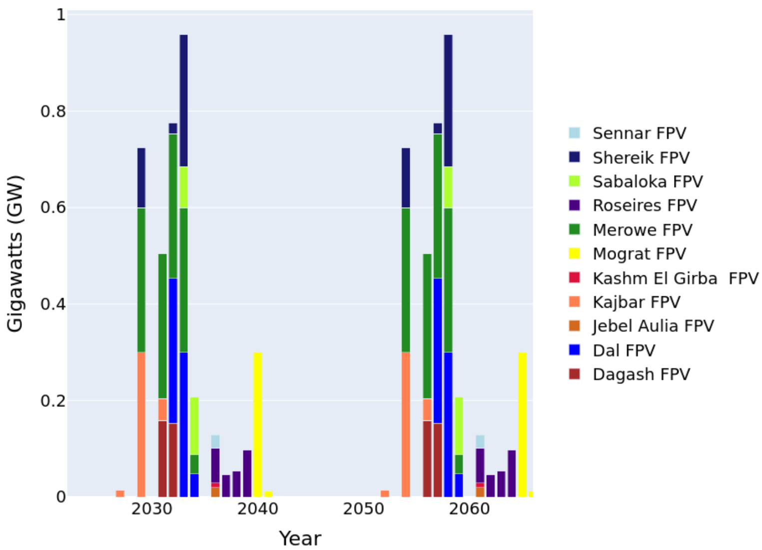
After showing that floating solar power is a competitive technology that can aid the energy development of Eastern Nile Basin countries, it is important to determine which reservoirs are the most promising for its installation and when, in order to invest economic resources in the most efficient way.
Since the FPVs technologies had been spatially disaggregated before being given as input to the model, it was possible to obtain the answer to this question from the model outputs without the need of any further modelling tool. The bar charts of the annually FPV installed capacity in each country can be seen in Figure 24. Here we notice that Egypt and Sudan show a symmetrically distribution of the installed capacity, repeating after 25 years. This has to do with the fact that the operational life of this technology was set to this amount of years, and plants are immediately re-built after they are decommissioned. This is not necessarily a very realistic behaviour, but OSeMOSYS does not explicitly allow to model mantainance or renovations of plants. However, this behaviour shows that the same expansion pathway is optimal in two different periods. From these bar charts, we can see that the locations developing the most capacity are the High Aswan Dam (Lake Nasser) for Egypt, the Renaissance Dam for Ethiopia and the Merowe Dam for Sudan. This has to do with the fact that these three locations are the largest hydropower plants in each country, and have therefore the highest potential for floating solar power. In fact, the model chooses the technologies to implement based on costs (which are the same for every FPV technology), capacity constraints and capacity factors. Between these last two parameters, the one that varies most is the capacity constraint, which then influences the choice of location the most. The effects of the different scenarios on the floating solar capacity expansion at these selected locations is reported in Appendix B.

(a) Egypt



(b) Ethiopia





(c) Sudan

Figure 24: Installed FPV capacity for each country

Another important variable to take into account regarding the choice of best locations for the implementation of floating solar power on a hydropower reservoir is the saved water from evaporation and the consequent increase in hydropower production.
The aggregated data regarding this analysis were presented in Section 3.6, and showed significant water reduction rates and very slight hydropower generation increases. Here, the contributions of each reservoir to the water savings are reported in figure 25.

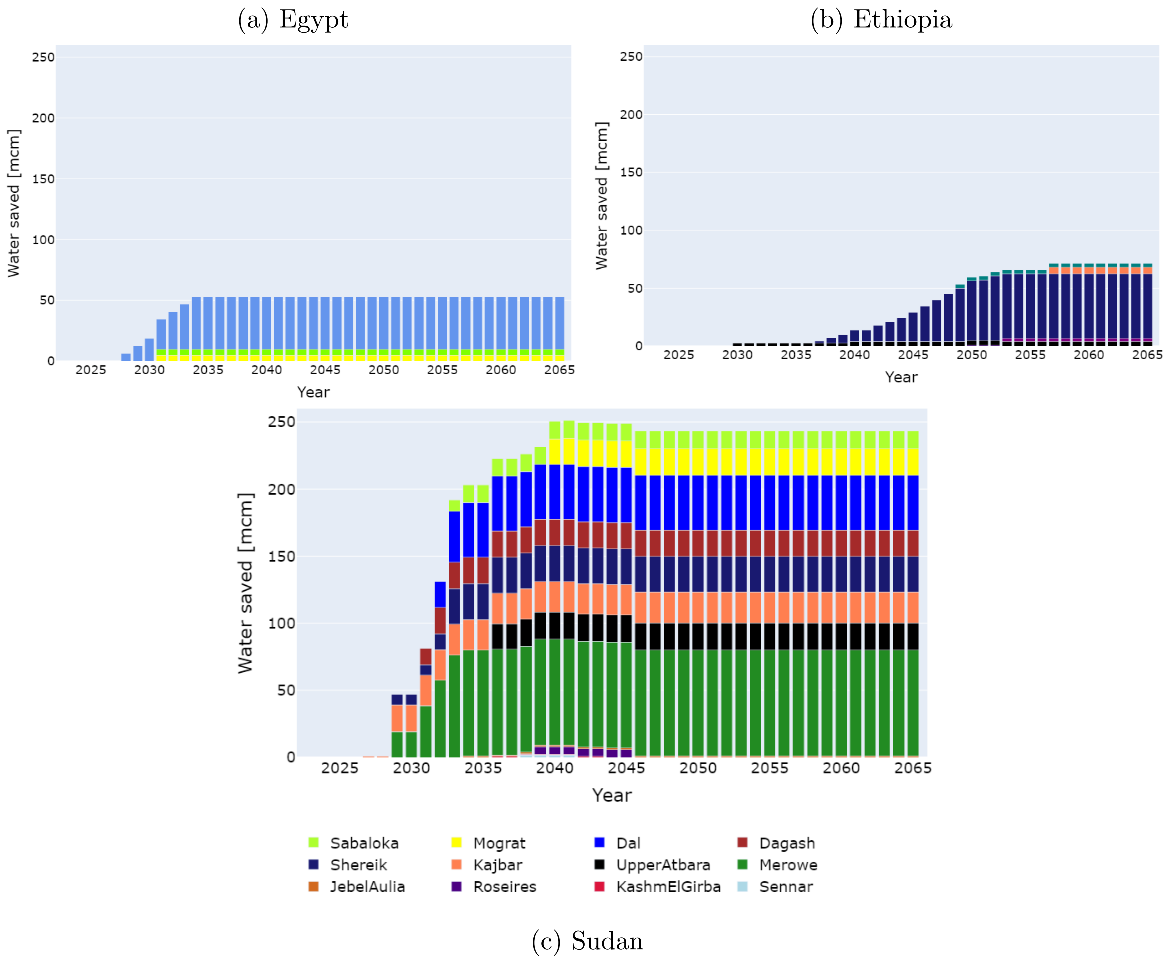


Figure 25: FPVs water savings from each reservoir

From this charts it is quite easily noticeable how the largest contributions to the total water savings of each country come from the largest three reservoirs: Lake Nasser, Renaissance and Merowe, showing values of 43 mcm/y, 55 mcm/y and 79 mcm/y respectively. The reason behind this is once again the magnitude of these reservoirs: even though the FPV coverage percentages are low (0.3% for Lake Nasser, 3.4% for the GERD and 2.6% for Merowe), if multiplied by the huge evaporation rates these reservoirs show (7130 mcm/y for Lake Nasser, 880 mcm/y for Renaissance and 1625 mcm/y for Merowe), the total water savings are the highest in the basin. In order to reach the maximnum capacity of FPVs and thus the maximum evaporation reduction rates, the capital investments in these three largest plants would be 1 B$ for High Aswan, 4.3 B$ for the GERD and 0.6 B$ for Merowe.
If we consider the percentage of water saved from the single reservoirs, however, the ranking changes quite drastically. In fact, Lake Nasser only reaches 0.6% reduction, Merowe 4.8% and Renaissance 6.33%. Smaller reservoirs, instead, can reach way higher evaporation reduction percentages: in Ethiopia Finchaa reaches 84%, in Egypt Aswan 1 and 2 reach over 50% and in Sudan Dagash reaches 7.3 %.
Analysing the extra hydropower production, instead, the three locations showing the highest values are all in Sudan: Merowe, Dal and Shereik, with 0.11, 0.08 and 0.06 PJ/y respectively. If we translate

this to percentage increase, however, other two reservoirs in Sudan show the highest increases: Upper Atbara and Mograt, with 1.3% and 1.1% yearly increases in hydropower production. The meaning and relevance of these values is further discussed in Section 4.4.

3.9 Sensitivity analyses

In this section the results relative to the two sensitivity analyses are reported. In fact, it is important to assess the sensitivity of the model to key parameters such as costs and capacity constraints of relevant technologies in this study: solar and floating solar technologies.

Costs of solar

As far as the first sensitivity analyses that is concerned (relative to the costs of solar technologies), two cases were built: starting from the REF_FPV scenario assumptions, one case was built with higher capital costs for every solar technology and the other one with lower capital costs.
The plots of the difference between the generation mix of these two cases and REF_FPV are reported in Figure 26. As it can be see from the figure, the mix changes significantly (up to 10%) in the lower costs case, where solar generation replaces generation from gas, wind, hydropower and geothermal. In particular, concentrated solar power becomes competitive from the late 2050 and reaches around 5% of generation. In the higher costs case, instead, the differences are slightly smaller but still significant, with solar technologies being replaced mainly by wind, hydropower, and gas.

(a) Lower costs of solar (-20% CAPEX) (b) Higher costs of solar (+20% CAPEX)

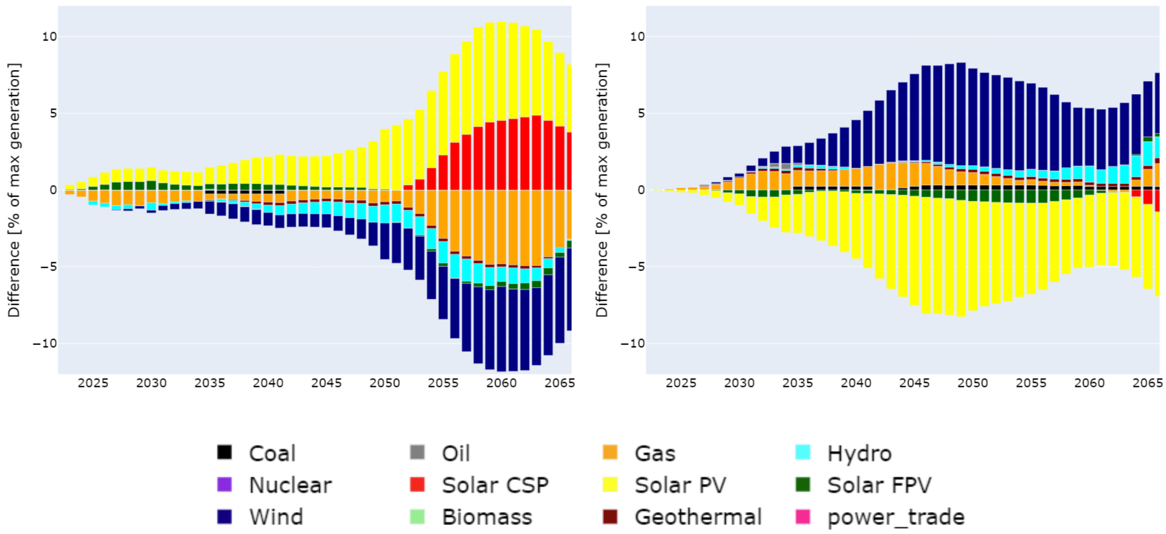


Figure 26: Difference between generation mix in the modified solar costs simulations and reference FPV scenario for the Whole region

In order to better understand how floating solar power is affected under these two assumptions, their capacity expansion was plotted and reported in Figure 27. In this chart, it can be seen how the case with higher solar costs causes a delay in FPVs expansion, even though the total maximum potential is still reached at the end of the simulation. In the lower cost of solar case, instead, the behaviour is more interesting. In fact, the expansion of floating solar power happens earlier than in the reference scenario, and reaches the highest potential around 2050. Afterwards, however, their capacity starts decreasing. The reason behind this is that with lower costs of solar another type of solar technologies become more cost optimal than floating solar: roof top solar power. In fact, this technology has generally higher capital costs than FPVs, but it does not have the costs of transmission and distribution, making it more cost optimal in this case.

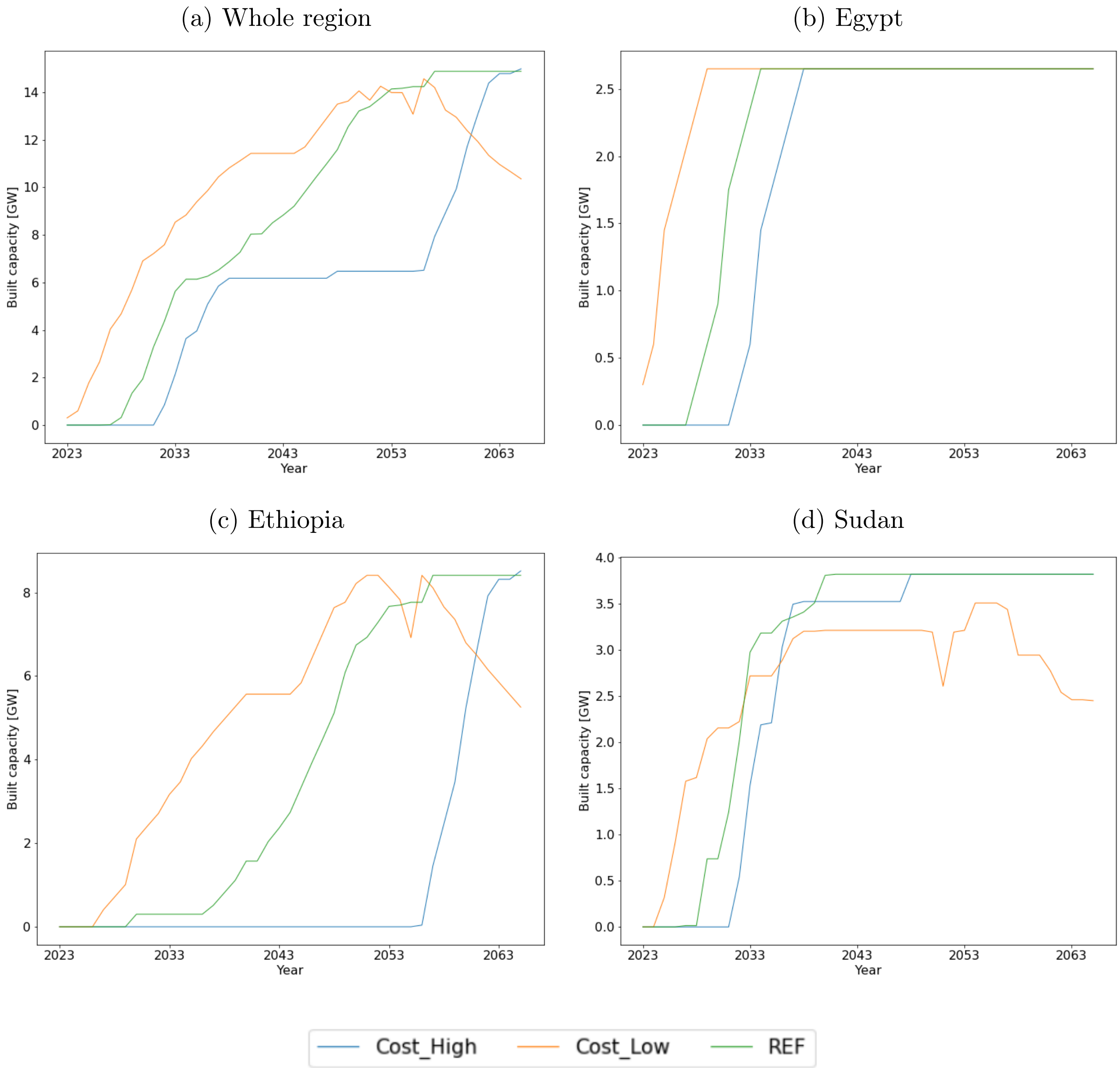


Figure 27: FPV capacity potentials across scenarios with changed solar technologies capital costs

Finally, the FPV maximum generation share reaches 2.3% in the case of higher costs of solar and 3.9 % in the case of lower costs of solar. These shares are different from the reference scenario (3 %), but not too drastically.

Capacity constraints

The second sensitivity analyses that was conducted regarded the constraints on floating solar panel technologies. The plots showing the difference between the reference scenario ran with a looser constraint and the reference scenario are visible in Figure 28. From the plots we see that there is a substantial increase in floating solar power generation in all the regions. In Egypt, this extra generation replaces gas, while in Ethiopia and Sudan wind and solar.

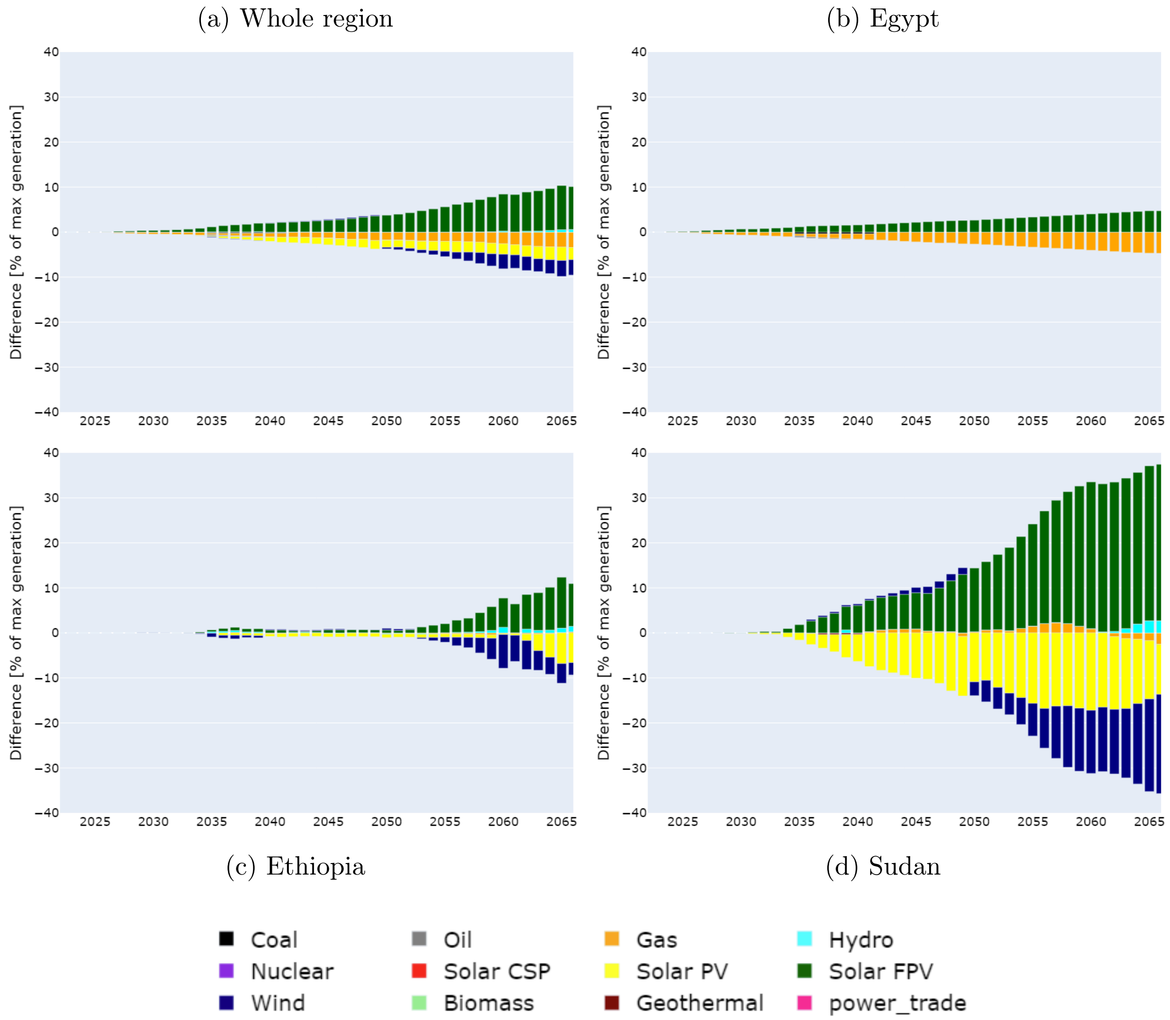


Figure 28: Difference between generation mix with the looser FPV constraint and reference FPV scenario

Moreover, the capacity expansion in each scenario was also assessed, and the related graphs are shown in Figure 29.
From these plots, we can see that the full potential is developed in Egypt in and Sudan in all scenarios at the very end of the simulation. In Ethiopia, instead, the exploited potential reaches only around 30-35% of the maximum. If all the three countries are considered, the total capacity reaches around 65% of its maximum at the end of the simulation. The reason for this difference between regions can be found in the potential of other renewable resources: Ethiopia, in fact, has a higher potential for solar energy compared to Egypt, and wind energy has higher capacity factors in Ethiopia compared to Sudan. Therefore, with a higher competition from other renewable energy sources, the expansion of FPVs is still important but limited to their cost optimality.
Finally, the maximum generation share of floating solar power in the case with the looser constraint reaches 14% for the whole region, showing a significant increase from the reference scenario where it reached 3 % only.

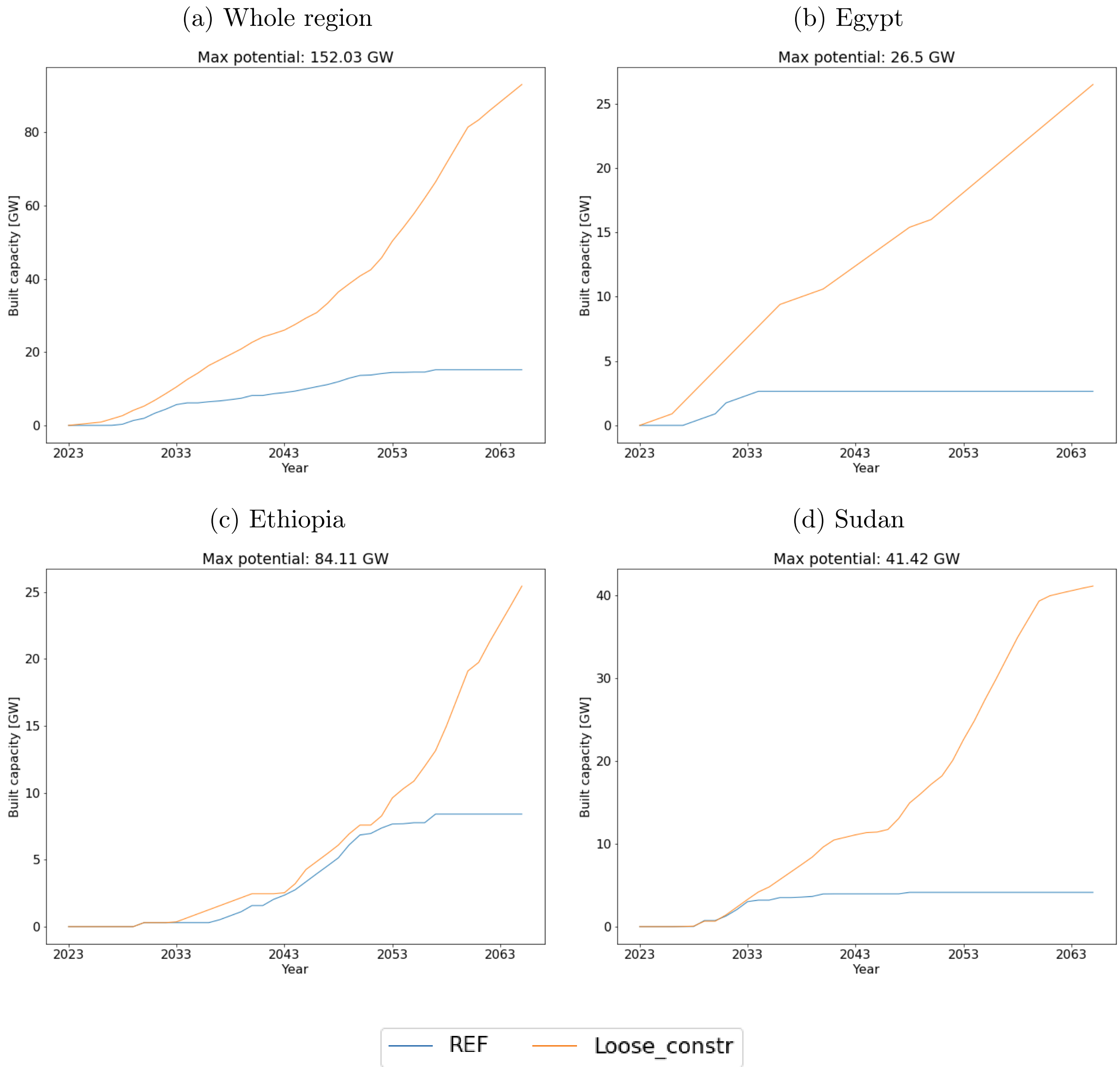


Figure 29: FPV capacity potentials across scenarios with a looser FPV constraint

4 Discussion

In the following chapter, the results of Section 3 are discussed. First of all, some remarks on the reference scenario are given, followed by an interpretation of the results from the other scenarios. Then, the role of floating solar power is discussed, aiming to answer the main research questions. Finally, the methodology limitations are explained, together with suggestions for future work.

4.1 General remarks on the model

In order to understand if the general results from the model were acceptable, the energy generation mix of the reference scenario without floating solar power was compared to the most recent (2020) data from IEA (2020). The modelled and actual data generation mixes for the whole region can be seen in Figure 30. From these charts, we can see that the model overestimates the hydropower production by 4%, and underestimates the oil generation by 4%. Moreover, the mode presents shares of 1% geothermal and biomass generation that replace the actual 2% of solar generation. These variations may depend on different factors: capacity constraints, capacity factors and wrong parameterization of existing technologies. However, the main composition of the mix (gas and hydropower domination) is well represented, and the differences only reach maximum 4%.

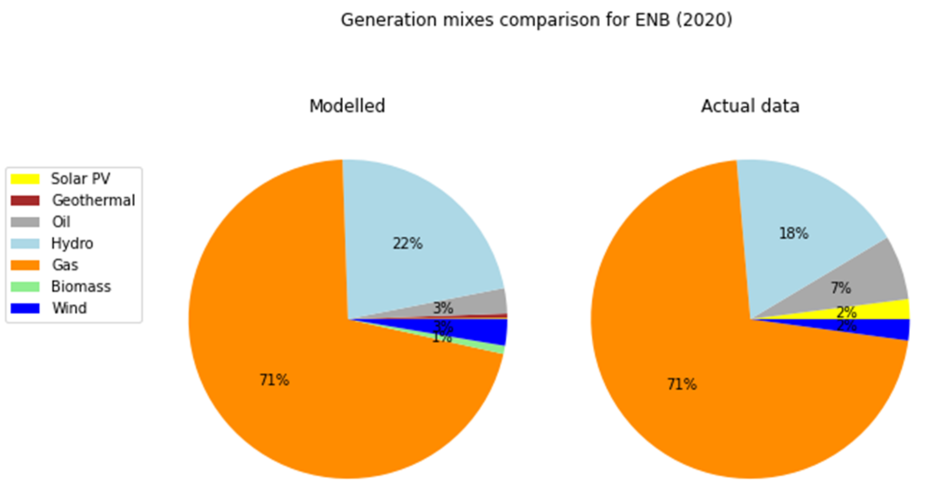


Figure 30: Comparison between modelled and actual generation mix in 2020

Afterwards, the results were compared with projections from similar studies. The first study used for comparison was the original TEMBA 2.1 model (Pappis et al., 2022). The electricity generation projection obtained from this study for the Eastern African Power Pool in the reference scenario can be seen in Figure 31.

We can see that this projection is very similar to what obtained with the modified model of this study (Figure 12). However, since the model was adapted as described in the methods section, some differences exist. First of all, the power trade share of the mix is not visible in Figure 31, while it is quite important in Figure 12. This has mainly to do with the fact that Kenya is included in the Eastern African Power Pool in the study from Pappis et al. (2022), while it is an external country in this study. Another difference is relative to geothermal power, which plays a very marginal role in the mix of Figure 12, while it constitutes a relevant part of the mix in Figure 31. The reason behind this are probably the addition of nuclear in the mix and the reduced cost of wind power that have been applied in this study: these two technology substitute the geothermal share of the mix in Figure 31. Finally, it has to be noticed that the Eastern African Power Pool in Figure 31 includes more countries than what analysed in this study, namely Djbouti, Kenya, Rwanda, Tanzania,Uganda and Burundi. However, even including these countries, the role of Egypt in the power pool mix is still prevalent,

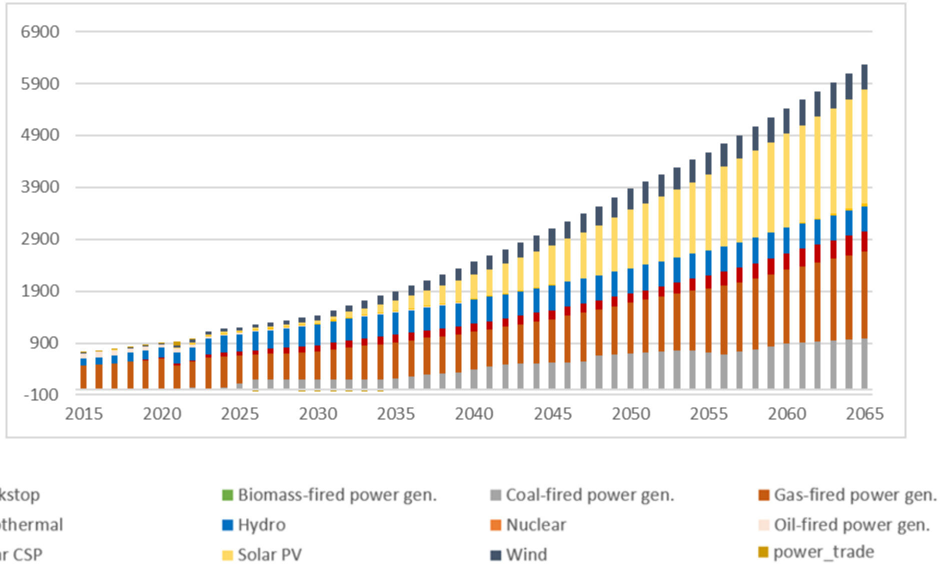


Figure 31: Electricity generation projections from Pappis et al. (2022) for the EAPP

hence making the comparison between the studies reasonable.
The second comparison was conducted with IRENA (2021). Even though this study does not provide generation projection charts of the single countries nor power pools, some other variables were used to compare the results. For example, IRENA (2021) reports the projected installed capacity of solar and wind in 2040 for Ethiopia and Egypt. These can be seen in Table 22 together with the corresponding values found from this study.

Country	Solar	Solar IRENA	Wind	Wind IRENA
Egypt	19.83	49.1	8.04	41.5
Ethiopia	15.5	18.1	1.04	2.1

Table 22: Projected capacity values [GW] in 2040 for solar and wind

From the table, we can see a very large difference in the values for Egypt, while the values for Ethiopia are more similar between the studies. Since the costs assumptions for solar and wind are the same between the two studies (as described in Section 2), the reason behind this difference is to be found in the annual installable capacity constraints in this model. In fact, the original data used for this study limits the annual installable capacity of solar and wind to a few GWs, while this is not the case in the study from IRENA (2021). This is also one of the main reasons why Egypt, differently from the other countries, develops high shares of fossil fuels generation. In fact, renewables alone can't satisfy the huge electricity demand of this country with these annual maximum capacity constraints, while they can satisfy the smaller demands of the other three countries. Given this, a more extensive study on how to choose the annual installable capacity constraint for renewable technologies would be useful in making the model results more realistic.

4.2 Effects of scenarios on the energy system's evolution

In this section, the results from the different scenarios are discussed, focusing on how much their assumption affect the model results in each country in terms of general energy system's evolution. A more in-depth discussion about the role of floating solar power specifically is conducted in section 4.3

Climate change scenarios

As far as the climate change scenarios are concerned, they affect the model modifying the capacity factors of hydropower plants. As it was presented in the results (Figure 16), changing these parameters

leads to changes in the yearly generation mix of the whole area to around 1-3% of the maximum annual generation of the reference scenario. In terms of single countries, Egypt is basically not affected under all the projections, while the other three countries are affected with different magnitudes depending on the projection. Ethiopia, for example, is quite affected for RCP2.6 dry, RCP2.6 wet and RCP6.0 wet, with differences up to around 12%, while it is less affected for RPC6.0 dry, with differences up to 7%. Sudan, instead is more affected by dry scenarios (in particular RCP6.0 dry) than wet scenarios, showing differences up to around 10% and 4% respectively. Something similar happens in South Sudan, but here the effect of RCP6.0 dry scenario is significantly higher than all the other scenarios and all other countries, with more than double the difference values (up to more than 20%). This happens because the energy mix of South Sudan relies highly on hydropower generation (up to 90% in 2040), and given the small size of the country small changes in capacity factors influence the mix a lot.
Summarizing these findings, it can be said that the energy system of the whole region is not particularly sensitive to climate change induced alterations of the flow regimes. However, the single countries are affected more relevantly and in different ways.

Taxation scenarios
The externality scenarios, instead, affect the model in terms of costs, since they add economic penalties to certain technologies. This leads to higher effects on the results compared to the climate change scenarios, with differences for the mix of the whole area reaching up to around 15% of the maximum yearly generation. Also in this case, these differences are distributed differently in the single countries. Egypt is highly affected in both scenarios due to its high share of coal generation, and shows differences up to almost 20%. Ethiopia, is less affected in the slow scenario compared to the high, with differences up to 10 and 15% respectively. Sudan, instead, shows similar differences in both the slow and the aggressive scenarios, reaching maximum 13% in both cases. Finally, South Sudan is the least affected in the slow scenario, but shows differences up to 9% in the aggressive scenario.
It is also interesting to analyse the different shapes of the graphs in the different countries in the taxation scenarios. In Egypt, for example, the difference chart is showing increasing differences, because in the reference scenario the generation share of coal keeps increasing over the modelling period. In Ethiopia, instead, the differences reach a peak in 2055 and then decrease: this has probably to do with the potential of wind energy reaching its maximum and then decreasing its possibility to replace solar power. Something similar happens in Sudan, but here the wind potential is fully exploited and this causes the trend to revert and solar to substitute wind again in the last part of the modelling period. South Sudan, finally, shows a peculiar shape in the aggressive scenario, once again due to a different pattern in the hydropower development: the two major hydropower plants come online in different years than in the reference scenario, causing the differences from 2023 to 2040. After that, the substitution pattern follows the constant increase in generation from solar power.
Finally, in terms of the effects that each tax has on the total energy system's carbon emissions and land use, the results showed that the carbon tax is the most effective for the reduction of both footprints. As mentioned in the results section, this happens because coal generation is the most carbon intensive and the third most land intensive technology, and the carbon tax on coal is the highest one. Therefore, penalising coal generation is the most effective way of reducing both land use and carbon emissions.
Summarizing all the points of this section, it can be said the energy system of the entire region is not particularly sensitive to the used climate change projections, even though in the single country this affects the mix more intensively. On the other hand, the introduction of penalties does affect the mix in a relevant way both at global and local scales.
Finally, as far as the single countries are concerned, Egypt is most affected from penalties on carbon emissions, Ethiopia and Sudan are mostly affected from penalties on land use, and South Sudan is mostly affected by the RCP6.0 climate change projection with dry flow conditions.

4.3 The role of floating solar power

After the general comments of the previous section, the key points of discussion that are needed to answer the research questions are discussed. In the following paragraphs, the role of floating solar power emerging from the results chapter is critically analysed.

RQ1: What is the role of floating solar power on the energy expansion of ENB countries?

Effects on the energy mix

First of all, the introduction of floating solar power in the fleet of possible technologies produce some relevant changes in the generation mix already since the late 2020s, with differences from the reference up to 2% for the whole area and a peak of 8% in Ethiopia and Sudan (Figure 15). It is also interesting to see how in Ethiopia the introduction of FPVs causes an increase in hydropower generation: the combination between floating solar power and hydropower results more cost optimal than the combination between solar and wind. This has probably to do with the fact that in this country the capacity factors of floating solar power and hydropower have a certain complementarity between timeslices and the combined energy generation of these two technologies is more cost efficient than the combination of wind and solar power. This positive complementarity between hydro and solar energy generation was mentioned in the introduction as a positive effect of hybridizing solar and hydropower plants, and has been found by other studies as well Lee et al. (2020), Cazzaniga et al. (2019).

It is also important to state that even though the generation from hydropower increases after the addition of floating solar power to the mix, the hydropower capacity expansion is not affected. In the other countries, instead, it is harder to see any similar indirect effect of floating solar on the mix, with this new technology mainly replacing gas in Egypt and solar and wind in Sudan. The reason behind these substitutions are that floating solar power is cheaper than wind, and has very slightly higher capacity factors than solar (especially in some locations). Moreover, they become cheaper than gas from the 2030s, hence the substitution in Egypt. This is also the reason why the total system costs are slightly lower for the scenarios with floating solar power (Table 17): the introduction of these technologies allows a slightly more cost-optimal solution.

Next to the changes in the generation mix, it is important for an energy system's planner to understand the changes in the capacity mix, since these are needed to delineate investment plans for each technology. The plot with the capacity differences for the whole region due to the introduction of FPVs can be seen in Figure 32.

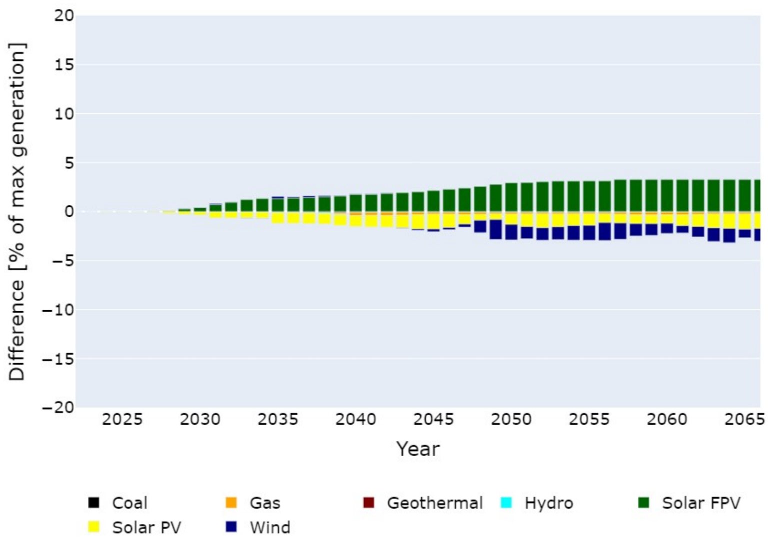


Figure 32: Capacity differences between REF_FPV and REF scenarios for the whole region

Here, it can be seen that the installation of FPVs replace almost entirely solar and wind capacity, apart from some very small gas capacity. As mentioned before, the increase in hydropower generation does not correspond to an increase in hydropower capacity.

Role in satisfying the energy demand

Apart from the changes that the introduction of FPVs causes in the generation mix, it is also crucial to assess how much of the energy demand this technology can satisfy. This can be quantified by the maximum generation share. In the reference scenario, FPVs show different values depending on the analysed region: they arrive to produce 2.89% of electricity in the whole region, 1.74% in Egypt, 6.74% in Ethiopia and 14.56% in Sudan. However, these percentages depend on several factors, such as the total energy demand, the total FPV potential and the competition from other cheap energy sources.

In fact, Egypt has the largest electricity demand by far, together with the smaller FPV potential. Therefore, it is logic that floating solar power supplies a very small part of its energy mix. However, the results show that the full potential is developed relatively fast (around 10 years) in every scenario, and it is reached even if increased by a factor 10, as shown in the sensitivity analysis results. This proves that this technology is very competitive in Egypt, but its limited potential doesn't allow it to reach important shares of the generation mix. Ethiopia, instead, has a smaller electricity demand and a higher FPV potential. Therefore, the share of FPV generation is more relevant, and the full potential is reached almost at the end of the modelling horizon. Besides, in the case with a looser constraint, the full potential is very high and it is not reached. This has also partially to do with the fact that Ethiopia is the country with the highest potential for other renewables, especially showing higher capacity factors for wind than the other countries. Finally, Sudan has an electricity demand similar to Ethiopia combined with a smaller FPV potential. However, since the competition from wind power is lower in this country, the generation shares of FPV reach a higher value (up to 15%), and the full potential is developed in all the scenarios as well as in the looser constraint simulation.

To summarise this paragraph, it can be stated that the role of floating solar power in the generation mix reaches very different values in each country, mostly depending on the total available FPV potential and on the potential of other energy sources. Besides, it is very important to highlight that the full potential of the region is exploited under every scenario, showing the overall cost optimality of this technology.

RQ1a: How does this role change under different scenarios?

The second point of focus of this work (RQ1a) was to analyse how the importance of floating solar power changes under different scenarios.

Climate change scenarios

First of all, in the climate change scenarios, FPVs technologies are only marginally affected in terms of maximum generation shares. That is to say, their weight on the mix does not change relevantly in any of the analysed climate change projections. However, if the capacity expansion is considered, the results showed that in wet scenarios the deployment of FPVs is sensibly delayed in Ethiopia. The opposite does not happen in the dry scenarios, with the capacity expansion being similar to the one in the reference scenario. Moreover, this delay is basically identical for the two climate change projections. However, considering the whole region, this delay is not particularly relevant, and if we keep in mind that this scenarios assume the very high estimate of flows (95th percentile), we might consider this not particularly relevant for planning decisions. Besides, even if such a scenario would actually take place, ignoring the delay and investing earlier in floating solar power would only be economically sub optimal but not cause any troubles in the energy system. Putting together all of these insights, it can be stated that (keeping in mind all the hypothesis of the study) the role of floating solar power on the energy mix and the relative planning decisions may not change under different climate change scenarios.

Taxation scenarios

The effect of taxation scenarios on floating solar power is more relevant than what seen for climate change scenarios. In fact, we see in each country an increase in maximum generation shares from floating solar panel technologies, with the high taxes scenario showing the highest values (+1.3% in the whole region, +2% in Ethiopia and +3% in Sudan).

Besides, in all the countries the application of either the low or high taxes causes an anticipation of floating solar power development. This shows that if carbon emissions and land use penalties are

introduced in the cost optimization, floating solar power becomes even more competitive and it is cost optimal to develop a larger capacity at an earlier stage.
This result already shows how floating solar power can play a role in reducing the overall energy system's footprint, but a more detailed analysis is conducted in the next paragraph.

RQ1b: How does the implementation of FPVs affect the energy system's footprints?
In this paragraph the effects of the introduction of floating solar power on the energy system's environmental footprints are discussed.
As shown in the results in Figure 15, floating solar power mainly substitutes combinations of other emission free technologies (wind and solar). However, they also replace a small fraction of gas generation (mainly in Egypt), therefore they help reducing very slightly the total system emissions (Table 18).
Secondly, in terms of land use reduction, the effect is slightly more relevant, with a reduction of 1.2% of the total land use thanks to FPVs. This mainly comes from the substitution of ground mounted solar PVs, which is the technology with the highest land use intensity. Even though this number may not look very relevant on the scale of the whole region, saving land in some specific area might be very valuable independently of the absolute size of the areas. For example, the areas in proximity of reservoirs can have a high agricultural potential being relatively easily irrigable. In such cases, it would make more sense to exploit the water surface instead of the land for energy generation purposes. Therefore, the importance of this 1.2% of saved land highly depends on where this land lies. This could not be assessed in the present study due to the large scale nature of the modelling framework, but remains an interesting open question for future research.
Finally, in terms of evaporation reduction thanks to floating solar panels, the results obtained with the proposed procedure show interesting values, with maximum annual rates for the whole area up to almost 2% and peaks of 2.61% in Sudan and Ethiopia. These values lead to maximum total water savings of 376 mcm/y, of which 251 mcm/y in Sudan, which can be a very valuable results for non-energy related uses. In fact, the results showed that the saved amount of water is not enough to produce any particularly relevant increase in hydropower generation, but it could be very valuable for other purposes (irrigation, drinking water supply, environmental flows). Similarly to what explained for land, the value of these saved amounts of water really depends on the local surroundings of each reservoirs, and on the seasonal variation of water availabilities. Both of these aspects would be interesting to assess in future works. However, what can be stated at the large scale that this study considers is that every saved amount of water is relevant in the very arid climate of the study area. This becomes even more relevant considering the water crisis in Egypt, which is leading the country towards investment in desalination programs (Ministy of Planning and Economic Developement, 2023).
Summarising the above findings, it can be concluded that floating solar power helps reducing the energy system footprints in terms of carbon emissions, land use and water savings. However, the magnitude of these reductions are very slight in the case of carbon emissions and more relevant in the case of land use and water savings. Finally, the actual value of these impacts depends on the dynamics that take place at smaller spatial and temporal scales, and such analyses certainly deserve further research.

4.4 RQ2: What are the best locations for floating solar power in the region?

In this paragraph, the choice of the best locations for floating solar power in the studied region is discussed.
In Section 3.8 it was shown how the largest three hydropower plants in the system were found to be the ones developing the largest floating solar capacity and also yielding the highest evaporation reduction volumes. Therefore, in the scope of a large scale and long term frame, it is suggested to prioritize the investment for floating solar power in these reservoirs. Supporting this choice is also the fact that large hydropower plants are huge infrastructures that already have the labour and managing power to allow for further expansion without the necessity of setting up such an operation from scratch.
However, if considered on a smaller scale, developing FPV plants in other locations could be very beneficial for local developments. For example, smaller reservoir show higher evaporation reduction

rates in percentage (e.g. Finchaa in Ethiopia with 84 % yearly). Even though these reductions are in volumetric terms very small compared to those from the large reservoirs, such high percentage values may be very valuable on the local scale. In fact, such infrastructures are often multi-purpose reservoirs, and high evaporation reduction rates could have a significant impact on other sectors (e.g. agriculture). This could be even more relevant if the seasonality within the year were to be considered: evaporation reductions might be even more valuable in dry months.
Something similar can be said for the increase in hydropower production due to the water savings: even though at large spatial and temporal scales this increase is not relevant, it might be at local and monthly scales. For example, Upper Atbara and Mograt reservoirs show an increase in hydropower production of more than 1% yearly, which could be relevant for the local communities.
In terms of capital investments, the large plants show relatively high prices to reach maximum capacity (in the order of billion dollars). For example, the cost obtained for the installation of 6.4 GW of floating solar on the Renaissance reservoir is around 4.3 B$, which is similar to the cost of the hydropower plant itself. However, the adopted procedure does not consider economy of scales, since the capital cost for all FPV plants was assumed to be the same. Therefore, these capital expenditures probably overestimate the realistic prices. For the GERD, Getie and Jember (2022) found a total capital cost of 425 k$ for 1 MW installation, which is lower but in the same order of magnitude than the cost found in this study for the same capacity (4.3 B$ / 6400 MW = 672 k$). This shows once again how important the cost assumptions behind these analyses are, and suggests that more single-plant detailed techno economic analyses are needed to estimate the investments in a more reliable way.
For all these reasons, starting from the results of this study in terms of optimal capacity for floating solar power at large scales, future work is needed to investigate the effects on the smaller spatial and temporal scales, as well as to improve the cost estimations of such plants.

4.5 Sensitivity analyses

The results from the sensitivity analyses also show some important insights worth discussing. In this section, the sensitivity of the results to costs and capacity constraints are discussed in terms of total energy system evolution and floating solar power role.

Capital costs of solar technologies
First of all, it can be seen from Figure 26 that lowering the cost of solar technologies influences the mix more than increasing it. This means that in the case with lower costs solar technologies are clearly more competitive; and in the other case, even with an increased price their role is reduced but still quite important. Moreover, the differences reach up to 12% of the maximum yearly generation, which is a relevant amount. As far as of floating solar power is concerned, the maximum reached capacity is the same as in the reference scenario both in the high and low costs cases, and also the maximum generation share changes by less than 1%. However, the FPV expansion pathways (Figure 27) change significantly, with the high cost case showing a delay in capacity expansion and the low cost case showing an even more different behaviour, reaching the peak earlier and then decreasing. Therefore, it is clear that the assumptions behind costs of solar technologies affect the results in an important way, and need to be studied carefully.

Capacity constraints
The results of the other sensitivity analysis also show high variations (Figure 28). Here, in fact, altering the maximum capacity constraint of floating solar power causes differences in the mix of the whole modelled area up to almost 10%. Also in this case the effects on the four countries are diverse: Egypt has differences of less than 8%, Ethiopia reaches 10% and Sudan shows the highest differences with values of up to 40%. In terms of floating solar power, the capacity expansion increases significantly when the constraint is relaxed, reaching up to 100 GW in the whole region (almost a 7 fold increase from the 15 GW developed in the reference scenario). The maximum generation share of floating solar power also increases very significantly, reaching 14% (compared to the 3%of the reference scenario).

Given these results, we can state that the model is quite sensitive to capacity constraint variations. In fact, these constraints deeply affect the results since they force certain technologies to be adopted or not despite their cost optimality. Besides, only the constraints relative to FPVs were tested in this sensitivity analysis. The mix is supposed to change even more drastically by altering constraints of other technologies as well.
Another important thing to mention is that in this analysis only the total annual maximum capacity (i.e. the total capacity that can exist in each year) was altered. However, another very important parameter limiting the expansion of a certain technology is the maximum annual installable capacity (i.e. the new capacity that can be installed in each year). This parameter is even harder to model, since it can depend on many different factors, like the learning curve of a technology, the available labour, the supply of construction materials and so on. In this study, this parameter was modelled for FPVs on the base of the one for ground mounted solar already present in TEMBA in order to guarantee the coherence with original data, but it may not be realistic. More data-based and in depth research is needed to make sure these parameters reflect the actual possibilities of each technology.

4.6 Methodology limitations

In this section, the methodology limitations and the main shortcomings of this study are presented. Firstly, the main shortcomings of the used modelling tool are presented, followed by the critical points of the used parameters. Then, the main limitations behind the scenarios are presented and finally some remarks on the water consumption calculations are given.

Model limitations

The main modelling tool used for this study (OSeMOSYS) is a linear cost-optimization model, that assumes central decision making (full cooperation between countries) and perfect foresight. This means that the energy expansion is optimised for the whole modelling area as if the decisions were taken by a centralised authority for all the four countries. However, for the countries under study, we know this to be quite unrealistic given the ongoing tensions between Egypt and Ethiopia and the current civil war in Sudan.
Secondly, the model assumes to know at each timestep the current, past and future energy demand that needs to be satisfied in each timeslice, together with the cost and capacity factor of each technology. This is also unrealistic, since such parameters depend on many external factors like social, demographic and political dynamics, economic incentives and investments and climate alterations which are all very hard to predict. Moreover, the energy demand projections themselves are subject to high uncertainty, especially with such long term horizons like the one adopted in this study. Given this, the results from this work still shed some light on the role of FPVs in such energy pathways, but they shall not be translated directly into policy decisions before integrated assessments with non-energy related dynamics are conducted.

Parameters shortcomings

As presented in the previous paragraphs, the model is quite sensible to certain sets of parameters, that need to be implemented carefully. In this work, this was attempted by adapting some of them, but there is still plenty of room for improvements.
First of all, the current energy system characteristics need to be modified with more up-to-date data that includes the most recent power plants and infrastructure developments in each country. Moreover, the planned and commissioned infrastructures need to be checked thoroughly, since major plants may really affect the results changing the electrification pathways substantially.
Secondly, the costs of each technology need to be checked thoroughly and studied in depth, since they are one of the parameters affecting the results the most. In this study, the data was taken from a previous research (Pappis et al., 2022), but here the author also built on previous studies, making the original data already a few years old. Therefore, the prices subject to the biggest changes (wind and solar technologies) were adapted based on more recent data (IRENA, 2021), but the costs of the other technologies were not analysed as thoroughly. Besides, since hydropower plants and floating solar

panel plants were spatially disaggregated it is possible to assign them location specific costs. This was partially done with hydropower, basing the cost on the capacity of the single plant, but it was not done with floating solar power, which plants were all implemented with the same costs and thus not taking into account economy of scales nor location specific circumstances.
Apart from the costs, capacity constraints are also a very important parameter, as it was shown in the results. In this study, the capacity constraints of most technologies were not modified from the original data. These may not be completely realistic and need to be studied more in depth. The FPVs capacity constraints, in particular, were implemented quite superficially, taking as proxy for the total maximum capacity the capacity of the corresponding hydropower plant and limiting the yearly installable capacity to a certain amount of what is considered to be realistically feasible based on the current FPV existing plants and the solar power learning curve. However, a more detailed study needs to be conducted on how to limit the floating solar power capacity at each plant. For example, the available water surface of a reservoir could be used as upper boundary for the total maximum capacity. Moreover, for huge bodies as lake Nasser and lake Tana, such a boundary would be unrealistic and would need to be restricted to the area closest to the dam. Besides, as far as the maximum yearly installable capacity is concerned, more in depth study is needed to assess what is considered to be realistically feasible in each country, not only for floating solar power but for other generation technologies as well.

Scenarios limitations

As far as the scenario development is concerned, both the climate change and the taxation scenarios present some shortcomings. First of all, the hydrological scenarios assume the same flow uncertainty range (dry or wet) throughout the whole modelling horizon, failing to represent any kind of inter annual variability of flows. In fact, the model is missing a proper hydrological modelling module, and relies on the output from another study Sterl et al. (2021). Therefore, in each scenario the capacity factors of hydropower plants vary within the year, but remain constant over the modelling horizon. This is definitely not realistic, especially under climate change assumptions, but it still gives an idea of how the electricity system reacts to certain hydrological conditions. Besides, constant capacity factors of hydropower plants also do not take into account possible reductions due to sedimentation issues, a known problem in the Nile basin (Salih and Ali (2014), Easton et al. (2010)).
The taxation scenarios, instead, suffer mostly from uncertainties due to price estimations and projections. Carbon prices, for example, are really debatable and depend mostly on political decisions of single countries and areas. The methodology used to estimate land use pricing is also quite uncertain. First of all the agricultural yield value is used as a proxy for land value, even though power plants do not necessarily lie on agricultural land, but actually are often close to urban areas, which generally have way higher land values than rural areas. Moreover, the crop values are valued at 2010 international prices and do not change over the modelling horizon apart from being discounted with the global discount ratio.

Water consumption limitations

The water consumption analysis is also presenting some uncertainty. First of all, the procedure used to calculate the evaporation reductions due to floating solar panels uses evaporation reduction rates that were derived from a Penman Equation model (Scavo et al., 2021). This model was theoretically modified assuming changes to the radiation balance that are logic but not empirically proven. Moreover, it is based on the Penman equation, which relies on the assumption that the water surface has a similar temperature as the above lying air. This is however not always the case, especially for large water bodies in arid climates. The estimations of total evaporation rates from the single reservoirs are also based on the Penman equation (Sanchez et al., 2020). Moreover, they were not spatially disaggregated based on the climate at each single reservoir, but they were calculated based on the total country evaporation rates and re-assigned to each reservoir depending on its area. Finally, the estimations of the reservoir areas themselves were based on very simple linear regression models between the reservoir area and its volume or even its hydropower capacity, and may be very different from the actual values. For the above reasons, the results from this procedure can just give an idea of the magnitudes of these dynamics, but the uncertainty that they are subject to must be kept into account.

4.7 Future work

In this last paragraph, possible future research works are suggested, based on what presented in the previous paragraphs.

Model improvements
First of all, the modelling of the energy system and of the FPV technologies could be improved by carrying on additional research on the parameters. The most important points would be to improve the capacity constraint and costs of FPV technologies carrying out an in-depth analysis of the potential locations and identifying the maximum dimensions of candidate plants in terms of covered water area and capacity, as well as their potential costs. Additionally, the capacity constraints and costs of other technologies could be updated and further disaggregated by looking into the most recent infrastructure projects and literature studies.

Link to hydrological model
Secondly, the model could be extended by linking the energy model to an hydrological model, in order to allow the representation of inter-annual variation of flows and strenghten the water-energy nexus approach of the analysis. Adding such a module could also allow the representation of sedimentation in hydropower reservoirs, either with an explicit modelling of sediment transport or just with a reduction of capacity factor for hydropower plants over time. Besides, different cooperation scenarios could be implemented by altering the water discharge policies of hydropower reservoirs across the river basin, similarly to what done in a study from Almulla et al. (2018), or by altering the power trade infrastructure parameters.

Improving water savings assessment
Another interesting line of research could shed more light on the link between solar panels and water savings. This could be done by extending the research on the water reduction rates from solar panels, aiding the model with evaporation measures from existing plants (for example the Bui reservoir in Ghana). Moreover, it could be interesting to force the evaporation models with climate change projected data, in order to assess how the magnitude of evaporation savings changes under different climate change scenarios. Additionally, it would be useful to link the potential water savings to the energy optimization procedure, in order to make FPVs more convenient the more water they help saving. However, since the model function is to minimise the total system costs, the only way to do so would be converting the saved water to a cost reduction or negative penalty for floating solar power, raising the challenge of giving a monetary value to a resource like water.

Smaller scale analyses
Finally, further studies may start from the optimal capacity found here at each location and carry on in depth feasibility assessments with smaller spatial and temporal scales, in order to better capture the advantages of floating solar power at the monthly and local scales.

5 Conclusion

In this study, energy system expansion projections were developed for the Eastern Nile Basin countries (Egypt, Ethiopia, Sudan, South Sudan). In the introduction, it was highlighted how this region is affected by unsufficient energy systems and endangered water resources. Moreover, it was shown how these countries are subject to demographic and socio-economic trends that will drive a sharp increase in the energy and water demands. Looking at these dynamics into the frame of climate change, it becomes evident how these countries need a type of planning that will ensure an evolution of the energy systems that is sustainable in economic, social and environmental terms. Besides, relatively new technologies can aid the practical realization of this vision. Floating solar power in particular has been raising the attention of energy authorities in the last decade, given a series of interesting advantages such as the benefits of hybridization between solar and hydropower resources, the exploitation of already existing infrastructures and the reduction of water evaporation rates. All of these advantages could potentially be very relevant for the studied area, given the energy and water systems context described above. However, there is a gap in the literature when it comes to integrating this new technology into regional and long term energy system's projections, with the existing literature focusing on single plants techno-economic analysis. Finally, the impacts of different climate change and policy scenarios have to be taken into account if a sustainable development is to be guaranteed.
Keeping all of the above in mind, the research questions of this study were formulated. These focused on finding the cost-optimal energy system's expansion of the region, assessing the role of floating solar power in this expansion under different scenarios. The role of this technology on the energy system's environmental footprints (carbon emissions, land use and water consumption) was also studied. Finally, the best locations to invest in such technology wanted to be determined.
To answer these questions, a long term regional energy system cost-optimisation was carried out for the Eastern Nile Basin countries. To this extent, an existing energy modelling tool for African countries (OSeMOSYS-TEMBA, Pappis et al. (2022)) was adopted and further extended. The main methodological contributions of this work include the spatial disaggregation of hydropower technologies at the single plant scale, the introduction of floating solar power technologies, the addition of a land use accounting and costing scheme and the adaptation of renewable energy costs and trade links. Besides, the study used a regional approach where the different countries are connected via the Nile river (through hydropower production) and the electricity trade links.
Furthermore, seven different scenarios were developed to test the importance of floating solar power under different conditions, regarding hydrological flows under climate change projections and the introduction of taxes aimed at internalising the pressure on the environment due to carbon emissions and land use change.

The results of the simulations showed that the floating solar power is a cost-optimal technology from early in the modelling horizon in each scenario and in each country apart from South Sudan, mainly because this country does not develop suitable reservoirs. Moreover, the full available potential of floating solar power is exploited under every tested condition, allowing this technology to supply up to 3% of the generation mix. In particular, if the land use and CO2 emissions are taken into account and penalised with taxes, the importance of FPVs in the energy mix increases (+1.3%) and their deployment is anticipated. On the other hand, climate change scenarios don't affect the role and deployment of this technology significantly. However, the sensitivity analysis showed that the results are quite sensitive to costs and capacity constraints assumptions. In particular, the absolute magnitude of floating solar power deployment and its role in the generation mix highly depend on the value of these parameters. In fact, increasing the maximum capacity constraint by a factor 10 causes an increase in the total maximum installed capacity of almost 7 times and an increase in the maximum FPV generation share of 11%. On the other hand, changing the capital cost assumptions of solar technologies by ± 20% changes the maximum generation share of less than 1%, but it relevantly changes the FPV capacity expansion pathways.
In terms of reducing the energy system's environmental footprints, the results showed that floating

solar technologies can help slightly reducing the total CO_2 emissions (-0.37%) and the total land use (-1.19%). Moreover, implementing their optimal capacity could lead to maximum evaporation reductions of 2% yearly, saving up to 376 mcm/y in the whole region. However, the actual relevance of these reductions is expected to be higher at smaller spatial scales, taking into account local contexts of intersectoral competition over land and water resources, for which further research is needed.
The optimal locations for FPV plants are found to be Lake Nasser, the Grand Ethiopian Renaissance Dam and Merowe Dam, but the reason of this choice relies in the very large size of these plants, which emerge for highest FPV capacity deployment and water evaporation savings at the large scales considered. Hence, further analyses at smaller spatial and temporal scales are needed to highlight the effects of floating solar implementation on the local communities.
Given all of the above, multiple future research lines can be individuated. First of all, there is space for improvements on the model parameters, especially in terms of technology costs and capacity constraints. Another approach could instead focus in strengthening the energy-water nexus by adding a hydrological module to better represent the hydropower production. Additionally, the water savings assessment could be improved by integrating the evaporation models with measurement campaigns and testing them under climate change assumptions. Lastly, the floating solar capacity obtained in this study in the large scale system optimization could be used as a starting point for further local scale research, which could shed more light on the effects of this technology at smaller scales.

To summarise all the above findings in a possible recommendation for energy planning authorities, floating solar power has shown to be a very promising technology for the needed electrification expansion of the study area, and it is cost-optimal to invest in it already since the end of the decade. Besides, its implementation can help reducing the energy system's footprints in terms of carbon emissions and land use, and aid reducing the large water evaporation losses typical of the region. Moreover, this recommendation is robust to different climate change projections and taxation policy decisions. Finally, further single plant, multi-sectoral techno-economic feasibility study have to be undertaken, in order to make sure that local environmental, social and economic conditions are taken into account.

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A Additional methodology

A.1 Adapting TEMBA 2.1

Adapting electricity trade links

Trade links are modelled as technologies that output the electricity fuel of the importing country taking as input the electricity fuel of the exporting country. Moreover, they can operate in both directions depending on the mode of operation. If both of the countries are inside the model boundaries (in this case restricted to the Eastern Nile Basin countries), the trading price is set as null, since any transaction internal to the system does not affect the total system costs. This dynamic assumes that there are no electricity losses on the interconnection lines, i.e. the entire amount of power that leaves a country reaches the other country. In this case, the model uses the trade link based on the demands and productions of each country at each time step, allocating power across the system more efficiently. On the other hand, if one of the two countries connected to a trade link is external to the model boundaries, its demand and production are not explicitly represented in the model. Therefore, the model uses the trade link as a production technology, importing and exporting when it is convenient. Such "convenience" is modelled in terms of trading costs: these are positive when the energy is imported in the system and negative when it is exported.
The main reason behind having to change some parameters relative to the trade links was the fact that many countries were removed from the original model. This caused a few trade links that were originally internal to the modelled area to become external. These were the interconnectors between Libya and Egypt, Ethiopia and Kenya and Ethiopia and Djibouti. After Libya, Kenya and Djibouti were removed from the model, trading prices for these links had to be set. Moreover, some capacity expansion parameters were considered unrealistic, in particular the one between Egypt and Sudan, that could reach up to 6 GW of capacity. The sources behind these parameters are mainly news announcements (Egypt Today (2022), The Reporter Ethiopia (2022)) and the original TEMBA dataset. The final paramters used for each trade links are summarised in table 23.

Trade link	Max capacity	Starting year	Trading price
EGYPT - SUDAN	0.3 GW	2023	-
EGYPT - SAUDI ARABIA	3 GW	2025	0.3 $/kWh
EGYPT - LIBYA	0.17 GW	Existing	0.14 $/kWh
EGYPT - JORDAN	0.3 GW	Existing	0.3 $/kWh
ETHIOPIA - KENYA	2 GW	Existing	0.065 $/kWh
ETHIOPIA - DJIBOUTI	0.18 GW	Existing	0.065 $/kWh
ETHIOPIA - SUDAN	0.2 GW	Existing	-

Table 23: Parameters for trades links

Adapting renewable technology costs

A second important adaptation that had to be conducted on the original dataset from TEMBA regarded the costs of variable renewable energy sources. In fact, comparing the cost curves from TEMBA with the cost curves used in a more recent study by (IRENA, 2021), it was clear that the latter contained lower cost values with a faster decrease over time (especially for wind power). Being IRENA a well-recognised international authority, its values were considered to be more accurate, and were therefore adopted for this study. However, the projections only reached 2040, making it necessary to extrapolate the values up to the end of the modelling horizon (2070). For such an extrapolation, the decreasing trend originally present in the TEMBA dataset was used. The results from this procedure can be seen in Figure 33.

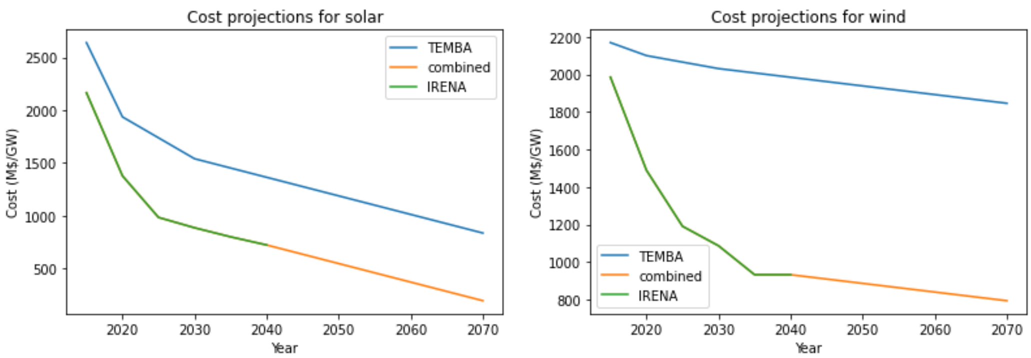


Figure 33: Capital cost projections for solar and wind technologies

Adding explicit parameters for nuclear power in Egypt

A final modification that was applied to the original TEMBA dataset was the explicit modelling of nuclear expansion plans in Egypt.
In fact, according to various sources (World Nuclear Association (2023), Power Technology (2023)), Egypt has started the construction of a nuclear power plant in El Dabaa, comprising four large reactors of 1.2 GW of capacity each. The first unit is expected to begin commercial operations in 2026 while commissioning of the remaining three reactors is scheduled for 2029.
Therefore, the parameters were set in order to force the model to build such power plant in those years, and this was achieved through setting a minimum annual installable capacity of 1.2 GW between 2026 and 2030.

Hydropower plants disaggregation

The full list of modelled existing and planned hydropower plants can be seen in Table 24. This list is represented on a map in Figure 34

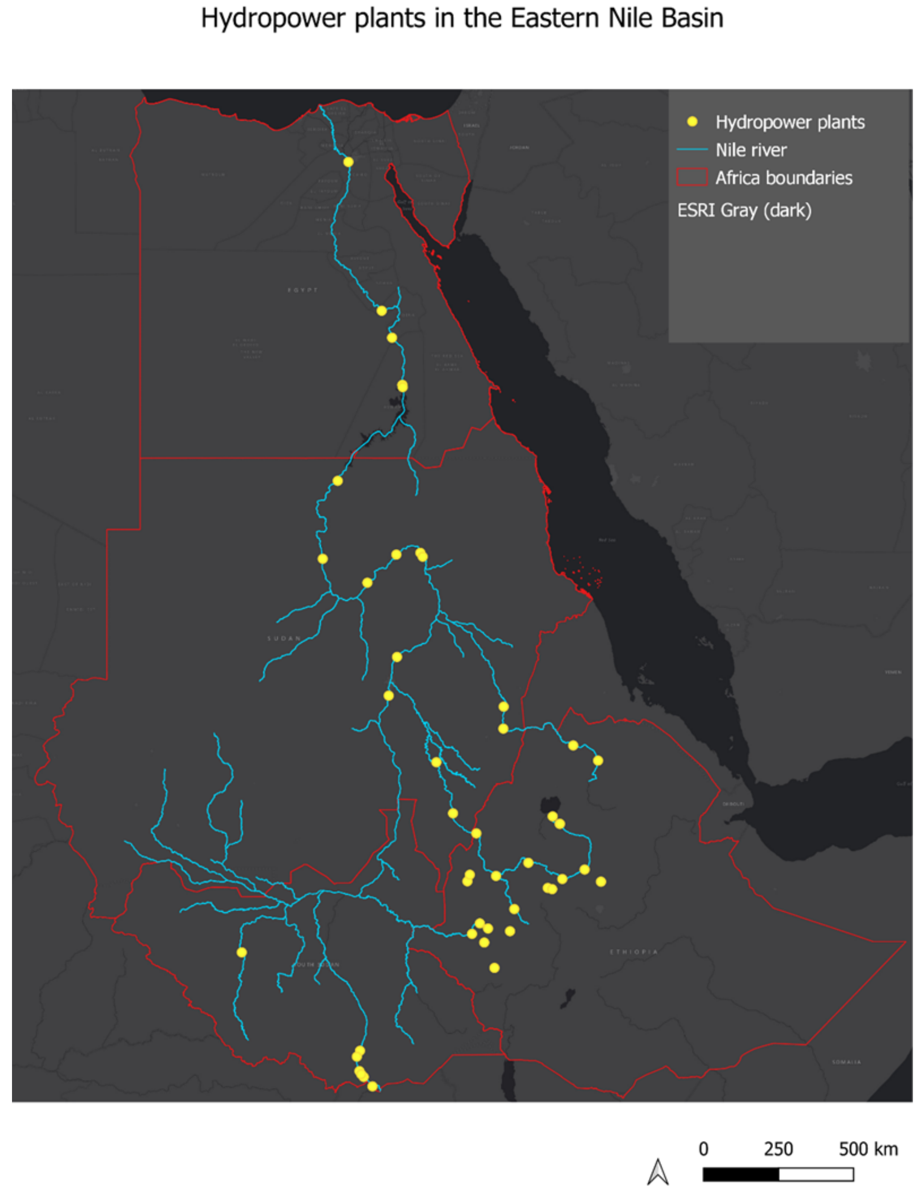


Figure 34: Map of modelled hydropower plants

Country	Unit Name	Status	Type	First Year	Capacity (MW)
EGYPT	Aswan 1	Existing	Reservoir	2010	280
EGYPT	Aswan 2	Existing	Reservoir	2010	270
EGYPT	High Aswan Dam	Existing	Reservoir	2010	2100
ETHIOPIA	Finchaa	Existing	Reservoir	1973	128
ETHIOPIA	Beles	Existing	Reservoir	2010	460
ETHIOPIA	Tekeze 1	Existing	Reservoir	2010	300
ETHIOPIA	Amarti-Neshe	Existing	Reservoir	2013	98
ETHIOPIA	Renaissance	Existing	Reservoir	2023	6400
ETHIOPIA	Baro	Candidate	Reservoir	2025	645
ETHIOPIA	Birbir	Candidate	Reservoir	2025	467
ETHIOPIA	Chemoga Yeda	Candidate	Reservoir	2025	280
ETHIOPIA	Geba	Candidate	Reservoir	2025	372
ETHIOPIA	Genji	Candidate	Reservoir	2025	216
ETHIOPIA	Lower Dedessa	Candidate	Reservoir	2025	550
ETHIOPIA	Tekeze 2	Candidate	Reservoir	2025	380
ETHIOPIA	Upper Dabus	Candidate	Reservoir	2025	326
ETHIOPIA	Karadobi	Candidate	Reservoir	2026	1600
ETHIOPIA	Beko Abo	Candidate	Reservoir	2028	935
ETHIOPIA	Upper Mandaya	Candidate	Reservoir	2030	1700
ETHIOPIA	Aleltu East	Candidate	Reservoir	2031	189
ETHIOPIA	Aleltu West	Candidate	Reservoir	2031	265
ETHIOPIA	Lower Dabus	Candidate	Reservoir	2031	250
ETHIOPIA	Tams	Candidate	Reservoir	2031	1000
SOUTH SUDAN	Juba Barrage	Candidate	Reservoir	2026	120
SOUTH SUDAN	Wau	Candidate	Reservoir	2030	10.4
SUDAN	Sennar	Existing	Reservoir	1962	26
SUDAN	Kashm El Girba	Existing	Reservoir	1964	10
SUDAN	Roseires	Existing	Reservoir	1966	270
SUDAN	Jebel Aulia	Existing	Reservoir	2003	19
SUDAN	Merowe	Existing	Reservoir	2009	1240
SUDAN	Upper Atbara	Existing	Reservoir	2017	320
SUDAN	Kajbar	Candidate	Reservoir	2024	360
SUDAN	Shereik	Candidate	Reservoir	2025	420
SUDAN	Dagash	Candidate	Reservoir	2028	312
SUDAN	Dal	Candidate	Reservoir	2030	648
SUDAN	Mograt	Candidate	Reservoir	2030	312
SUDAN	Sabaloka	Candidate	Reservoir	2030	205
EGYPT	Esna	Existing	RoR	2010	86
EGYPT	Naga Hamadi	Existing	RoR	2010	64
EGYPT	New Assiut Barrage	Existing	RoR	2018	31.74
ETHIOPIA	Tis Abay 1	Existing	RoR	2000	11
ETHIOPIA	Tis Abay 2	Existing	RoR	2010	78
ETHIOPIA	Sor	Existing	RoR	2014	5
SOUTH SUDAN	Bedden	Candidate	RoR	2024	570
SOUTH SUDAN	Fula	Candidate	RoR	2024	890
SOUTH SUDAN	Lakki	Candidate	RoR	2024	410
SOUTH SUDAN	Shukoli	Candidate	RoR	2024	235
SOUTH SUDAN	Fula Small	Candidate	RoR	2025	42

Table 24: List of hydropower plants from Sterl et al. (2021) and Peters et al. (2023)

The assumptions behind the main parameters for the single hydropower plants are as follows:

- Capacity factors: the values of the all-online, normal scenario from Sterl et al. (2021) were used (more details in the scenarios design section).
- Costs: the values used in Carlino et al. (2023) were applied here: the capacity - cost points for CAPEX that can be seen in table 25 were interpolated linearly to all the capacity values of the selected plants. For the operational costs, the values used in the original version of TEMBA 2.1 were kept.
- Availability factor: value already present in TEMBA for generic hydropower technologies (0.95).
- Residual capacity: nominal capacity of existing plants, assuming an operational life of hydropower plants of 80 years.
- Total annual max capacity: nominal capacity of the plant (the model can't build more capacity than the nominal over the whole modelling period).
- Total annual max capacity investment: nominal capacity of the plant (the model can't build more than the nominal capacity in one single year).

Capacity (MW)	**CAPEX ($/MW)**	**OPEX ($/MW)**
0.1	3744.4	65
1	3256	65
10	2836	65
500	2446	55
11000	2054.5	55

Table 25: Costs assumptions for hydro technologies

As far as the planned reservoirs are concerned, their capacity constraints were set in such a way that the model is not allowed to build any capacity before the planned first year (from Peters et al. (2023)). This is achieved by setting the total annual max capacity and total annual max capacity investment to 0 until the planned first year.
Another challenge was to model the rest of the hydropower plants present in the countries' energy systems but not in the Nile basin. For these plants, the original generic (non-disaggregated) hydropower technologies were kept as a reference, but their capacity constraints (residual capacity, total max capacity and total max capacity investment) had to be changed, updating the values so that they included the plants outside of the Nile only. To do so, these values were calculated aggregating the capacities of non-Nile plants present in the RePP database (Peters et al., 2023). From this procedure, it resulted that only Ethiopia had hydropower development planned outside of the Nile. The capacity boundaries for these technologies can be seen in table 26.

Technology	**Residual Capacity (GW)**	**Total annual max capacity (GW)**
Large hydropower (>100MW)	0.604	3.262
Medium hydropower (<100MW)	0.107	0.291
Small hydropower (<10MW)	0	0.006

Table 26: Capacity assumptions for Ethiopian non-Nile hydropower

Another constraint to implement was to force the model to build the planned capacities for hydropower plants all at once. In fact, without this constraint, the model could freely choose how many MW of a single plant to build over the modelling period. To prevent this, the built-in parameter CapacityOfOneTechnologyUnit was used, which specifies the exact amount of capacity that has to be implemented at once, and set equal to the nominal capacity of each plant.

A.2 Additional information on model parameters

Energy demands

In Figure 35, the assumed total energy demand for each country is plotted, as well as its variation throughout the year.

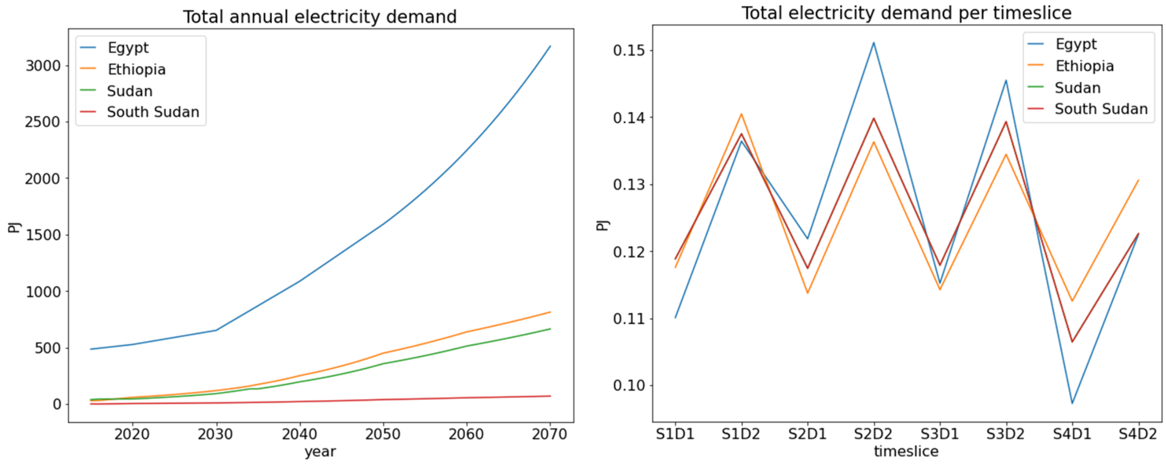


Figure 35: Electricity demands for the single countries

Capacity factors assumptions

In the following charts (Figure 36), the capacity factors of solar technologies across all the timeslices are presented.

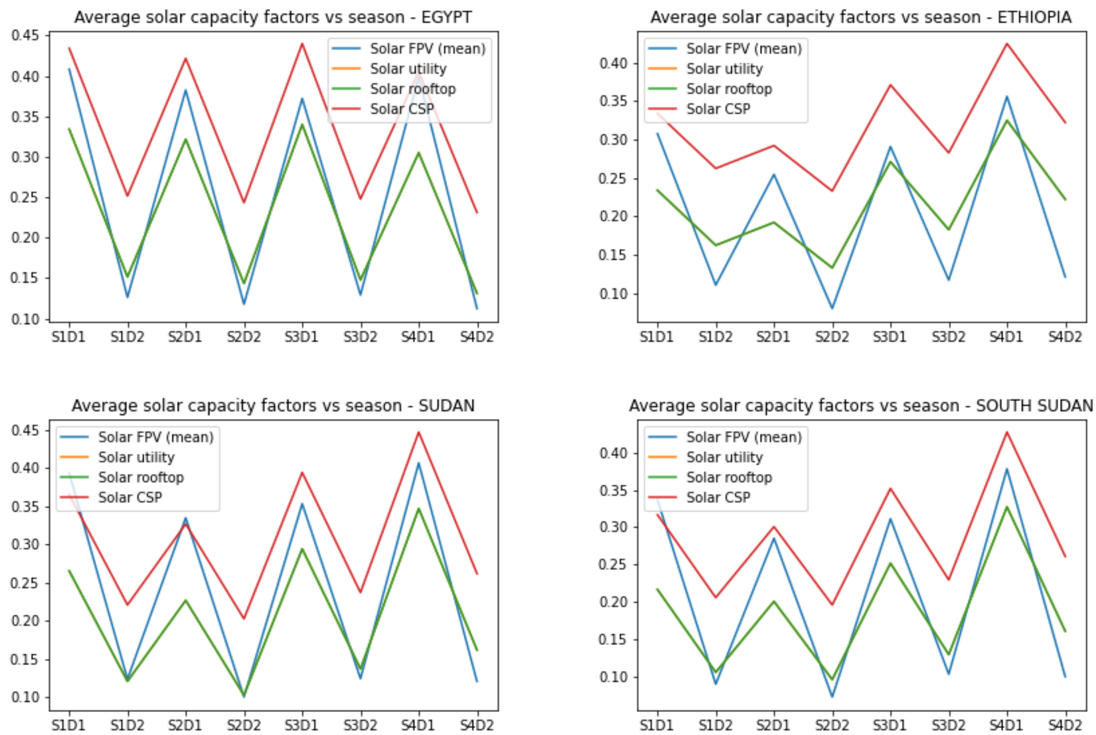


Figure 36: Average capacity factors for solar technologies across the seasons

In Figure 36 we can see that FPV technologies have higher capacity factors in the day and lower capacity factors in the night compared to traditional solar panels (rooftop and utility have the same

values). Concentrated solar power is the technology with highest capacity factors. The capacity factor in the "night" part of the day (D2) is not zero because this timeslice goes from 18:00 to 9:00, thus including a few hours in which the incoming solar radiation is not null.
In the following charts (Figure 37), the same plot is produced for the different floating solar panels candidate locations in each country.

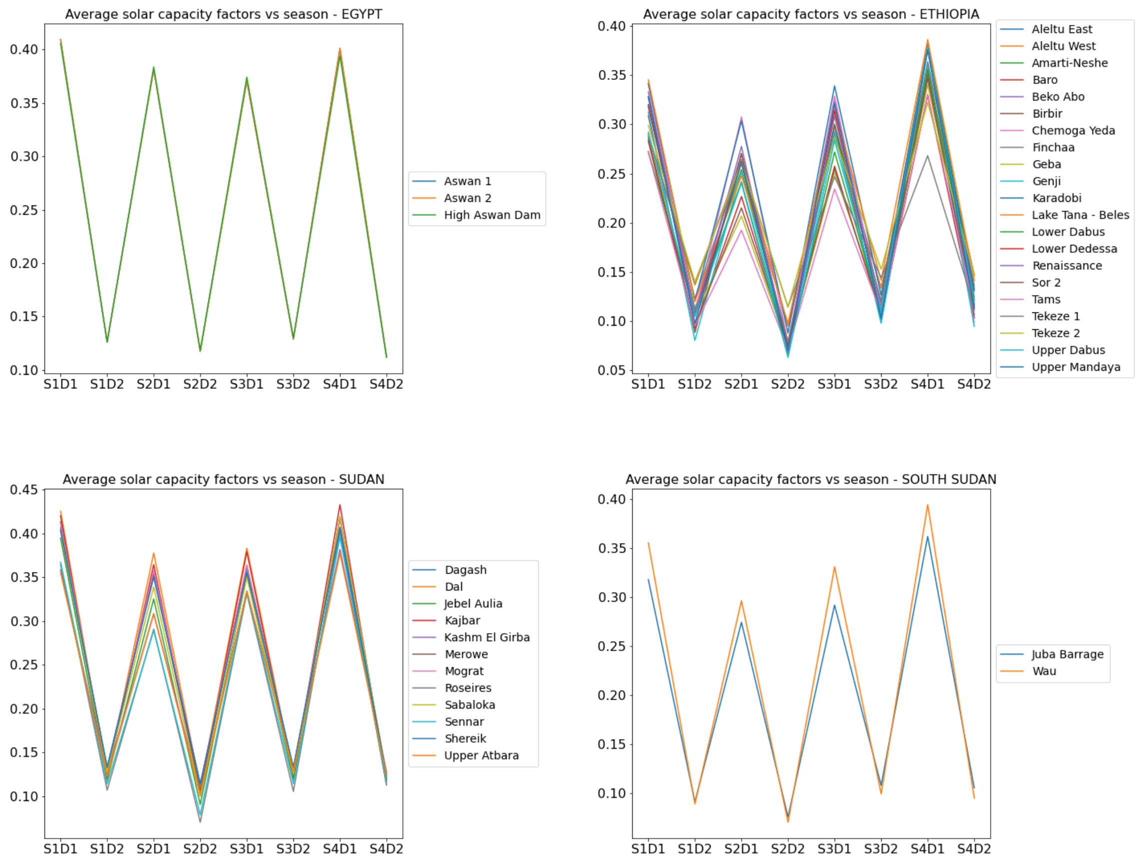


Figure 37: Average capacity factors for solar FPV technologies across the timeslices

Here we can see that in Egypt the three plants have the same capacity factors (since they are more or less on the same location), while Ethiopia shows the highest variability in capacity factors, together with Sudan. South Sudan has only two candidate plants, with Wau showing higher capacity factors than Juba Barrage.

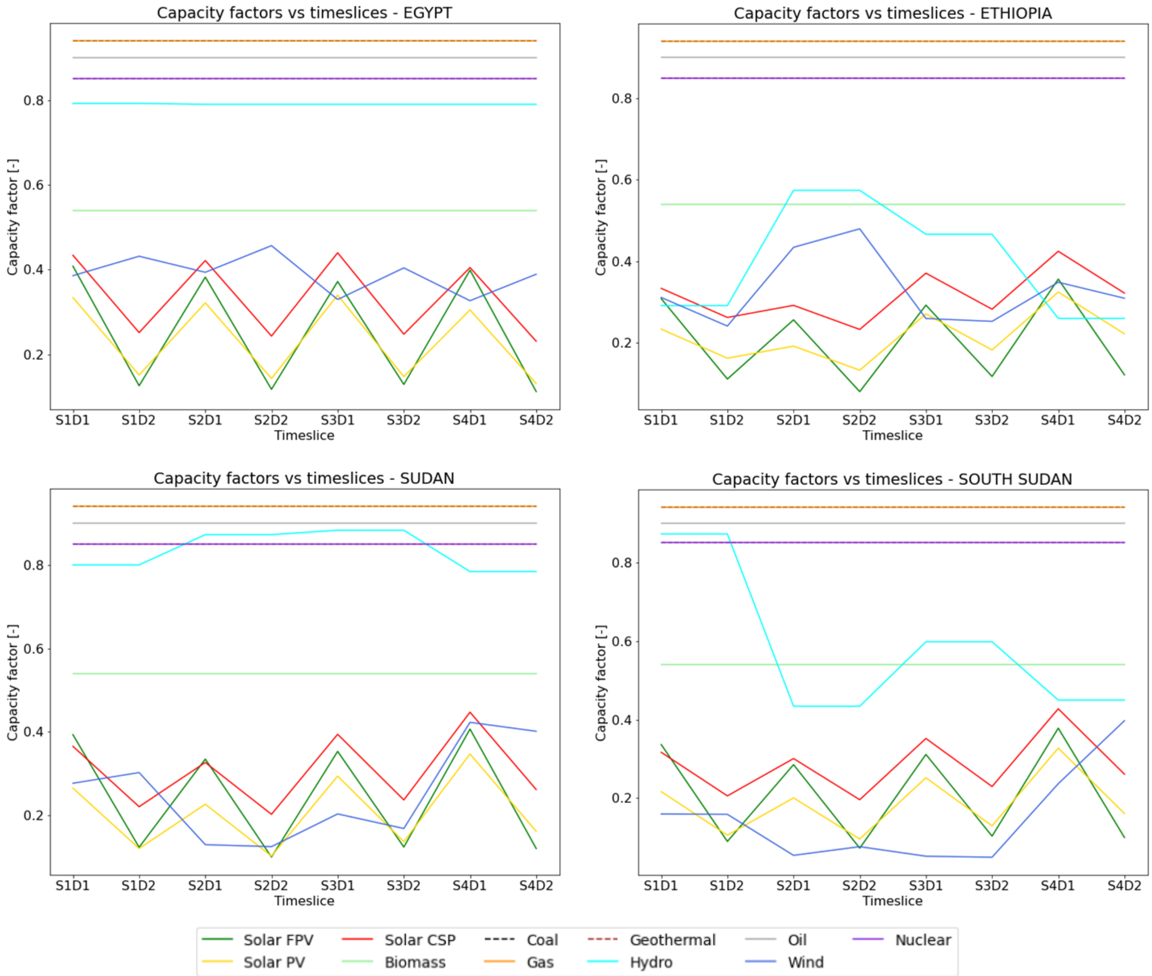


Figure 38: Average capacity factors for technologies across the timeslices

In Figure 38, the capacity factors for all the different energy generation technologies are reported.

Costs assumptions

In figure 39 the capital and operational costs of each technology along the modelling period are plotted. In Table 27 the cost breakdown of floating solar panels from different literature sources is reported.

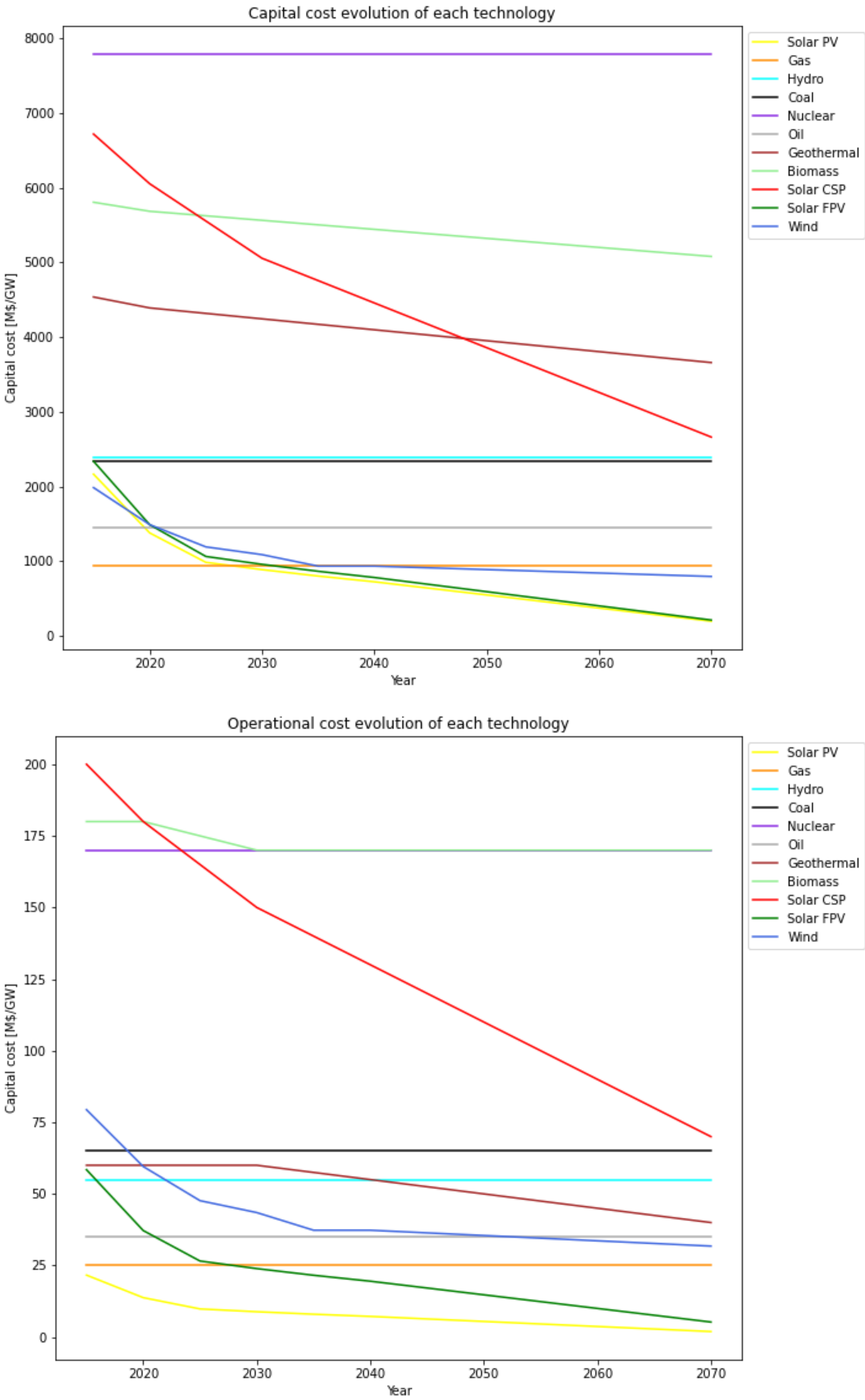


Figure 39: Capital and operational costs evolution for each technology

Capital costs (CAPEX) FPV										
Modules	Value	Unit	Year	Installed capacity	Unit	Source	Notes	Average	Max	Min
Modules	220	$/kWp	2020	100	MWp	Pinto	Brazil	689	2060	220
Modules	250	$/kWp	2018	50	MWp	Floating solar market report		$/kWp	$/kWp	$/kWp
Modules	260	$/kWp	2022	1	MWp	Getie	GERD			
Module and inverter	647	$/kWp	2019	10	MWp	Ravichandran	Aswan, crystalline			
Modules	700	$/kWp	2015	0,2	MWp	Campana 2019	Thailand			
Modules	2060	$/kWp	2022	0,335	MWp	Ghasempour	Iran			
Invertes	Value	Unit	Year	Installed capacity		Source	Notes	Average	Max	Min
Inverters	58	$/kWp	2022	1	MWp	Getie	GERD	92	150	58
Inverters	60	$/kWp	2018	50	MWp	Floating solar market report		$/kWp	$/kWp	$/kWp
Inverters	100	$/kWp	2020	100	MWp	Pinto	Brazil			
Inverters	150	$/kWp	2015	0,2	MWp	Campana 2019	Thailand			
Structure	Value	Unit	Year	Installed capacity	MWp	Source	Notes	Average	Max	Min
Mooring and anchor	10	$/kWp	2022	0,335	MWp	Ghasempour	Iran	436	2467	10
Support	43	$/kWp	2022	1	MWp	Getie	GERD	$/kWp	$/kWp	$/kWp
Floating structure	85	$/kWp	2014	0,2	MWp	Campana 2019	Thailand			
Other hardware (racking and wiring)	150	$/kWp	2015	0,2	MWp	Campana 2019	Thailand			
Mounting system	150	$/kWp	2018	50	MWp	Floating solar market report				
Floating structure	150	$/kWp	2022	0,335	MWp	Ghasempour	Iran			
Floating structure	2467	$/kWp	2019	10	MWp	Ravichandran	Aswan, crystalline			
BoS	Value	Unit	Year	Installed capacity	MWp	Source	Notes	Average	Max	Min
BoS	130	$/kWp	2018	50	MWp	Floating solar market report		206	258	130
BoS	230	$/kWp	2020	100	MWp	Pinto	Brazil	$/kWp	$/kWp	$/kWp
BoS	258	$/kWp	2019	10	MWp	Ravichandran	Aswan, crystalline			
Installation	Value	Unit	Year	Installed capacity	MWp	Source	Notes	Average	Max	Min
Installation	60	$/kWp	2022	1	MWp	Getie	GERD	178.16	310	60
Installation	81	$/kWp	2019	10	MWp	Ravichandran	Aswan, crystalline	$/kWp	$/kWp	$/kWp
Design & construction	140	$/kWp	2018	50	MWp	Floating solar market report				
Installation	300	$/kWp	2015	0,2	MWp	Campana 2019	Thailand			
Installation	310	$/kWp	2020	100	MWp	Pinto	Brazil			
Other	Value	Unit	Year	Installed capacity	MWp	Source	Notes	Average	Max	Min
Soft costs	50	$/kWp	2015	0,2	MWp	Campana 2019	Thailand	191	336	50
Profit	150	$/kWp	2015	0,2	MWp	Campana 2019	Thailand	$/kWp	$/kWp	$/kWp
other	230	$/kWp	2020	100	MWp	Pinto	Brazil			
Soft Costs	336	$/kWp	2019	10	MWp	Ravichandran	Aswan, crystalline			
Tot	Value	Unit	Year	Installed capacity	MWp	Source	Notes	Average	Max	Min
Tot	425	$/kWp	2022	1	MWp	Getie	GERD	1641.388	3787.65	425
Tot	456	$/kWp	2020	70	MWp	Sanchez	India	$/kWp	$/kWp	$/kWp
Tot	730	$/kWp	2018	50	MWp	Floating solar market report				
Tot	798	$/kWp	2019		MWp	Sanchez	India			
Tot	980	$/kWp	2019	10	MWp	Goswami 2019	India			
Tot	1090	$/kWp	2020	100	MWp	Pinto	Brazil			
Tot	1250	$/kWp	2019	-	MWp	Piana	India high case			
Tot	2220	$/kWp	2022	0,335	MWp	Ghasempour	Iran			
Tot	2350	$/kWp	2015	0,2	MWp	Campana 2019	Thailand			
Tot	2760	$/kWp	2019	5	MWp	Piana	Japan			
Tot	2850	$/kWp	2019		MWp	Sanchez	Japan			
Tot	3788	$/kWp	2019	10	MWp	Ravichandran	Aswan, crystalline			
Tot	108% FPV	-	2018		MWp	Floating solar market report				

Table 27: Costs breakdown for FPVs

A.3 Additional figures on land use pricing procedure

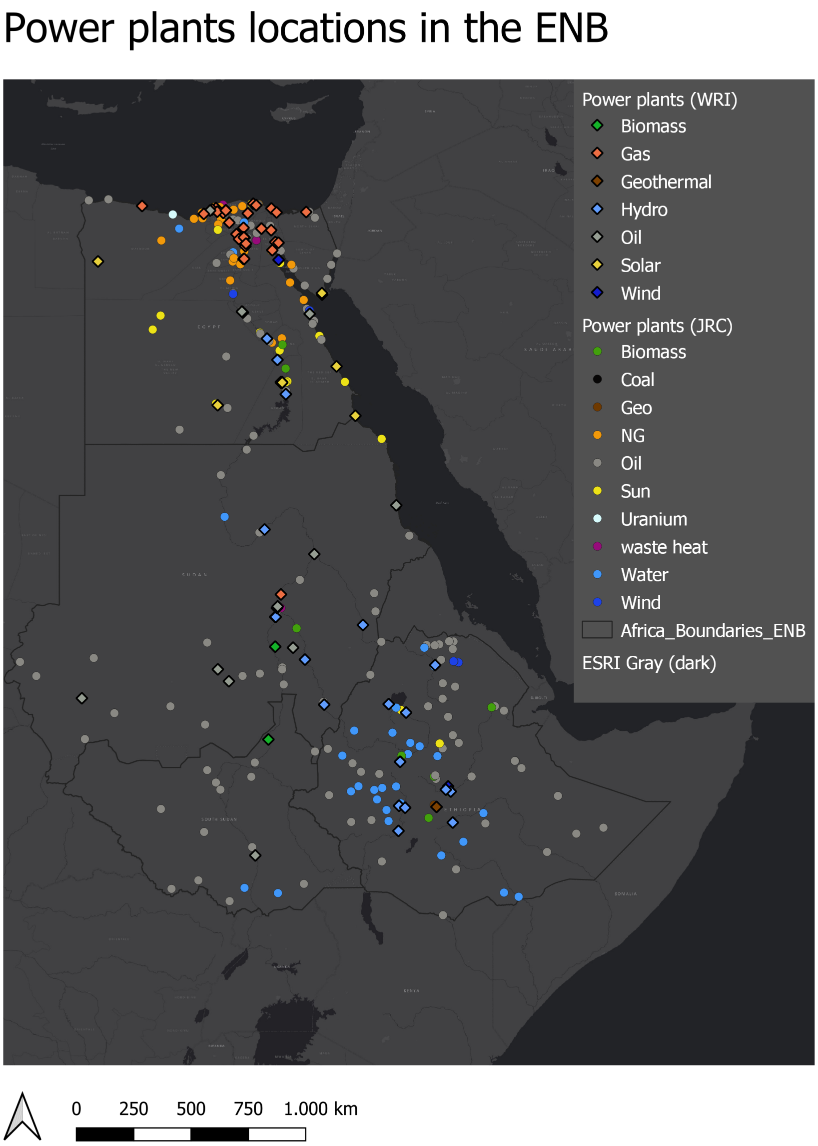
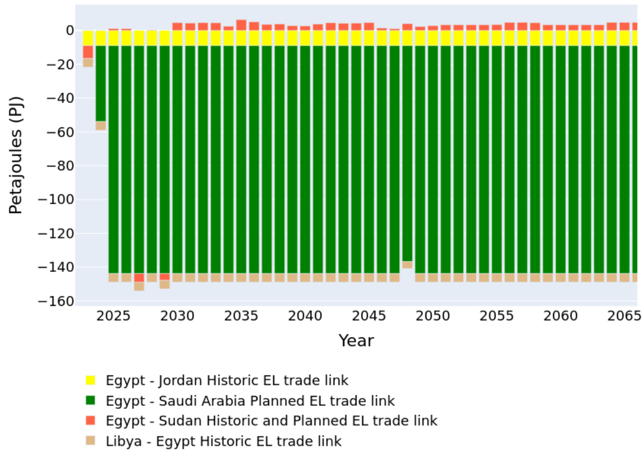


Figure 40: Map of power plants in the ENB region

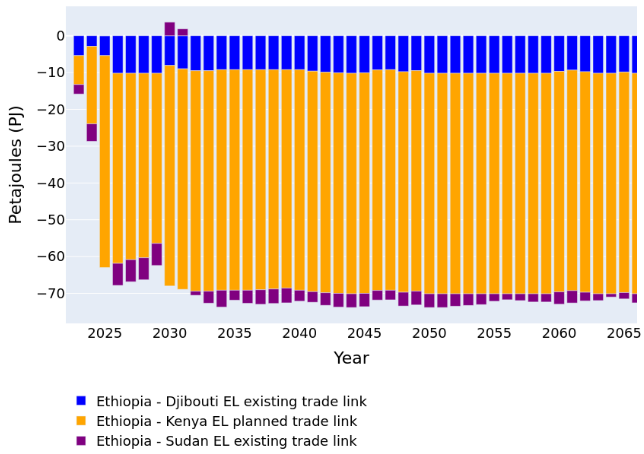
B Additional results

B.1 Detailed electricity trading results

(a) Egypt



(b) Ethiopia



(c) Sudan

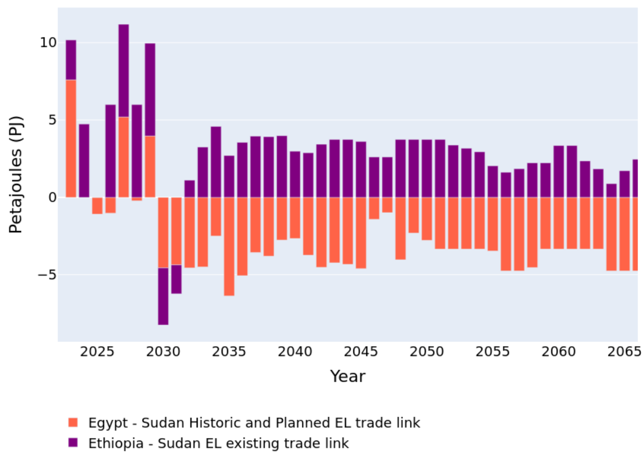


Figure 41: Electricity tradings of the single countries for the Reference scenario

B.2 Additional climate change scenarios results

RCP 2.6 projections

In the plots of Figure 42 referring to the dry scenario, it can be observed that even though in Egypt, Sudan and South Sudan the hydropower generation decreases, in Ethiopia this pattern is not respected. Here, in fact, the hydropower generation is higher. Besides, Ethiopia is the country being most affected by the changes in hydropower capacity factors (differences in generation up to 100 PJ/y), thus its effect on the total system mix is the heaviest. Consequently the total system's chart (Figure 16 a) also shows an increase in hydropower generation. The reason behind this exception derives from the fact that most of the Ethiopian hydropower generation comes from the Renaissance dam, which average capacity factor actually increases under this climate change projection, causing an increase in hydropower generation. This is also visible in the section 2 in Figure 4.

It is also interesting to analyse what technology hydropower replaces or is replaced with. In Egypt, for example, the mix is basically not affected, while in Sudan hydropower generation is replaced by renewable technologies like geothermal and wind, but also by coal from around half of the modelling period. South Sudan shows an interesting feature between 2034 and 2036, where gas is replaced by hydropower generation. This has to do with the fact that a major hydropower plant (Bedden, 570MW) comes online in a different year compared to the reference. In Ethiopia, instead, the increase in hydropower generation replaces mainly wind energy, aided by some solar generation increase.

As far as floating solar power is concerned, different behaviours are observed for the different countries. Egypt, for instance, does not show any difference in floating solar panel generation, while Ethiopia shows a reduction in the first part of the modelling period, but an increase in the last part. This has probably to do with the fact that due to the increase in hydropower generation, floating solar power is not needed until the demand becomes very high (in the last part of the period). Sudan, instead, shows hardly any change in floating solar generation. A more detailed analysis on floating solar panel generation across the scenarios is conducted in section 3.5.

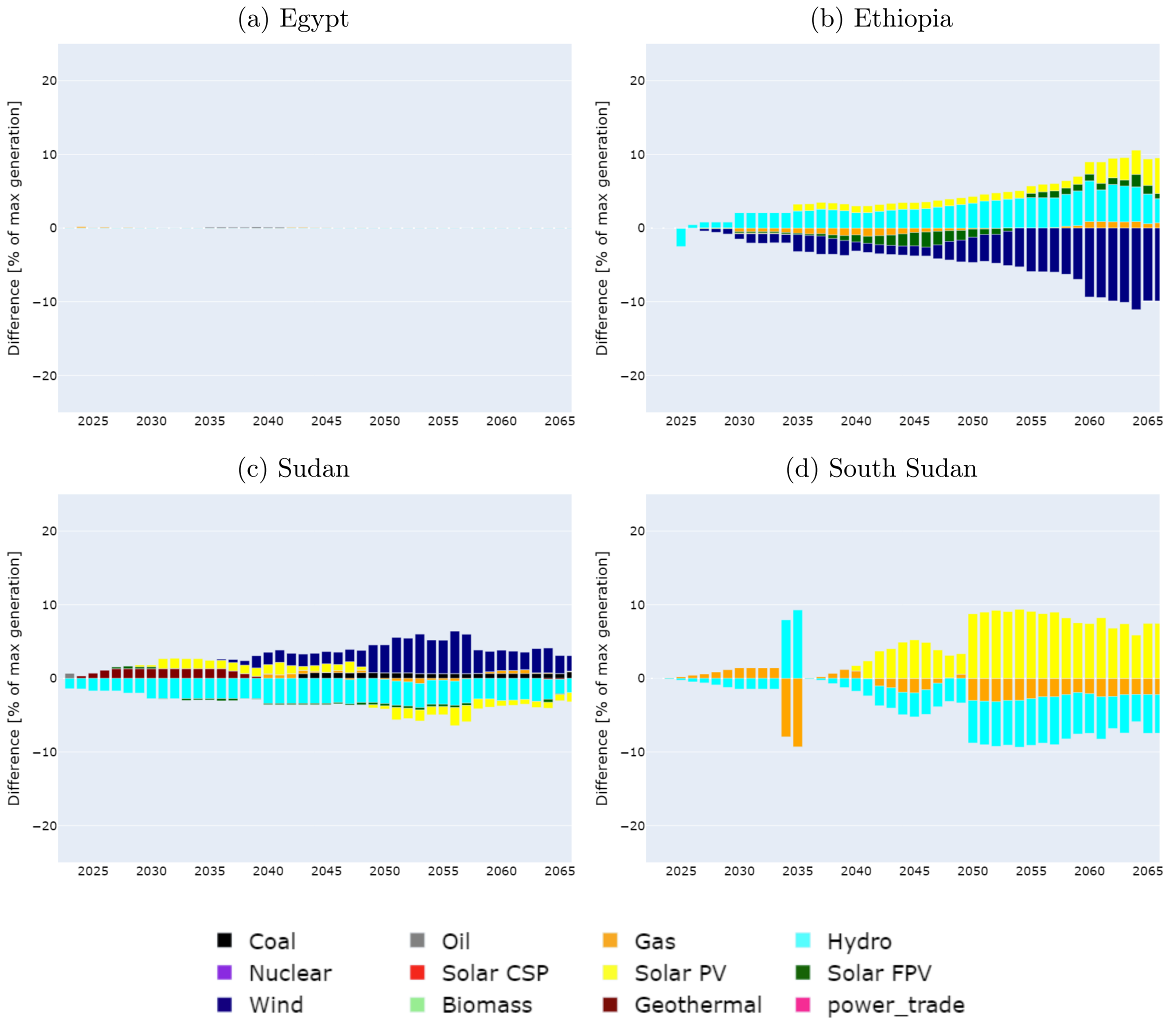


Figure 42: Difference between generation mix in the RCP2.6 dry scenario and reference FPV scenario

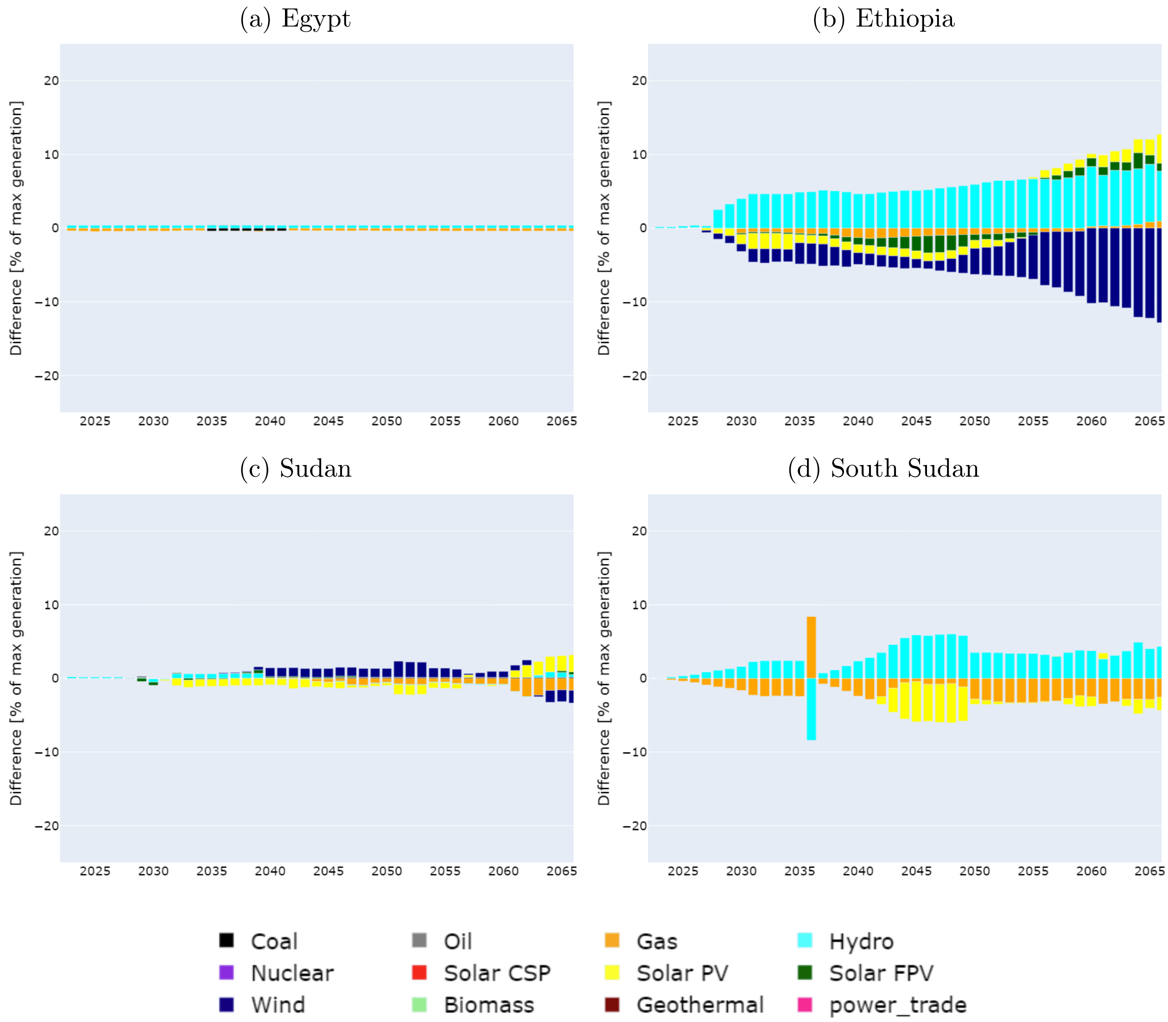


Figure 43: Difference between generation mix in the RCP2.6 wet scenario and reference FPV scenario

In the wet scenario, instead, the results of the different countries all show the same pattern: hydropower generation increases. While in Egypt, Ethiopia and South Sudan this increase is very clear, in Sudan the bar chart is more chaotic, also due to small difference values. However, calculating the difference in total hydropower generation over the modelling period proves that also Sudan features an increase of 60 PJ.
As far as the substitution dynamics are concerned, the behaviour is very similar to the dry case. However, in this scenario Egypt is more affected (differences up to 20 PJ/y) than in the dry scenario (differences up to 7PJ/y), while Sudan is less affected (differences up to 10PJ/y compared to 25PJ/y). In fact, the plots in Figure 4 show that the capacity factor in Egypt changes more under wet scenarios, while in Sudan it changes more under dry scenarios, causing the differences in this behaviour.
Finally, differences in floating solar panel generation also show the same dynamics as in the dry case.

RCP 6.0 projections

The second tested projection was SSP4-RCP6.0. For this projection, both the dry and wet hydrological regimes scenarios were run. Also in this case, the plot of the difference with the reference scenario is reported (Figures 44 and 45), in order to analyse the changes in the energy mix.
Under this projection, similarly to the RCP2.6 projection, there is a general reduction of hydropower generation in the dry scenario and a general increase in the wet scenario. However, under this more severe climate change assumption, certain dynamics are different from the previously analysed projection.

For example, in the dry case, this time Ethiopia shows a reduction of hydropower generation as well, and Sudan and South Sudan suffer a higher reduction than in the RCP2.6 dry scenario. Egypt, on the other hand, is basically not affected, if not with a negligible decrease (around 2 PJ per year) in hydropower generation.
In the wet case, instead the difference with the previous projection is less evident, with all the country showing increase in hydropower generation and changes in floating solar panel generation that are very similar to what presented in the RCP2.6 wet scenario (Figure 43).

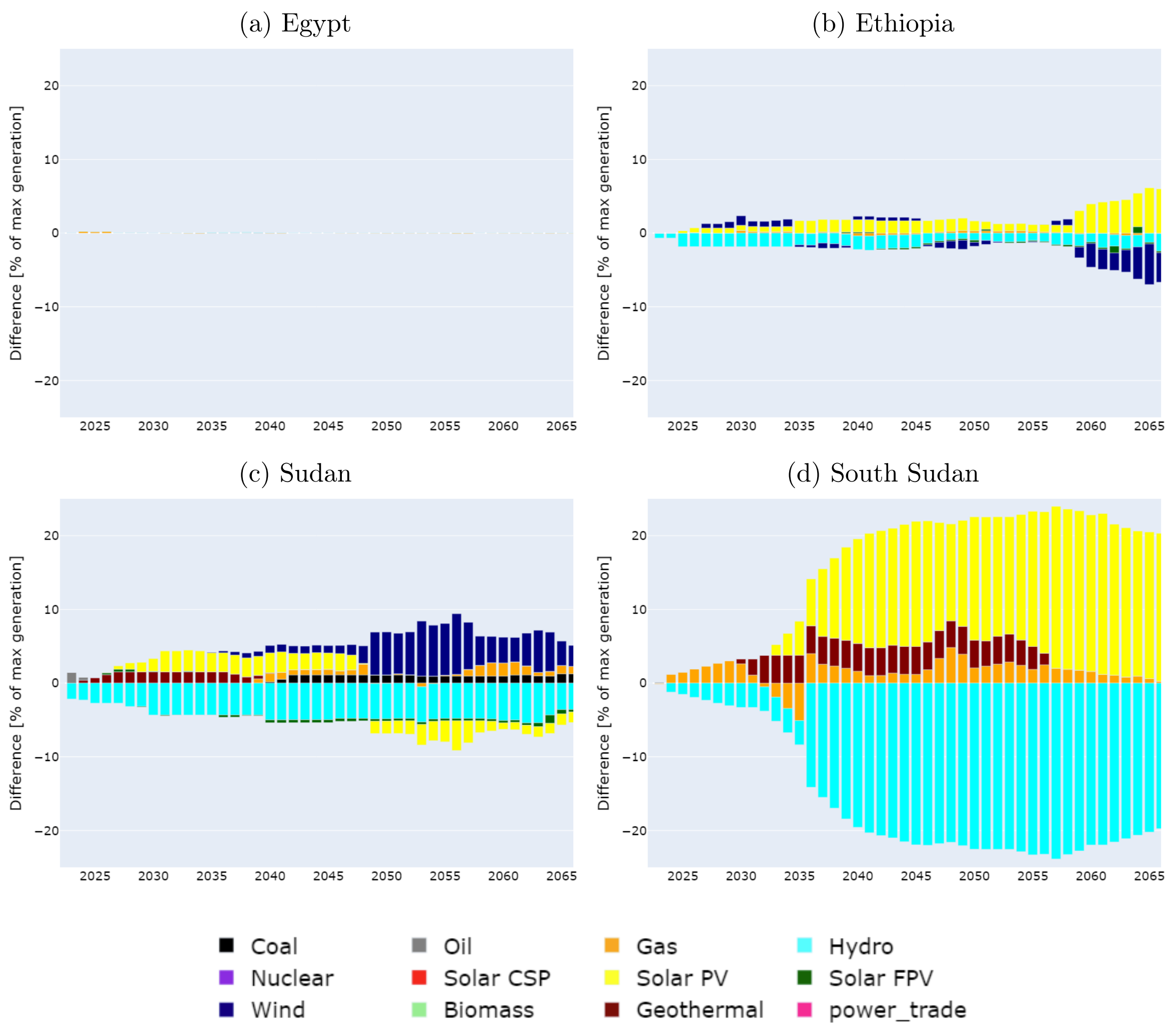


Figure 44: Difference between generation mix in the RCP6.0 dry scenario and reference FPV scenario

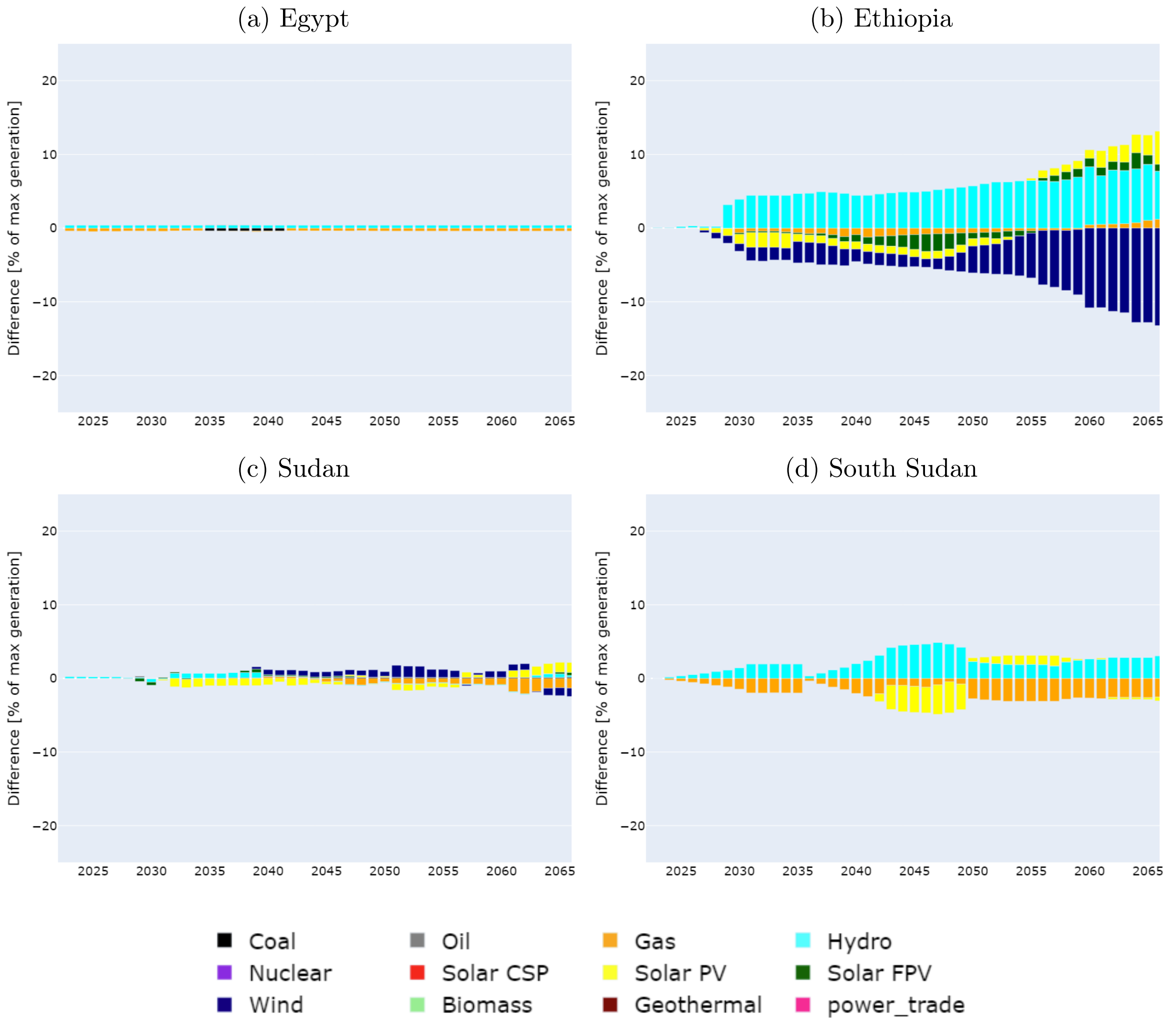


Figure 45: Difference between generation mix in the RCP6.0 wet scenario and reference FPV scenario

B.3 Additional taxation scenarios results

In this paragraph, the results of the taxation scenarios for the single countries are presented. From Figure 46, we can first of all understand how differently the four countries are affected: in Egypt the magnitude of the differences reaches up to 20%, in Ethiopia and Sudan up to around 15%, and in South Sudan up to 10%. Moreover, Ethiopia, Sudan and South Sudan show higher differences in the high taxes scenario than in the low taxes scenario, while in Egypt this increase is less pronounced.
Going more into details, we can see that in Egypt only coal generation is reduced and is replaced by gas, wind and solar CSP. In Ethiopia and Sudan, instead, mainly solar and some gas generation are reduced, substituted by wind, hydropower and floating solar power. In Sudan, however, we notice an inversion in the trend after 2055, with wind being replaced by solar. This happens because the wind potential of Sudan is filled earlier in this scenarios, and once that happens solar becomes the best option again despite the penalties. Additionally, also geothermal plays a minor role in replacing the penalised technologies in this country. Lastly South Sudan replaces mostly gas and solar with hydropower in the low taxes scenario and with geothermal and hydropower in the high taxes scenario. The years were hydropower is replaced show that the Bedden plant comes online later in the taxation scenarios than in the reference scenario.

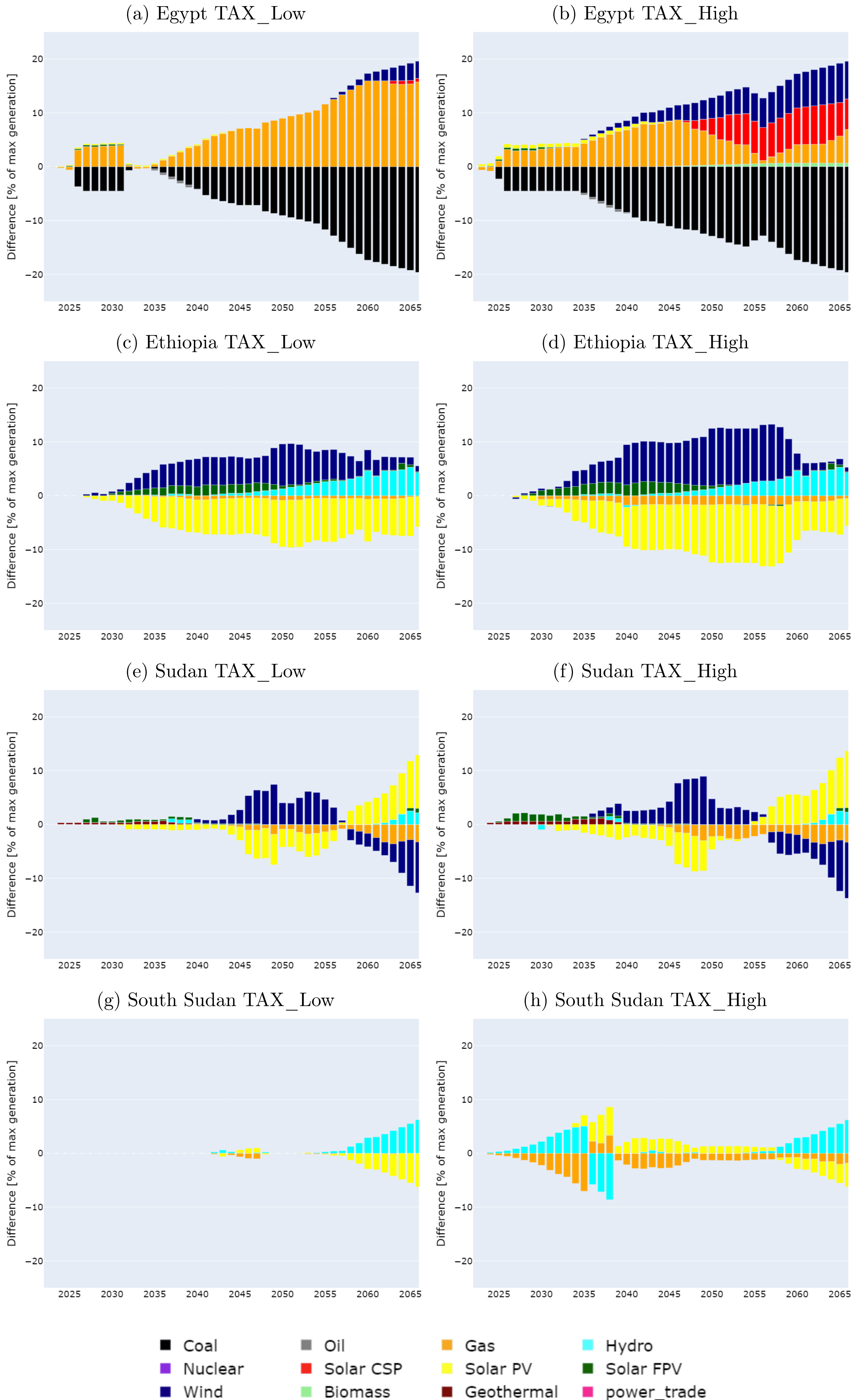


Figure 46: Difference between generation mix in the Taxes scenarios and reference FPV scenario

B.4 Detailed hydropower expansion results

In Table 28 the hydropower expansion in each scenario is reported. Here, we can see that in the effectively wet scenarios (RCP6.0_wet and RCP2.6) there is the largest hydropower expansion, with 11 plants built out of the 28 planned. In the Reference and Taxation scenarios, instead, the total amounts to 10, while in the RCP6.0_dry scenario this amounts to 7 only. Information about which plants are built in each scenario can be seen in Table 29. Here, we see that seven plants are built under every scenario (Baro, Dagash, Dal, Kajbar, Lakki, Sabaloka and Shereik), even though their onset year can vary a lot between scenarios (especially for Dagash and Shereik).

Scenario	Total built hydropower plants	Max HP Capacity (GW)
REF	10	19.7
TAX_High	10	19.7
TAX_Low	10	19.7
RCP2.6_dry	11	20.6
RCP2.6_wet	11	21.3
RCP6.0_dry	7	18.4
RCP6.0_wet	11	21.3

Table 28: Hydropower expansion across the scenarios

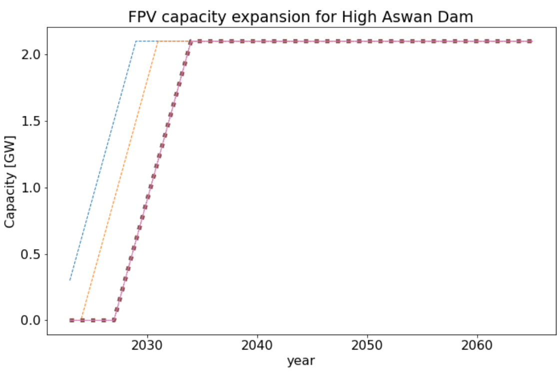
Country	Plant	REF_FPV	TAX_High	TAX_Low	RCP26_dry	RCP26_wet	RCP60_dry	RCP60_wet	% of appearances	Median onset year	Standard deviation
ET	Baro	2025	2025	2025	2030	2025	2025	2025	100	2025	1.7
SS	Bedden	2036	2024	2036	2030	2037		2036	86	2036	4.7
SD	Dagash	2030	2030	2030	2070	2024	2024	2024	100	2030	15.3
SD	Dal	2024	2024	2024	2024	2025	2025	2025	100	2024	0.5
SD	Kajbar	2040	2038	2037	2025	2028	2028	2028	100	2028	5.6
ET	Karadobi				2026	2025		2025	43	2025	0.5
SS	Lakki	2024	2039	2024	2034	2024	2024	2024	100	2024	5.8
SD	Mograt	2030	2031	2030	2028	2030		2030	86	2030	0.9
SD	Sabaloka	2025	2025	2025	2030	2032	2030	2032	100	2030	3.1
SD	Shereik	2025	2025	2025	2058	2030	2030	2030	100	2030	10.9
ET	Tekeze 2	2028	2028	2028		2028		2029	71	2028	0.4

Table 29: Hydropower expansion of each plant across scenarios

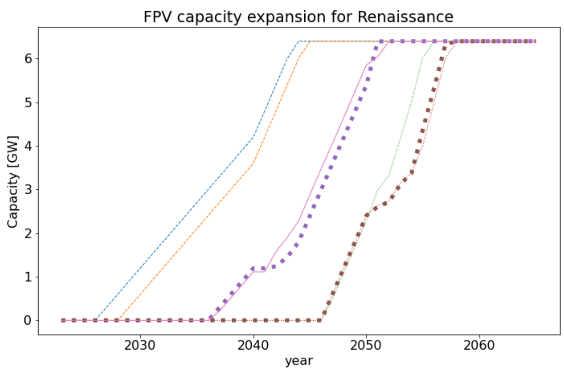
B.5 Effects of scenarios on FPV expansion at the best locations

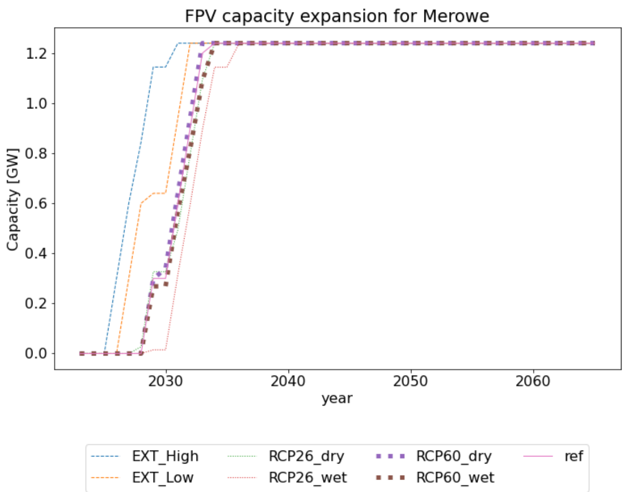
To understand the effect of the different scenarios on the implementation of floating solar power at the optimal locations (High Aswan Dam, Renaissance and Merowe), the cumulative capacity expansion was plotted. In Figure 47 we can see that these plants reach the maximum capacity under every scenario, proving to be suitable locations for the deployment of FPVs. In terms of scenarios, the taxation set cause the earliest capacity deployment at each location . The climate change sets, instead, sort no effects on the High Aswan Dam and little effects on the Merowe dam, with the only significant difference of RCP26 wet that delays the FPV deployment at this last location. The Renaissance Dam location, instead, is more influenced, with three climate change scenarios (RCP2.6 dry, RCP6.0 dry and wet) delaying the deployment of FPVs compared to the reference. This has to do with the fact that, as shown in Figure 16, these three scenario cause an increase in hydropower generation, hence postponing the necessity for floating solar power by almost ten years.

(a) Egypt



(b) Ethiopia





(c) Sudan

Figure 47: Cumulative capacity expansion for each location under different scenarios

B.6 Additional results for the evaporation reduction assessment

Reservoir area estimates

In Table 30, the estimates for the surface areas of each reservoir are reported, together with the method used to estimate them.

Plant name	Volume [MCM]	Capacity [MW]	Area [km2]	Area estimated from
Aswan1	5300	280	8.24	Literature
Aswan2	5300	270	8.24	Literature
HighAswanDam	162000	2100	6500.00	Literature
Finchaa	650	128	2.04	Literature
LakeTana-Beles	284000	460	3600.00	Literature
Tekeze1	9000	300	129.00	Literature
Amarti-Neshe	448	98	22.60	Literature
Renaissance	74000	6400	1874.00	Literature
Sennar	930	26	15.20	Literature
KashmElGirba	1300	10	125.00	Literature
Roseires	3000	270	233.00	Literature
JebelAulia	3500	19	1222.00	Literature
Merowe	12390	1240	476.00	Literature
UpperAtbara	2700	320	100.00	Literature
Baro		645	165.03	Capacity
Birbir		467	118.90	Capacity
ChemogaYeda	325	280	13.21	Volume
Geba	350	372	9.00	Literature
Genji		216	53.86	Capacity
LowerDedessa		550	140.41	Capacity
Tekeze2		380	96.36	Capacity
UpperDabus	2470	326	67.39	Volume
Karadobi	40200	1600	1020.55	Volume
BekoAbo	18	935	5.45	Volume
UpperMandaya	13	1700	5.32	Volume
AleltuEast	520	189	40.50	Literature
AleltuWest	619	265	20.63	Volume
LowerDabus	53	250	6.33	Volume
Tams	4800	1000	76.00	Literature
JubaBarrage		120	28.98	Capacity
Wau	2000	10.4	55.52	Volume
Kajbar		360	110.00	Literature
Shereik		420	106.72	Capacity
Dagash		312	78.73	Capacity
Dal		648	165.81	Capacity
Mograt		312	78.73	Capacity
Sabaloka	4000	205	106.05	Volume

Table 30: Area estimations for each reservoir

Detailed evaporation savings results

In Table 31, the FPV capacity, FPV area coverages, evaporation savings and extra hydropower electricity generation are presented for each single reservoirs, both in absolute values and in percentages.

Location	Evaporation [mcm/y]	FPV capacity [GW]	FPV coverage area [%]	Evaporation reduction [%]	Water savings [mcm/y]	Extra hp generation [PJ/y]	Extra hp generation [%]
Merowe	1625.79	12.40	2.61	4.85	78.84	0.11	0.40
Renaissance	879.84	64.00	3.42	6.33	55.73	0.01	0.07
HighAswanDam	7130.46	21.00	0.32	0.61	43.32	0.00	0.01
Dal	566.32	6.48	3.91	7.23	40.96	0.08	0.55
Shereik	364.51	4.20	3.94	7.28	26.54	0.06	0.56
Kajbar	375.71	3.60	3.27	6.07	22.82	0.04	0.46
UpperAtbara	341.55	3.20	3.20	5.94	20.29	0.03	1.31
Dagash	268.92	3.12	3.96	7.33	19.72	0.04	0.56
Mograt	268.92	3.12	3.96	7.33	19.72	0.04	1.07
Sabaloka	362.20	2.05	1.93	3.61	13.07	0.01	0.28
Roseires	795.82	2.70	0.38	0.72	5.75	0.00	0.03
Baro	77.48	6.45	3.91	7.23	5.60	0.00	0.02
Aswan1	9.04	2.80	33.98	54.37	4.91	0.02	0.29
Aswan2	9.04	2.70	32.77	52.76	4.77	0.02	0.28
LakeTana-Beles	1690.20	4.60	0.13	0.24	4.06	0.00	0.00
Tekeze2	45.24	3.80	3.94	7.30	3.30	0.00	0.01
Tekeze1	60.57	3.00	2.33	4.33	2.63	0.00	0.01
Sennar	51.92	0.26	1.71	3.20	1.66	0.00	0.39
JebelAulia	4173.77	0.19	0.02	0.03	1.22	0.00	0.00
Finchaa	0.96	1.28	62.75	84.10	0.81	0.00	0.15
KashmElGirba	426.94	0.10	0.08	0.15	0.64	0.00	0.01

Table 31: Water savings and extra hydropower generation for each location