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PAPER

Floating photovoltaics in the long-term energy planning of Easter Nile Basin countries: synergising water conservation, land use, and emissions

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Abstract

This manuscript presents a method for integrating floating photovoltaics (FPVs) into long-term energy planning, addressing rising electricity demands amidst water stress, land competition, and climate vulnerabilities. This integrated framework is applied to four Eastern Nile Basin countries, where renewable technologies are projected to dominate the power mix. Here, FPVs are evaluated for cost-effectiveness, water savings, and land efficiency. The study advances the OSeMOSYS energy planning framework by spatially explicitly modelling water savings and land values for various energy technologies, incorporating CO_2 emissions and land use costs in the optimisation. To this end, new methodologies for land-use accounting and FPV potential for reducing evaporation in hydropower reservoirs were developed. We then evaluate FPV potential across a network of hydropower plants, incorporating electricity trade links between basin countries and simulating under different CMIP six climate change scenarios and tax scenarios. Across all scenarios, results indicate that FPVs can cost-effectively provide up to 3% of the region's electricity generation by 2065, saving up to 376 million cubic meters of water annually. Scenarios introducing carbon and land-use taxes increase FPV's share in the power generation mix to 4.5% and enable earlier FPV deployment. While climate impacts minimally affect FPV's role, the technology slightly reduces CO2 emissions (0.4%) and land use (0.8%) in the baseline scenario without taxes. Compared to baseline scenario, a carbon tax alone reduces emissions by 11%–23% but raises land use by up to 8% due to increased renewable technologiesdeployment. On the other hand, land tax alone would reduce land use by 5%–8% with minimal impact on emissions. However, combining land and carbon taxes affects emissions (cuts up to 22%) and land use (a decrease of 1.6% or an increase of 1.2%). The study concludes that FPVs offer a promising solution for cost-effective and sustainable power expansion in the Eastern Nile Basin.

1. Introduction

1.1. Energy access, sustainability transitions and the role of floating solar

The coming decades are projected to bring sharp increases in energy demand, particularly in developing regions (IEA 2020) such as the Nile basin countries. At the same time, these countries currently face significant challenges, including low energy access levels (World Bank 2021), unreliable power infrastructure, and growing environmental concerns. To cope with these challenges, strategic, long-term energy planning frameworks that not only addresses immediate needs but also sustainable growth are critical. Such tools must then include environmental impacts, to advance the development of climate-robust and sustainable energy systems capable of meeting future demands.

According to IEA (2023), the energy sector is estimated to account for more than three-quarters of the total global greenhouse gas (GHG) emissions. To reduce this share, many countries have submitted and updated their Nationally Determined Contributions (NDCs), in which they clearly state their ambitions to cut the GHG emissions in the energy sector by presenting concrete strategies. To fulfill these ambitions, it is crucial to integrate emissions in the energy system planning processes.

Another relevant environmental footprint of energy systems is their land use intensity. In fact, recent studies (Kaza and Curtis 2014, Lovering *et al* 2022) have brought this topic to attention, 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. While many developing countries may have large areas of low-value land, such as deserts and shrublands, it is important to remember that energy production sites are often placed near urban areas or key infrastructure to minimise transmission and distribution costs. This proximity can create competition over land resources between energy generation and other sectors such as agriculture, a particularly pressing issue in developing countries where food scarcity often takes priority over energy access. Moreover, land use concerns are especially significant for the most promising renewable energy technologies—solar, wind, and hydropower—which are expected to play a major role in meeting rising energy demands and achieving carbon neutrality goals. For all these reasons, including land use footprints in the energy planning framework is crucial.

Energy systems can have a significant footprint in terms of water withdrawals and consumption; therefore system transitions should also assess the impacts on water resources (Kaandorp *et al* 2021). Mekonnen *et al* (2015) assessed the consumptive water footprint of energy and heat generation systems worldwide and found that energy systems account for 9%–22% of the total water consumption, depending on the world region. The study also highlights how hydropower causes the highest contribution, being accountable for 49% of the global water footprint. Given this and the ongoing climate change and water crisis, the inclusion of water footprints in the design of future energy systems cannot be neglected.

In order to meet their growing energy demands without increasing the above-mentioned pressures on the environment, energy investment can prioritise carbon-neutral, land-use-neutral and less water consumptive renewable energy sources. Among these, floating photovoltaics (FPVs) have raised the interest of researchers because of a range of benefits, such as the reduction of land use and evaporation rates through their deployment on water bodies (Gadzanku *et al* 2021).

In this study, we analyse the current state of the energy system in four Eastern Nile river basin (ENB) countries (Ethiopia, Sudan, South Sudan, and Egypt), explaining why the floating solar technology could be relevant for the sustainable expansion of these systems. Additionally, we introduce this technology in a long-term capacity expansion cost-optimisation model for the region's energy system. This methodology includes a novel approach to account for environmental footprints spatially explicitly and ways to endogenise environmental footprints in the optimisation. We also conduct the analysis of considered energy pathways under different scenarios of climate change and policy levers to explore various outcomes.

1.2. Study area

The Eastern Nile basin region is characterised by a strong connectivity via water resources as a result of a high spatio-temporal climate variability. The region is also projected to undergo rapid economic development and population growth in the next few decades (Nile Basin Initiative 2012). By 2040, the population is expected to surge to 400 million-an increase of 209% from 1990 levels (The World Bank 2020). This demographic shift is expected to be accompanied by a 22 fold increase in annual electricity demand, reaching 890 TWh (Eastern Africa Power Pool 2014, U.S. Energy Information Administration 2020). Even though energy consumption rates in the region have already increased significantly in the last two decades, they still are among the lowest in the world (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 consumers and so their demand is suppressed, and many of them do not even have access to the grid since it reaches only mostly urban users. In fact, while Egypt has achieved almost 100% electricity access for its population, Ethiopia, Sudan and South Sudan have much lower access levels at 51%, 55% and 7% respectively (World Bank 2021). Electricity production also varies considerably among the Nile Basin countries. According to recent data from IEA (2020), Egypt heavily relies on natural gas (83.9% of the power 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 electricity from hydropower and 40.6% from oil, and South Sudan production is dominated by oil (98%, IEA (2020)).

To meet their growing demands, these countries need to expand their energy portfolio, leveraging the abundant energy resources available in the Nile region. These include hydropower, natural gas, oil, geothermal energy, coal, peat, biomass (including biogas and waste-to-energy), solar, and wind (Nile Basin Initiative 2021). Among these, hydropower is favored by policy makers, due to its long economic lifespan and low levelised cost of energy. However, recent studies (Carlino *et al* 2023) have shown that not all of these proposed hydropower plants are cost-optimal for a climate resilient energy system expansion. Since water is an increasingly scarce resource in the region (mean annual runoff is estimated to be between 84 and 91 billion cubic meters (Nile Basin Initiative 2021)), and it is currently fully utilised, with the increasing demand being dominated by irrigation and evaporation losses from reservoirs (Nile Basin Initiative 2021). At the same time the ongoing climate change and environmental degradation are adversely impacting the long term water availability of the basin, endangering the energy security of hydropower dominated systems (Nile Basin Initiative 2021). Next to the competing water needs of hydropower plants, the decreasing costs of other renewable energy sources are changing the energy systems evolution projections. The global weighted average levelised cost of electricity of utility-scale solar PV plants declined by 90% between 2010 and 2023, with a year- on-year reduction of 12% in 2023 alone (IRENA 2024). In the same time period, onshore wind costs fell by 70%, and offshore wind by 63% (IRENA 2024). Eastern Africa, with its substantial solar and wind potential, stands to benefit significantly. According to IRENA (2021), the region's total potential for solar and wind is 9 TW, but in 2024 the installed solar capacity in the Eastern Nile basin countries was 2832 MW, and the installed wind capacity 2523 MW only (IRENA 2025). Expanding this potential would not only boost generation capacity but also reduce carbon emissions and lessen the energy system's reliance on water resources.

1.3. The potential for floating photovoltaics in the ENB

Emerging energy technologies, such as floating photovoltaics, can play an important role in achieving capacity expansion and sustainability goals. In the last two decades, some progress has been made in advancing and scaling up FPV technology. The first commercial FPV installation began in 2007 at a California winery with a capacity of only 175 kW. Since then, global FPV capacity has grown to 2.6 GWp by August 2020, with 73% of capacity in China and the remainder in Japan, Korea, and Europe (Sanchez *et al* 2021). The largest plants, each with a capacity of 150 MWp, are in China (World Bank 2019). FPV systems are now being integrated into hybrid setups with hydropower plants, although such systems are still nascent. The first hybrid project, a 220 kWp system, was installed in Portugal, with larger projects, such as the 45 MW floating solar installation at Thailand's Sirindhorn Dam, becoming operational in 2021 (Solomin *et al* 2021). In Africa, a hybrid hydro-solar project on the Bui reservoir in the Volta Basin aims for 250 MW of solar capacity, with 5 MWp of floating panels already operational and 50 MWp of on-land solar farm nearby. Smaller FPV plants are also running in Tunisia (200 kW), Kenya (69 kW), and South Africa (60 kW).

In the Eastern Nile Basin countries, the benefits of this technology look promising. These could include a reduction of evaporation losses from reservoirs, a reduction of land use from overall solar deployment, a cheaper grid integration and an improved power quality (Gadzanku *et al* 2021). 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. A more specific study on lake Nasser also showed potential water savings of up to 5.9 billion $m^3\ y^{-1}$, which could aid the irrigation schemes of this water-scarce area (Ilgen 2024).

Moreover, given the current underdevelopment of the region's electricity grid, another significant advantage of FPV system in this area is the possibility to use the already existing infrastructure of the hydropower plants to distribute on the grid the additional capacity generated by the floating panel arrays, without the need of expensive transmission infrastructures expansions (Cazzaniga *et al* 2019, Lee *et al* 2020). The combination of hydropower plants with FPVs could also stabilise the oscillating PV output (Silvério *et al* 2018), because hybrid systems can take advantage of the complementary nature of solar and hydropower generation patterns (Lee *et al* 2020). Finally, a recent study from Arnold *et al* (2024) showed promising results for a similar African river system, finding that the same capital investment earmarked for planned dams in the Zambezi watercourse could be used more efficiently by building fewer reservoirs and substituting the energy supply with FPV.

2. Methodology

2.1. Model selection for long-term energy planning

Among the various energy modelling frameworks available for Africa (Musonye *et al* (2020)), OSeMOSYS-TEMBA 2.1 was selected for this study due to its convenience as a fully open-source tool, equipped with multiple open data sets useful to model the African energy system (Pappis *et al* 2022). OSeMOSYS solves the capacity expansion problem by minimising the cost of operating and expanding the energy system. To do so, it takes as input the projected electricity demand, the existing and planned generation technologies and the techno-economic parameters related to them. After calculating the least cost solution, it outputs the projected capacity mixes, the energy supply and consumption mixes and the related carbon emissions. OSeMOSYS-TEMBA 2.1, the most recent version of this tool available for Africa, contains the necessary data to describe the African energy system at a single country resolution. In order to adapt it to the purposes of this study, the countries outside of the Eastern Nile Basin were removed, and some parameters relative to electricity trade links and costs of renewable technologies were updated. Apart from adding FPV as a new technology, we also introduce spatial explicitness for some technologies. We provide the OSeMOSYS framework and detailed information on parameter choices and assumptions in the *supplementary material.*

2.2. Modelling the FPV technology

The floating solar power technology (FPV) was not part of the TEMBA 2.1 dataset, and was therefore introduced by the current study as a new technology. To avoid a misrepresentation of the technology that could lead to unrealistic results, important temporal and spatial considerations had to be made. Regarding the first, when modelling solar generation technology, it is crucial to ensure the correct representation of generation profiles in terms of diurnal and inter-annual availabilities. To do so, we carefully chose a time slice structure that allows balance between computational tractability and accurate representation of generation patterns. This structure is composed of eight representative time slices: two day parts (D1: h 9–18 and D2: h 18–9) for four seasons of three months (S1: March–May, S2: June–August, S3: September–November, S4: December–February). Since the split between day and night slices does not coincide with sunset and sunrise, night slices can contain hours with sunlight. Therefore, the night time capacity factors of solar generation in figure 10 of the supplementary material is not exactly zero but slightly above. Moreover these capacity factors are derived from actual solar irradiance data for the region (please refer to the supplementary material document for more details). While higher temporal resolution could be desirable when modelling renewable energy technologies, previous studies using OSeMOSYS (Carlino *et al* 2023, Arnold *et al* 2024) have demonstrated that our chosen temporal resolution is sufficient for long-term planning purposes.

Regarding the spatial resolution, the model we adopted aggregates the generation technology at the country level (Pappis *et al* 2022). Even though we kept this approach for most of the generation technologies, we chose to increase the spatial resolution of hydropower to the single-plant resolution. Given that the feasible locations for FPV plants in the study region are mostly hydropower reservoirs, representing these directly in the energy model allows to model the FPV technology at the single plant resolution as well, enhancing the reliability of the results and adding important insights for the development of FPVs in the region. To achieve this, a list of the existing and planned reservoirs in the ENB countries was compiled from the RePP database (Peters *et al* 2023) and merged with the African Hydropower Atlas (Sterl *et al* 2021). This list also includes the capacity factors needed to model each reservoir inside OSeMOSYS (see the supplementary materials for more details). On top of this, FPV technologies were created with *site-specific* parameters and constraints for each reservoir location (more details are in the supplementary materials).

2.3. Assessing evaporation reductions

In the introduction, we highlight how floating solar panels could theoretically play a role in reducing evaporation from water reservoirs. Although estimating evaporation is generally quite complicated, this study reviews existing methods and calculates the magnitude of water saved by the installation of FPVs with a simplified procedure. First, the maximum optimal FPV capacity (GW) for each reservoir obtained from the OSeMOSYS simulations was converted to water surface area coverage (km^2) using a conversion factor. By dividing the total coverage area by available surface of each reservoir, we then obtain the reservoir area coverage percentage. This fraction of covered area is then linked to evaporation reduction percentages using relations developed in Scavo *et al* (2021) and used by Sanchez *et al* (2021) for a similar study. Finally, data on each reservoir's yearly evaporation rates were gathered from Sanchez *et al* (2020) and multiplied by the evaporation reduction percentages to obtain the yearly water savings. More details and assumptions behind this procedure are reported in the sections A.1.5 and A.1.6 of the supplementary material.

2.4. Endogenising land use costs in long-term system optimisation

In the context of integrated water-energy-food systems, a crucial role is played by land resources. For this reason, endogenising land use in the long term energy planning analyses can shed more light on the impact that each technology has on land use. Here, we propose a new methodology to integrate the land component into the OSeMOSYS modelling framework. Since this framework is based on a cost-optimisation of the energy expansion pathways, an effective way to integrate land use is by assigning an economic value to the land footprint of energy pathways. However, pricing land is particularly challenging, especially in a region as

Table 1. Land use intensity per electricity production technology and unit of energy (Lovering *et al* 2022).

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

[a] For these technologies, land use footprint mainly comes from the mining of fossil fuels.

vast and diverse as the Eastern Nile Basin. In order to get an idea of the value of land typically used for power plants in the region, a spatial dataset of existing and planned power plants was compiled from data portals of the European Commission's (EU Joint Research Center 2022) and the World Resources Institute (2021). A map of the resulting merged dataset can be seen in figure 31 of the supplementary material. Based on these locations, the economic value of land was assumed to correspond to the value of crops that could be cultivated if the land were used for farming instead of energy production. This approach effectively links land value to its opportunity cost in the alternative use, here mostly agricultural production. Then, the actual agricultural yields from the GAEZ data portal of the FAO (FAO 2021) were used as a proxy for the value of land at each power plant location. It has to be noticed that at the locations of the coal plants present in the JRC and WRI datasets, no data of land value was available from the FAO GAEZ dataset. Therefore, the land value for coal plants was assumed to be the same as the value for oil power plants.

The next critical step was to assign a land use rate to each power technology, measured as the land area required to generate a unit of energy. For this purpose, the land use intensities of electricity production (LUIE) calculated by Lovering *et al* (2022) were adopted (table 1). Since the dataset lacked values for oil power plants, the land use intensity of this technology was assumed to be the same as the one of gas power plants. Since the land footprint of fossil fuel technologies primarily arises from fuel extraction, this footprint was attributed only to local production technologies. That is, in simulations, fossil fuel technologies were considered to have a land use impact only when using locally sourced fuel. The assumptions behind fossil fuels reserves and import/export rates of the region were available in the original TEMBA 2.1 dataset and used here. Our approach enables the incorporation of land use considerations into energy planning, and will be used to provide insights into the trade-offs between energy system impacts on emissions, water and land resources.

2.5. Assessing FPV integration under climate and policy scenarios

In the evolution of an energy system, many factors that are external to the cost-optimisation process 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. In this study, the capacity expansion of the region is optimised from the present (2023) to 2065 (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. Three types of external factors are taken into account: (i) the introduction of a new technology (FPVs), (ii) climate change impacts, and (iii) the introduction of taxation policies on the energy system's environmental footprints. 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-optimisation process itself, but it still lies within the energy planning framework as it can affect costs and resource constraints. Climate change impact, instead, is something that is external to this framework, and does not depend on the energy authority's decisions (i.e. we make the small country assumption that ENB energy system change does not affect the climate).

2.5.1. The reference scenario and introduction of floating solar

The reference simulation scenario (REF) is developed starting with the OSeMOSYS-TEMBA (Pappis *et al* 2022) model for Ethiopia, Sudan, and Egypt includes demand projections, existing infrastructure, fuel prices, technology costs, and current national energy policies, without significant changes. It also considers cross-border electricity trade based on existing interconnected grid systems in 2020, and plans into the future. As detailed in the appendix A of the supplementary material document, we have adapted the original

OSeMOSYS dataset to include updated data on electricity trade links, renewable technology costs and planned nuclear power plants. As such, the reference case analyses cost optimal capacity expansion under the business as usual scenario. In this model, floating solar power is not present among the possible technologies, and no taxation policies on land and carbon are included.

Our first new scenario set for simulation (REF_FPV), assesses the effect of the implementing floating solar power on the energy mix evolution. To do so, floating solar power is characterised and added to the list of possible technologies for the cost optimisation problem in OSeMOSYS, while all the other assumptions are the same as in the reference set. In this way, the effects of the introduction of FPVs can be assessed comparing the model results of the REF_FPV simulation with those of the REF simulation.

2.5.2. Incorporating climate change impacts

The second simulation set is aimed at understanding how the role of FPVs on the energy system's expansion changes under the influence of climate change. This analysis is also crucial in order to make sure that the electrification plans are reliable in the long term. Climate change can impact energy systems in many ways, for example by altering natural renewable resources availability profiles (water, wind and solar radiation) and energy demand patterns for cooling and heating (Seljom *et al* 2011). Modelling all of these dynamics explicitly falls outside the scope of this work, but less time-consuming strategies are possible. Carlino *et al* (2023) conducted a study 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). The latter 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 (here we consider the combinations SSP1-RCP2.6 and SSP4-RCP6.0). Each of these combinations also provides the capacity factor values for the lower and higher uncertainty ranges of the flows, named the 'dry' and 'wet' cases, corresponding to the 5th and 95th percentile of average annual flow respectively. Following this scheme, four scenarios were obtained: the two flow uncertainty estimates (dry and wet) for each of the two SSP-RCP combinations. Finally, since the capacity factors were calculated by Sterl *et al* (2021) at a monthly resolution, they had to be aggregated for the purposes of this study to the same resolution used in the OSeMOSYS model (seasonal). The average of the three months composing every season was used as aggregation method.

2.6. Incorporating the impacts of potential land use and emissions taxes

Carbon pricing mechanisms, as a strategy to mitigate greenhouse gas emissions, can affect the development of energy systems. Although no such mechanisms are currently in place in the ENB, the potential introduction of these schemes in the future is plausible, driven by global trends and potential national policy changes (World Bank 2024b). For example, incorporating carbon pricing scenarios into energy planning can help ENB countries to enhance their resilience to potential CO_2 price increases and align with emission reduction targets in their NDCs (Njenga and Phiri 2022). In addition, carbon pricing can incentivise the adoption of renewable energy sources, such as wind and solar, which are typically exempt from such taxes. Assessing the impact of carbon pricing on technologies like FPVs can therefore support informed policy-making.

In this study, we use 'carbon tax' scenarios as a proxy for various mechanisms that may influence greenhouse gas emissions from the power sector. While the ENB countries currently lack explicit carbon pricing policies, this approach captures several potential drivers of emission costs that could emerge in the planning horizon, in addition to business-as-usual scenarios. Such an approach helps understand both immediate practical options and longer-term strategic possibilities as global climate policies evolve. In effect, the 'carbon tax' parameter in our energy system model represents any policy instrument that would internalise emission costs in electricity planning decisions. Emissions trading systems (ETSs) allowances can create various levels of incentives for the power sector to reduce emissions, for example by investing in less carbon-intensive power supply, reducing electricity demand or changing the merit order of electricity dispatch in favour of low-carbon power supply (Re *et al* 2020). Additionally, achieving NDC commitments may require policy instruments that effectively price emissions—all ENB countries have submitted NDCs with emission reduction targets, yet current policies are insufficient to meet these goals. Therefore, a carbon tax proxy includes not only direct carbon taxes or ETS, but also regulatory standards, renewable energy mandates, or technology-specific policies that create implicit carbon prices by affecting the relative costs of different generation technologies. In power system planning models such as OSeMOSYS, both explicit carbon pricing (taxes or ETS) and implicit pricing (through regulations or standards) can be represented as a USD/tCO_2 cost applied to emissions, creating similar effects in dispatch and investment decisions by increasing fossil fuel generation costs proportionally to their carbon content.

Secondly, indirect carbon pricing may arise through international trade mechanisms. The EU's carbon border adjustment mechanism (CBAM) is already in effect and will impose tariffs on carbon-intensive imports from exporting countries with less stringent climate regulations to prevent carbon leakage. CBAM currently targets specific industrial products like cement, steel, aluminum, fertilisers, and hydrogen, and explicitly includes electricity, with potential expansion to additional sectors (Zhong and Pei 2023). For Egypt, World Bank projections (World Bank 2024a) indicate that while aggregated CBAM impacts may be relatively small (0.6% decline in real income by 2030), the power sector faces disproportionate effects. The gas power industry could experience an estimated 15% output reduction (USD 52 billion), while electricity transmission may see a 5% output reduction (USD 22 billion) and 8.3% export losses (World Bank 2024a). These sector-specific impacts underscore why carbon considerations in electricity planning are crucial—even without domestic carbon pricing, the carbon intensity of power systems directly affects economic competitiveness. While the ENB region's current export profile to the EU may not be electricity-intensive, limiting immediate CBAM impacts, the mechanism becomes increasingly more important as African countries pursue industrialisation strategies. For ENB countries seeking to develop their manufacturing sectors and expand regional electricity trade, the carbon intensity of their power systems will in future directly impact industrial competitiveness. This creates incentives to consider reducing electricity sector emissions from future energy systems in long-term planning, even when domestic carbon pricing mechanisms do not yet exist.

The last set of simulations, therefore, deal with the introduction of 'taxes' aimed at endogenising the energy systems' land and carbon footprints in the cost-optimisation process. Most of the energy technologies impact the environment, for example in terms of carbon dioxide emissions and land use. In the reference scenario, these negative environmental effects of the power generation technologies were not taken into account in their cost parameters. In the introduction it was highlighted why it is important to include specifically these two footprints in the planning of energy systems, both for their global climate mitigation and regional effects. Floating solar power can help reduce these footprints significantly, since it does not produce emissions while operating and does not require land resources (being installed on existing water bodies). Taking these footprints into account could then increase the competitiveness of floating solar technologies in the cost-optimisation process of OSeMOSYS.

Two scenarios were hence developed by introducing taxes on both carbon emissions and land use: the 'TAX_Low' scenario, which implies a relatively mild taxation of both footprints starting with a small value and a gentle yearly increase; and the 'TAX_High' scenario, which imposes a higher value and a steeper annual increases. 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\$/tCO_2 in 2023, rising up to 140\$/tCO_2 in 2030 and 200\$/tCO_2 in 2050. These three values were then linearly interpolated (and extrapolated) to cover the whole modelling period (2015 to 2070). The scenario we label 'TAX_Low' is based on 'scenario I' of Caron *et al* (2018), a study that explores various carbon pricing models. In this scenario, the carbon tax starts at USD 25\$/tCO_2, growing slowly at 1% annually. We note that the low value considered here is a fraction of the current EU ETS price (i.e. circa 73 USD/tCO_2e on June 6, 2025 [1].) and so could be considered as the much less ambitious scenario for the ENB's alignment with the EU's commitment to climate policy leadership.

Finally, the land pricing methodology presented in section 2.4 was integrated in the model by assigning a different land tax for each technology type. Due to the large uncertainty in land-use intensity for the technologies, the values adopted for the 'TAX_Low' and'TAX_High' scenarios were (arbitrarily) taken as the 25th and 75th percentile of the surrogate land value respectively. Moreover, differently from the carbon tax, the land use tax was assumed to be constant over the whole modelling horizon.

3. Results and discussion

3.1. Determining land use pricing

Following the methodology described in section 2.4, a map of aggregated crop production value for the study area was obtained (figure 1). This map was used to sample the land value at each power plant location and these values were then aggregated into the main power technologies categories. As can be seen from the map in figure 1, 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

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[1] https://tradingeconomics.com/commodity/carbon

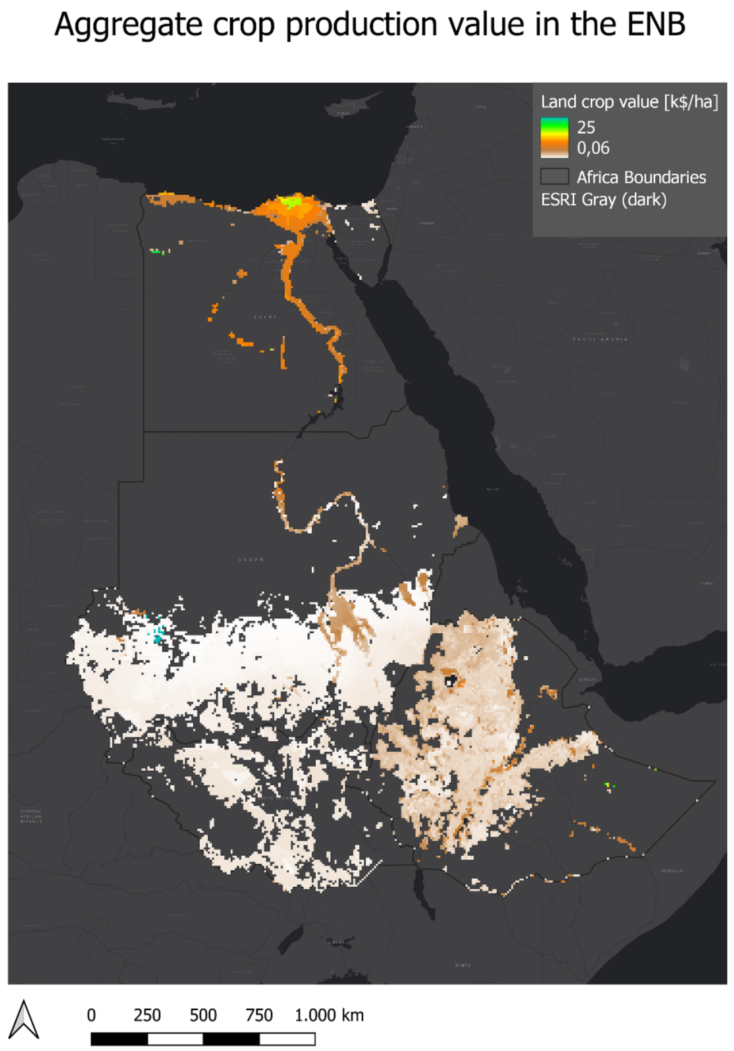
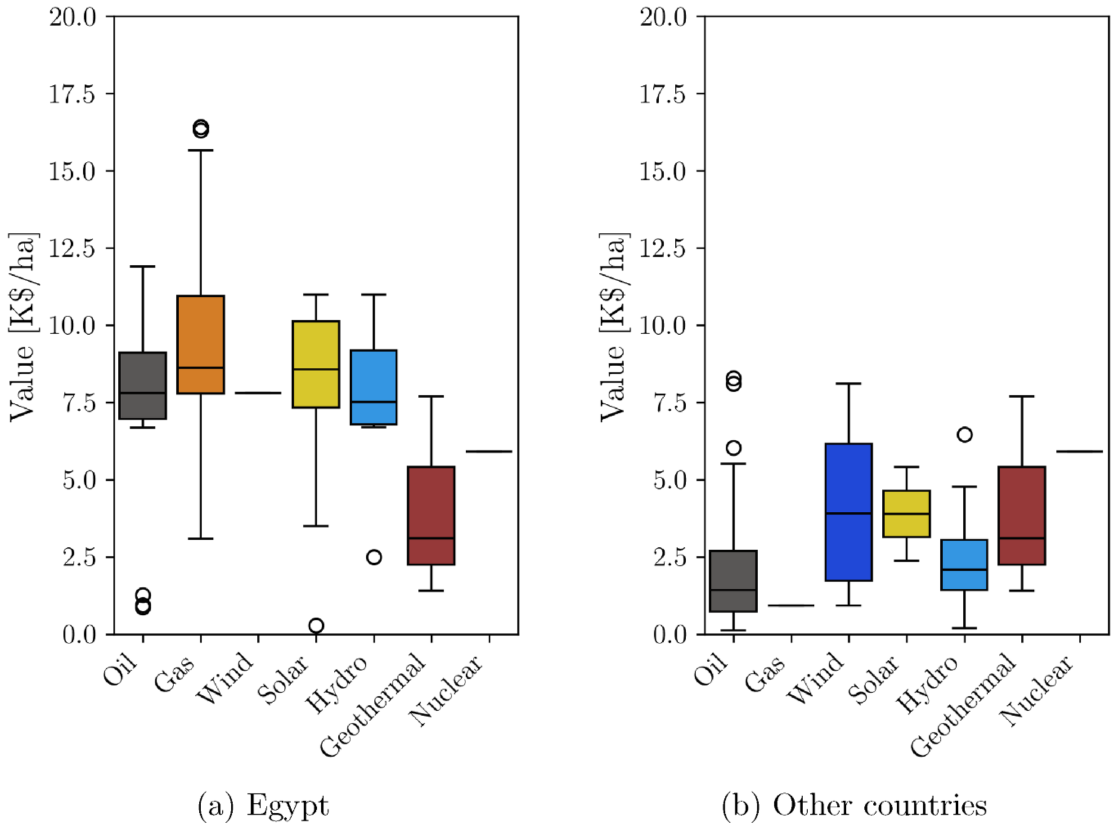


Figure 1. Spatially explicit estimates of aggregate crop production values per hectare, derived from agricultural yield data.

variability of land value, it was decided to disaggregate it in two different regions, one composed by Egypt and the other one by the other three countries. Still, the data had some gaps to be filled after the disaggregation. In fact, there were no data available of geothermal power plants in Egypt nor nuclear power plants in the other three countries. Thus, the geothermal values for Egypt were assumed to be the same as for the other three countries, and vice versa for the nuclear values. In figure 2 the statistical properties of the land values for each power generation category and for each area are reported. Here, 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.

3.2. Energy system expansion in the reference scenario

To give the reader an idea of the optimal expansion pathway found by OSeMOSYS in the reference scenario, we report its evolution in figure 3. The yearly energy generation mix (in PJ y^{-1}) over the modelling horizon is depicted in the bar chart. We chose to display generation rather than capacity to show how different generation technology are actually utilised in the simulations. Capacity plots would give information about the optimal deployment schedule of the infrastructures, but not about their actual simulated generation, which we believe to be more insightful for the purposes of this study. As it can be seen from the figure, in this scenario the largest share of the mix is 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 optimisation. Furthermore, the role of hydropower generation in the basin remains mostly constant apart from a slight decrease in the long term. 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



(a) Egypt (b) Other countries

Figure 2. Land value estimates for different power generation technologies per TWh.

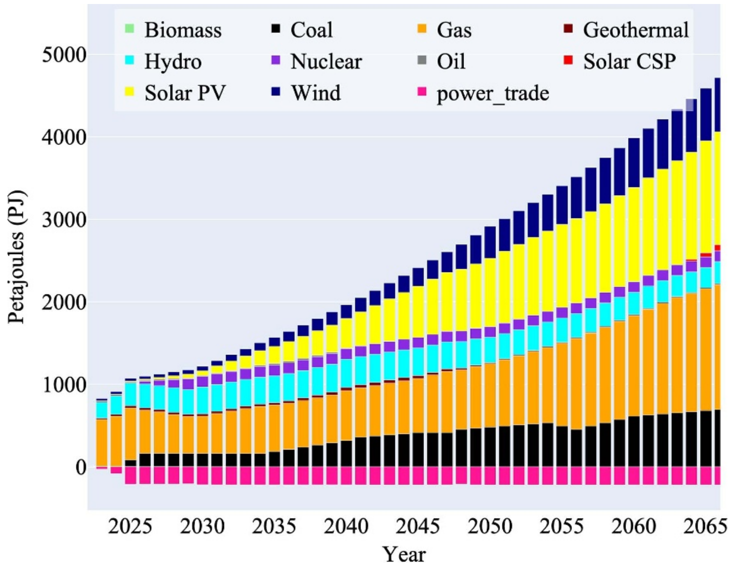


Figure 3. Generation mix pathways of the whole region for the reference scenario.

negative pink bars in the bar chart. This is mainly composed by exports from Egypt to Saudi Arabia and from Ethiopia to Kenya (more details in the supplementary material). 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^{-1}, Ethiopia and Sudan follow with 900 PJ y^{-1} and 650 PJ y^{-1} respectively, while South Sudan only reaches 70 PJ y^{-1}. Capacity expansion graphs of the single countries are also reported in the supplementary material.

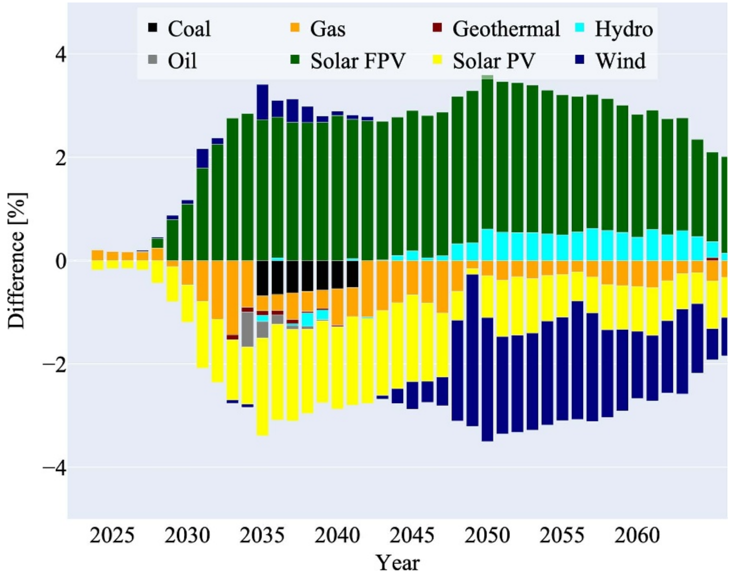


Figure 4. Percentage difference between yearly generation (PJ) between the reference and FPV scenarios.

3.3. Analyzing the impact of FPVs on the power mix

One effect of introducing floating solar power in the energy system is the change in the power mix; figure 4 depicts the difference between the generation mix (PJ) of the REF scenario and the REF_FPV scenario. The positive bars represent the generation that is added in the scenario with FPVs, and the negative bars represent the generation that is substituted for. In this way, it is easy to visualise what the floating solar panel technologies replace in terms of generation. In fact, displaying the total generation as done in figure 3 would make it hard to visually distinguish the changes in the mix since these are relatively small (up to 4% of the mix, as seen in figure 4). Hence, as is done in some literature, we display the differential generation, calculated for each year (y) as the percentage difference ($\text{GenDiff}_{\%}$) between the generation in REF scenario (Gen_{REF} in PJ) and the generation in the REF_FPV scenario ($\text{Gen}_{\text{REF\_FPV}}$ in PJ):

$$\text{GenDiff}_{\%}\left(y\right) = \frac{\text{Gen}_{\text{REF\_FPV}}\left(y\right) - \text{Gen}_{\text{REF}}\left(y\right)}{\text{Gen}_{\text{REF}}\left(y\right)} * 100. \tag{1}$$

The introduction of floating solar power among the energy technologies results in some relevant changes in the generation mix already from the late 2020 s, providing up to 3% of the generated electricity once the full capacity (15GW) is developed. FPVs mainly substitute other renewable technologies (wind and solar), but also gas and coal generation. These substitutions are driven by the model parameters reflecting that floating solar is cheaper than wind power, has slightly higher capacity factors than utility-scale solar on land and becomes cheaper than gas by the 2030 s. It is also interesting to see how the introduction of FPVs causes a small increase in hydropower generation; the combination of floating solar power and hydropower proves more cost-optimal than the pairing of solar and wind. This is in line with the fact that the capacity factors of floating solar power and hydropower have a certain complementarity between time slices and the combined energy generation of these two technologies is more cost efficient than, for example, 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 hybridising solar and hydropower plants, and has been found by other studies as well (Cazzaniga *et al* 2019, Lee *et al* 2020). 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 (see also section B.10 of the supplementary material).

3.4. Changes of FPV relevance across different scenarios

The second point of focus of this work was to analyse how the role of floating solar power in the energy system changes under different climate and policy scenarios. In order to quantify this role we analyse (I) the maximum FPV percentage in the electricity generation mix, and (II) the FPV capacity expansion pathways. The maximum electricity generation shares of FPVs across scenarios, useful to understand the contribution of the FPV technology in satisfying the total energy demand, are: 4.46% for TAX_High, 3.80% for TAX_Low, 2.98% for REF_FPV, 2.91% for RCP60_dry, 2.82% for RCP60_wet, 2.80% for RCP26_dry, and 2.78% for

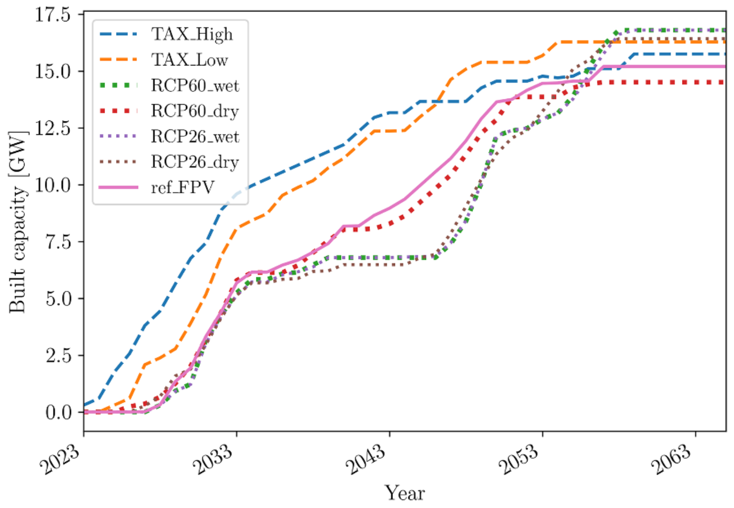


Figure 5. Floating photovoltaic (FPV) capacity expansion across scenarios.

RCP26_wet. We also produced differential plots equivalent to the one reported in figure 4 for each scenario, both for the whole region and at the single country level. These are included and analysed in sections B2–B4 of the supplementary material. The capacity expansion pathways followed by FPVs, instead, can give insight into when the optimal expansion of this technology happens; figure 5 shows the pathways and the maximum total capacity reached in each scenario. This information can give a better idea about how necessary the technology is for the mix: the higher the utilised potential and the earlier its development, the more cost-optimal the technology is in the near future. In figure 5 it can be noticed that the capacity expansion reaches a saturation point around 2055. This is a direct result of the maximum capacity constraints we implemented in the model for FPV technologies (as described in section A.1.5 of supplementary material). These constraints are necessary in order to take into account realistic limitations in the technology development, such as technical feasibility of reservoir coverage, or lack of local technical expertise, supply chains in the region to rapidly grow the total capacity. Without a constraint on the maximum installable FPV capacity, the economic optimisation could lead to unrealistic technology development, as shown in the second sensitivity analysis reported in section B7 of the supplementary material (figure 30).

Climate change scenarios

Climate change scenarios have a minimal impact on the maximum generation shares of floating photovoltaic technologies (deviations from REF_FPV scenario are around $\pm 0.02\%$). In other words, FPV contribution to the power mix remains relatively consistent across all the analysed climate change projections. However, considering the capacity expansion in figure 5, the results show more interesting dynamics. In particular, since these scenarios alter the capacity factor of hydropower plants and thus their development, the results allow us to observe the dynamics linking hydropower and FPVs in two ways. First, increases in hydropower capacity factors slow down the development of FPVs in the medium-term. Second, this increased capacity enables marginally higher FPV capacity in the long term. This happens because, with higher capacity factors, hydropower becomes more cost-optimal and the model increases its generation and capacity expansion. The increase in generation reduces the need for floating solar panels development in the medium term, while the increase in capacity creates more reservoirs, allowing for more FPV capacity development in the long term. This behavior is clearly visible in the scenarios where the capacity factors of hydropower increase (RCP2.6_wet, RCP6.0_wet and RCP2.6_dry): FPVs development is slowed down in the mid-term, but reaches higher built capacity at the end of the simulation compared to the REF_FPV scenario. In the RCP6.0_dry scenario, instead, the FPV development is similar to the REF_FPV scenario, but reaches a slightly lower final capacity due to decreased hydropower expansion. It is important to note that these dynamics, while observable, have a relatively small quantitative impact on the regional power system overall. Floating solar accounts for only up to 3% of the power mix in these scenarios. Therefore, while the role of FPVs in the energy mix and associated planning decisions may vary depending on hydropower development under different climate change scenarios, such variations have an almost negligible effect on the overall evolution of the whole energy system. Additional information on the hydropower expansion, total FPV potentials and capacity factors differences between scenarios can be found in the supplementary material.

Table 2. Yearly values relative to evaporation reduction analysis in the REF_FPV scenario.

	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 (M m^3 y^{-1})	19 536	7 149	2 765	9 622
Water savings (M m^3 y^{-1})	376	53	72	251
Evaporation reduction (%)	1.93	0.74	2.61	2.61

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 an increase in maximum generation shares from floating solar panel technologies, with the high taxes scenario showing the highest values: up to 4.46% in the aggregate regional power system (up to 2% in Egypt, 9% in Ethiopia and 19% in Sudan). Moreover, 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 optimisation, floating solar power becomes even more competitive early and tends to be cost optimal to develop a larger capacity at an earlier stage. The reason is quite straightforward: FPVs do not emit CO_2 nor consume land, hence they become more competitive that technologies with such footprints once taxes are included. In particular, results show how floating solar replace traditional solar and coal as a result of the introduction of the taxes (additional figures are reported in the supplementary material). 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.

3.5. The role of floating solar power in reducing environmental 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 4, 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 by 0.37% (66 MT CO_2) the total system emissions (cumulative over the whole modelling horizon) compared to the reference scenario without solar panels (REF). Secondly, in terms of land use reduction, the effect has a similar magnitude, with a reduction of 0.78% (154'756 ha) of the total land use as a result of deploying FPVs. This mainly comes from the substitution of ground mounted solar PVs, which is the technology with the highest land use intensity. These small percentage numbers have to be seen taking into consideration that the optimal FPV generation share is 3%. Besides, 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 154'756 ha 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 (table 2). These values correspond to maximum total water savings of 376 M m^3 y^{-1}, of which 251 M m^3 y^{-1} in Sudan, which can be a very valuable results for non-energy related uses. In fact, such saved amounts of water could be very valuable for other purposes (e.g. irrigation, drinking water supply, environmental flows). Similarly to what explained for land, the value of these saved amounts of water depends on the local surroundings of each reservoirs, and on the seasonal variation of water availabilities. However, in the very arid climate of the study area every saved amount of water is relevant. 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). Moreover, a recent study for lake Nasser (Ilgen 2024) found that the use of FPV water savings for irrigation appears to be most efficient. They also found the mean specific water saving of the FPV system to be 7.67 m^3 y^{-1} kWp^{-1}. This factor, applied to the installed capacity found by our study (2.65 GW), yields annual evaporation savings of around 20 M m^3 y^{-1}, which are in the same order of magnitude of what found by our much simpler model (53 M m^3 y^{-1}).

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. The magnitudes of these reductions are very slight in the case of carbon emissions and more relevant in the case of land use and water

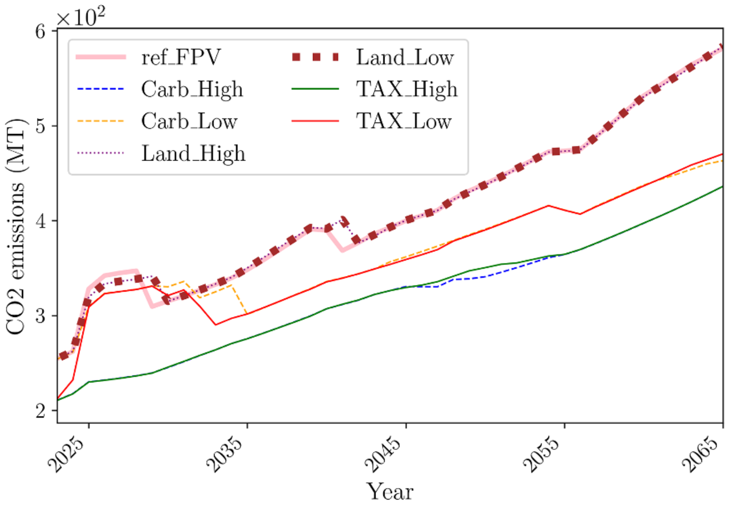


Figure 6. Evolution of annual CO_2 emissions under different tax scenarios for the whole ENB region; land tax on its own has negligible impact on emissions while inclusion of a high carbon tax has highest impact both in the single and combined tax cases.

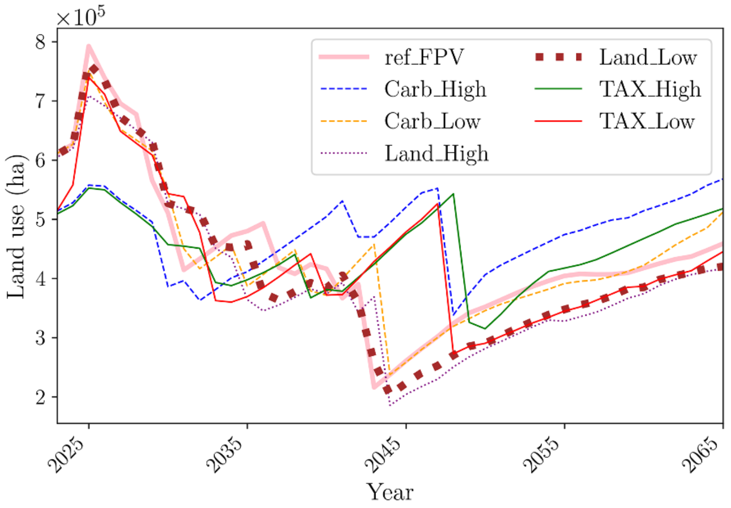


Figure 7. Evolution of annual land use intensities of the electricity system pathways in the single and combined tax cases.

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.

3.6. Decoupling the role of emission and land use taxes

In order to develop useful 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 the two to be applied by different mechanisms. In fact, there can be indirect effects on the environmental footprints that are harder to see when applying both penalties at the same time.

To analyse such dynamics, other four simulations were developed, applying either the carbon or the land tax in both their high and low versions (Land_low, Land_high, Carb_low, Carb_high). The results of this analysis were compared with the scenarios where both taxes are applied. The annual footprint evolution is reported in figures 6 and 7. In these plots, sharp discontinuities in the evolution of both CO_2 emission and land use can be noticed. Concerning the first, these are due to changes in the shares of carbon emitting technologies in the generation mix (coal and gas), visible in figure 3 and figures 22,24 of the supplementary material. Another reason behind sharp changes in the carbon emission profiles are shifts in fuel supply schemes, as shown in figure 34 of the supplementary material. The sharp changes in land use are also explainable with a similar reasoning. In fact, they are due to the increase of land-intensive renewable energies (solar PV, solar concentrated solar power (CSP) and wind) in the mix and shifts in gas supply. More details and a plot of land use by generation technology can be found in section B.9 of the supplementary material.

Table 3. Changes in CO_2 emissions and land use for each tax scenario.

Scenario	CO_2 emissions change (%)	Land use change (%)
Carb_low	−11.0	+0.3
Carb_high	−22.6	+8
Land_low	0.2	−5.4
Land_high	0.2	−7.9
TAX_low	−12.2	−1.6
TAX_high	−22.4	+1.2

In table 3, the cumulative CO_2 emissions and land use changes are reported as percentage difference between each scenario and the REF_FPV scenario ($\Delta_{(sc-ref)/ref}[\%]$). From table 3, we note that the land tax does not contribute to the reduction of CO_2 emissions, both in the high and low tax on land use scenarios. These reductions are then fully attributable to the carbon tax, as it can also be seen by the negligible difference in CO_2 emissions reduction between the Carb_High and Tax_High cases. This low correlation between land use tax and CO_2 emissions comes from the fact that high carbon-emitting technologies have a smaller land footprint in the region than clean technologies such as solar. This causes higher penalties and thus cuts in solar generation and does not affect fossil fuel generation (effects on the generation mix of scenarios where only land taxes are applied can be seen in section B5 of the supplementary material). This dynamic could be different in other regions, for example where fossil fuels are extracted in areas with a higher land value or where, for example, offshore wind is a low cost significant alternative in the power mix. In such regions, introducing a tax on land use might also be an effective lever of decarbonisation as in it would render extracting fossil fuels less competitive, with consequent reductions of CO_2 emissions. As far as land use is concerned, the results show that the carbon tax causes an increase in land use, especially significant in the Carb_High scenario. This comes from the fact that applying a high penalty on emissions drives an increase in land use intensive technologies, namely wind and solar power plants. This dynamic is much less relevant if the carbon tax is applied in its lower form: the increase in land use in this case is less than 1%. When both taxes are applied at their higher rates (TAX_High scenario), cumulative CO_2 emissions decrease significantly by 22%, while land use experiences a slight increase of 1.2%. In contrast, when the taxes are set at lower rates (TAX_Low scenario), CO_2 emissions still decline, but by a lesser extent of 12.2%, and land use is also reduced by 1.6%. These contrasting dynamics can be attributed to the impact of the carbon tax on gas generation. In the high tax scenario, the carbon tax heavily penalises gas generation, leading to its replacement by CSP, which has a higher land use intensity. Conversely, in the low taxation scenario, CSP does not enter the energy mix, preventing any increase in land use. Additional figures and discussions are included in Sections B.5 and B.10 of the supplementary material document.

3.7. Identifying optimal locations for FPV deployment

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 at which point in time, in order to invest economic resources in the most effective way. Our results show that the locations developing the most capacity are the High Aswan Dam (Lake Nasser) for Egypt with 2.1 GW, the Renaissance Dam for Ethiopia (6.4GW) and the Merowe Dam for Sudan (1.2 GW). This has to do with the fact that the largest hydropower reservoirs in each country are located in these sites, which have therefore the highest potential for floating solar power. In fact, OSeMOSYS chooses the technologies to implement based on costs per kW (which are the same for every potential FPV site), capacity constraints and capacity factors. Between these last two parameters, the one that varies most between locations is the capacity constraint, which depends directly on the reservoir surface area and then influences the choice of location the most.

Another important variable to take into account regarding the choice of FPV sites is the amount of water saved from evaporation. Our analysis finds that 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 M m^3 y^{-1}, 55 M m^3 y^{-1} and 79 M m^3 y^{-1} 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 M m^3 y^{-1} for Lake Nasser, 880 M m^3 y^{-1} for Renaissance and 1625 M m^3 y^{-1} for Merowe), the total water savings are the highest in the basin. Therefore, in the scope of a large scale and long term frame, it is suggested to prioritise 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 power and managing framework 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 considering the inter-annual hydrological seasonality: evaporation reductions might be even more valuable in dry months.

4. Conclusions

The Eastern Nile Basin region, including the countries Egypt, Ethiopia, Sudan, South Sudan, is affected by insufficient energy systems and stressed water resources. The projected demographic and socio-economic trends will drive a sharp increase in the demand for energy and water, making these sectors even more critical. Looking at these dynamics through the lens of climate change, it becomes imperative for the countries to strategically plan ensuring a sustainable evolution of the energy systems in economic, social and environmental terms. In this context, the integration of FPVs in long-term energy planning can provide multiple co-benefits over land-based photovoltaics, including the hybridisation between solar and hydropower resources in dispatch, lower capital costs through exploitation of existing hydropower dam infrastructure and the reduction of water evaporation rates.

In this study, we analysed the integration of floating solar panels in the long term energy expansion pathways of the Eastern Nile basin, taking into account the environmental pressures of the energy system by quantifying carbon emissions and water savings, and introducing a methodology to account for land use intensities in planning. Finally, we create cost-optimal pathways under different climate change and policy decision scenarios, specifically introducing taxes on carbon emissions and land use.

The results indicate floating solar power can emerge as a cost-effective option early in all scenarios, reaching its full capacity potential and contributing up to 3% of the electricity supply mix. In particular, if land use and CO_2 emissions are penalised with taxes as surrogates for endogenising the cost of environmental footprints, the share of FPVs in the generation mix increases by 1.5% and its deployment appears earlier in the planning period. On the other hand, climate change scenarios do not affect the role and periods of deployment of this technology significantly. 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 (-0.78%). Additionally, implementing their optimal capacity could lead to maximum evaporation reductions of 2% yearly, saving up to 376 $\mathrm{M\,m^3\,y^{-1}}$ in the whole region. 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; these plants with very large reservoirs emerge at the system scale because of their highest FPV capacity deployment and water evaporation savings.

In summary, for energy planning authorities considering the electrification expansion in the study area, floating solar power can be considered as a highly promising and cost-competitive investment starting from late 2020's. Its deployment not only could help in reducing the energy system's carbon emissions and land use intensity, but it can also marginally address the significant water loss from the basin's reservoirs. This recommendation remains robust across various climate change scenarios and environmental tax policy decisions. Moreover, as highlighted in the introduction, the stark differences in electricity access across the Eastern Nile Basin countries indicate that prioritising the various benefits of FPV deployment should be context-specific. For Egypt, with nearly universal electricity access, priorities likely focus on decarbonisation and water conservation, particularly considering its water scarcity challenges and commitments to emissions reduction (Arab Republic of Egypt 2022). The high land values identified in the Nile Delta also render land-saving benefits particularly relevant. For Ethiopia and Sudan, where electricity access is around 50%, the primary consideration is likely to be cost-effectiveness in expanding generation capacity, with environmental benefits being important but secondary. However, we note that even in low-access countries, environmental benefits should not be entirely overlooked as they contribute to long-term system sustainability. Rather than suggesting strict prioritisation, we advocate for a balanced approach that acknowledges both immediate development needs and longer-term sustainability goals, with the relative emphasis varying according to the country context. Future studies should focus on improving the precision of some components of the analysis or model them spatially more explicitly. Additionally, conducting studies at single FPV plant scale, and its multi-sectoral impacts would be crucial to ensure that local environmental, social and economic conditions are taken into account before directing any investment.

Data availability statement

The datasets and code that support the findings of this study are openly available at the following URL/DOI: https://github.com/apieruzzi/TEMBA_FPV.

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Conflict of interest

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

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