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Water Scenarios Modelling for Renewable Energy Development in Southern Morocco

***Sibel R. Ersoy**[*1]**, Julia Terrapon-Pfaff**[2]**, Lars Ribbe**[3]**, Ahmed Alami Merrouni**[4]*

[1]Division Future Energy and Industry Systems, Wuppertal Institute for Climate, Environment and Energy, Döppersberg 19, 42103 Wuppertal, Germany
e-mail: sibel.ersoy@wupperinst.org

[2]Division Future Energy and Industry Systems, Wuppertal Institute for Climate, Environment and Energy, Döppersberg 19, 42103 Wuppertal, Germany
e-mail: julia.terrapon-pfaff@wupperinst.org

[3]Institute for Technology and Resources Management, Technical University of Cologne, Betzdorferstraße 2, 50679 Köln, Germany
e-mail: lars.ribbe@th-koeln.de

[4]Materials Science, New Energies & Applications Research Group, Department of Physics, University Mohammed First, Mohammed V Avenue, P.O. Box 524, 6000 Oujda, Morocco
Institut de Recherche en Energie Solaire et Energies Nouvelles – IRESEN, Green Energy Park, Km 2 Route Régionale R206, Benguerir, Morocco
e-mail: alami.univ.oujda@gmail.com

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ABSTRACT

Water and energy are two pivotal areas for future sustainable development, with complex linkages existing between the two sectors. These linkages require special attention in the context of the energy transition. Against this background, this paper analyses the role of water availability in the development of solar thermal and photovoltaic power plants for the case of the Drâa Valley in southern Morocco. Located in a semi-arid to arid mountainous area, the Drâa Valley faces high water stress – a situation expected to worsen due to climate change. At the same time, the region has one of the greatest potentials for solar energy in the world. To examine whether limited water availability could accelerate or delay the implementation of solar thermal and photovoltaic power plants, this paper compares regional water availability and demand in the Drâa Valley for different scenarios, paying particular attention to potential socio-economic development pathways. The Water Evaluation and Planning System software is applied to allocate the water resources in the study region. The water supply is modelled under the Representative Concentration Pathway 8.5 climate scenario, while the water demand for the Drâa Valley is modelled for a combination of three socio-economic and two energy scenarios. The climate scenario describes a significant decrease in water availability by 2050, while the socio-economic and energy scenarios show an increase in water demand. The results demonstrate that during a sequence of dry years the reservoirs water availability is reduced and shortages in water supply can result in high levels of unmet demand. If this situation occurs, oasis farming, water for drinking and energy production could compete directly with each other for water resources. The energy scenarios indicate that the use of dry cooling technologies in concentrated solar power and photovoltaic hybrid systems could be one option for reducing competition for the scarce water

[*] Corresponding author

resources in the region. However, given that energy generation accounts for only a small share of the regional water demand, the results also suggest that socio-economic demand reduction, especially in the agricultural sector, for example by reducing the cultivated area, will most likely become necessary.

KEYWORDS

Water evaluation and planning, Water demand modelling, Hybrid concentrated solar power-photovoltaic systems, Scenario, Socio-economic development, Morocco.

INTRODUCTION

Concentrated Solar Power (CSP) is a promising renewable energy technology with the potential to become mainstream, like wind, hydro and Photovoltaic (PV) technologies [1]. Although, compared to an installed solar PV capacity of 300 GW the installed capacity of CSP worldwide is still low with 4.8 GW in 2016, but the International Energy Agency (IEA) expects that the capacities will be doubled by 2022 [2]. As consulted by Gauché *et al.* [3] or Brand *et al.* [4], CSP technology combined with thermal storage has the ability to become dispatchable, enabling to store solar energy during the day and to deliver electricity during the night compared to other technologies. Furthermore, thermal energy storage systems permit a flexible operation at high efficiencies and capacity factors while having the lowest storage costs as shown by Trieb *et al*. [5] who analysed the efficiencies and capacity factors of the CSP technology, by DLR [6] which likewise focused on innovative techniques for power generation and by experts for solar thermal electricity [7]. However, a key challenge for the development of CSP technology is its high level of water consumption compared to other renewable energy technologies [8].

Water consumption is particularly relevant in arid to semi-arid regions like Souss-Massa-Drâa and Tata in southern Morocco. On the plus side, however, these areas are characterised by high Direct Normal Irradiation (DNI) conditions that exceed 2,400 kWh/m^2 annually making them highly suitable for the implementation of CSP plants [9]. Morocco's CSP potential is estimated to amount to 20,000 TWh/y [10]. According to the Moroccan Ministry of Energy, Mines, Water and Environment [11] and official policy papers [12], CSP has been identified as a promising element in Morocco's ambitious strategy to increase its renewable share in the electricity mix from 8.7% in 2012 to 42% by 2020 and 52% by 2030, to achieve a 'low-carbon and climate change resilient development' [13]. Renewable energy technologies will also help to meet the country's increasing electricity demand (16 TWh in 2002 and 31 TWh in 2012 [13]), caused by a growing population and continued industrial development. Being an intermittent technology, solar energy technology only produces electricity during sunshine hours. To cover the country's peak demand hours, large storage systems such as molten salt can ensure the electricity supply. CSP with thermal storage is especially suitable to provide energy during the country's peak demand in the evenings and the annual peak, which has changed from winter peak to a summer peak due to air cooling demands according to the energy policy analysis conducted by IEA [13], the background paper of Morocco elaborated by Schinke *et al.* [12] and by the Moroccan Agency for Solar Energy (MASEN) [14]. Yet, despite these advantages the high water demand and the higher costs compared to PV lead to the question, if, to what extent and in which combination CSP can be implemented at specific sites in Morocco. According to some experts, the combination of PV and Solar Thermal Energy (STE) is the clear solution to provide base load in most days of the year [7].

According to the Moroccan Solar Plan (MSP), launched in 2009, MASEN plans to implement a sufficient number of large-scale utility solar complexes to produce 2,000 MW solar energy by 2020 [15]. One of the project sites is Akka Ighane, located in the region of Tata, where a 600 MW solar facility (NOOR Tata) is planned as stated by

MASEN [14], the German Chamber of Industry and Commerce Abroad (AHK) [16] and the Moroccan-German Energy Partnership (PAREMA) [17]. As it is sited in one of the regions of greatest water scarcity in Morocco, the linkages between energy generation and water resources need to be carefully considered in the development of the NOOR Tata project. This paper therefore addresses the question how different solar technology development pathways can influence the sustainability in regards to water resources in the region.

To date, a number of studies have addressed water consumption in the energy sector using an integrated approach in an attempt to find potential solutions by coupling the power and water generation sectors. Agrawal *et al.* [18], for example, analysed Long-range Energy Alternatives Planning System and Water Evaluation and Planning System (LEAP-WEAP) software climate change scenarios by forecasting water consumption and Greenhouse Gas (GHG) emissions from the power sector in Canada, while Valenzuela *et al.* [19] studied the integration of CSP and PV hybrid solar systems and seawater desalination in Chile and Bazilian *et al.* [20] presented a modelling framework that addresses the nexus with a focus on developing countries. Likewise, the literature has analysed water systems in arid to semi-arid mountainous regions in the Middle East and North Africa. Johannsen *et al.* [21] analysed the future of water supply and demand in the Middle Drâa Valley under the conditions of climate change and land use change, while Karmaoui *et al.* [22] applied a multidisciplinary approach to assess environmental vulnerability in the Upper Drâa Valley and Ben Salem *et al.* [23] modelled the Ziz basin in south-eastern Morocco under various water allocation scenarios. Droogers *et al.* [24] demonstrated that water shortages are mainly attributed to socio-economic factors, while López-Gunn *et al.* [25] found that water-saving measures can lead to rebound effects and increase the overall local water consumption. Yet, what is, however, still missing are integrated assessments that address the question of renewable energy development options and water resources in arid regions, which also take into account the potential socio-economic development pathways. This is especially critical as more and more renewable energy projects are deployed in water-scarce regions. This paper addresses this research gap by discussing potential technical configurations for NOOR Tata, considering the most sustainable development path regarding water resources for the region.

The analysis of these types of complex systems, combining energy, hydrological, cultural and socio-economic aspects, requires an appropriate system model. WEAP software developed by the Stockholm Environment Institute is such a model, that has been used successfully for the simulation of climate, land use, population growth change and different management strategies as shown by Amin *et al.* [26] who applied the WEAP model to the Upper Indus Basin and by Rochdane *et al.* [27] who studied the Rheraya Watershed in Morocco. In this paper, the WEAP software is used to model different socio-economic development scenarios in combination with different energy technology options under the worst-case climate change scenario Representative Concentration Pathway (RCP) 8.5. The objective of this paper is to study the impact of climate change on the water availability and water demand in the Drâa Valley under different socio-economic and energy scenarios to see how adequate energy system configurations or changes in crop shares and better irrigation techniques could positively influence the local water system. The results may rise awareness of the water-energy demand and supply relationship among decision makers, thereby contributing to a sustainable development in southern Morocco.

METHODS

Scenario modelling has become a state-of-the-art tool to properly assess environmental issues that include social, technological, economic and demographic changes [28]. A scenario describes a possible future situation of a complex system with different development pathways [29]. Scenarios can combine qualitative and quantitative analyses. This research makes use of scenarios to describe the potential developments of the water supply and demand in the Drâa Valley. By combining expert interviews and a modelling tool, qualitative and quantitative results are generated.

In this paper, WEAP is used as an allocation tool for modelling future water supply and demand scenarios under the development of renewable energies. WEAP is an integrated tool that helps in water resources planning and supports management decision-making strategies [30]. Its integrated approach makes it possible to simulate water demand and supply for a specific region under certain assumptions, such as, e.g., climate change. WEAP can address demand-side patterns such as water use, efficiencies and consumption for energy generation, and combine these with the supply-side such as groundwater and reservoir availability, water runoff, climate and water management priorities. The energy production and its water consumption have to be added to the model exogenously. To calculate the energy production of the CSP plant, the following equation has been used [3]:

$$E = I \times A \times \eta \tag{1}$$

where E is energy (kWh/y), I is irradiation (kWh/m^{2}y), A is effective aperture area (m^2) and η is overall efficiency.

To calculate the PV energy production, eq. (2) has been used [31]:

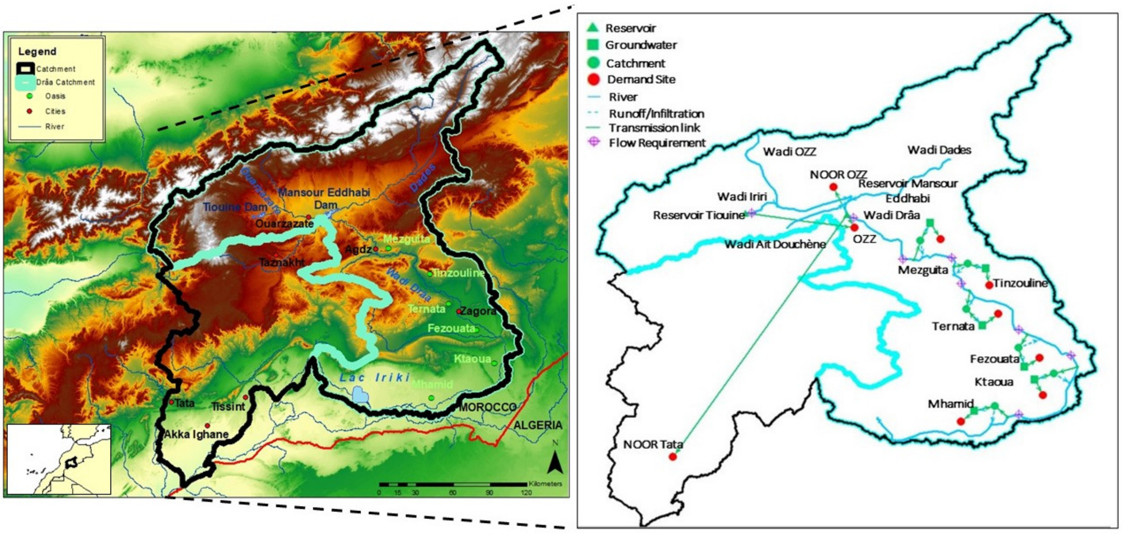
$$E = \frac{P \times G}{I \times Q} \tag{2}$$

where E is energy (kWh/y), P is power (kW), G is global irradiation (kWh/m^{2}y), I is irradiation at Standard Test Conditions (STC) (kW/m^2) and Q is quality factor.

The WEAP model is a useful tool for water modelling purposes, however, it must be considered that it has some limitations [26]. Lack in accuracy is encountered for the groundwater budgeting, the linkage between other models such as MODFLOW to WEAP could help to obtain certain quantitative results [21]. The applied discharge cycle approach is subject to uncertainties, but offers the advantage of a simple application that corresponds to the scope of the work presented here. WEAP shows as well a limiting function in the water-energy-forecast, because important parameters such as, e.g., efficiencies, specification in the dry cooling technologies, capacity factors cannot be taken into consideration. Thus, the study results regarding the water consumption in NOOR Tata are bonded with high uncertainties. A solution presents the combination of results from energy models such as System Advisor Model (SAM) from National Renewable Energy Laboratory (NREL) or ColSimCSP (Fraunhofer in-house tool) to allow more accuracy. Due to time constraints and limited access to these tools, the application of them could not be used for the present study purpose. However, despite these uncertainties, which exist in all approaches modelling the future, the results allow a more profound understanding of possible developments and potential critical trends associated with them.

STUDY AREA

The Drâa catchment comprises an area of about 34,609 km^2 in the south east of Morocco [32]. Figure 1 shows the administrative context of the Drâa catchment showing the city of Ouarzazate, Akka Ighane in the province of Tata, the Tiouine and Mansour Eddhabi dam and the oases along the Wadi Drâa {own Geographic Information System (GIS) creation – data based on [33-35]}. The Drâa catchment is classified as an arid and hot desert climate zone [36]. Precipitation is erratic, however, heavy rainfalls typical of desert and steppe climates occasionally occur [37]. The actual evapotranspiration (ET_0) sums up to 1,700 mm/y [38]. Akka Ighane, the proposed site for NOOR Tata located in the southern province of Tata, is characterised by an arid and hot climate with high levels of irradiation [9]. Figures 2a-c show climate diagrams of Ouarzazate (mean annual temperature of 22.3 °C and mean annual precipitation of 58 mm), Zagora (mean annual temperature of 22.2 °C and mean annual precipitation of 46 mm) and Tata (mean annual temperature of 23 °C and mean annual precipitation of 42 mm). DNI in Tata with daily average values of 6.7 kWh/m^2 and Global Horizontal Irradiation (GHI) with daily average values of 5.9 kWh/m^2 (2008) are shown in Figures 2d-e [9, 39]. Water availability is strongly dependent on the snow-covered High Atlas mountains [37], where the perennial river Wadi Dades originates, the river converges at the reservoir Mansour Eddhabi with the periodic river Wadi Ouarzazate into the river Wadi Drâa [36]. The hydrology in the Drâa catchment is controlled by 'lâchers' (releases) of the Mansour Eddhabi dam, feeding the agricultural sites at the six oases of Mezguita, Tinzouline, Ternata, Fezouata, Ktaoua and Mhamid [37]. As the Mansour Eddhabi dam loses 0.7% of its storage capacity per year compared to its initial capacity in 1972 (583 million m^3), its actual capacity is currently around 390 million m^3 [40]. Due to strong siltation and high evaporation losses, an additional dam, the Tiouine dam, with a storage capacity of 270 million m^3 was built and has been in operation since 2015. The Tiouine dam mainly provides the city of Ouarzazate with drinking water, but also supplies water for agricultural irrigation in the region as well [40].



(a) (b)

Figure 1. Administrative context of the Drâa catchment (a) and system graph of the Drâa catchment in WEAP (b)

The Middle Drâa Valley has a population of 306,905 and about 113,197 people live in the city of Ouarzazate [41]. The water availability per capita in the Drâa Valley is around 360 m^3/y, which is significantly lower than the national average of 700 m^3/y [42]. The Drâa Valley and its southern oases are economically marginalised [28]. Economic activities rely mainly on agriculture and farming, the only other industry in the region apart from tourism is mining [43]. Farmers in the oases cultivate crops such as wheat, barley, date palms, alfalfa, melons, henna and vegetables, 26,118 ha are irrigated area [21, 37, 44].

The cultivation of crops depends heavily on water availability from the Mansour Eddhabi dam. In years of drought, farmers use mostly groundwater as compensation for surface water irrigation. This has resulted in a drop of the groundwater table and has caused the water quality to decline due to salinization [45]. Livestock farming consists of cattle, sheeps, goats and camels which serve mostly for self-consumption [46]. Tourism attracts 411,232 visitors per year (2010) and is economically important for the region [46].

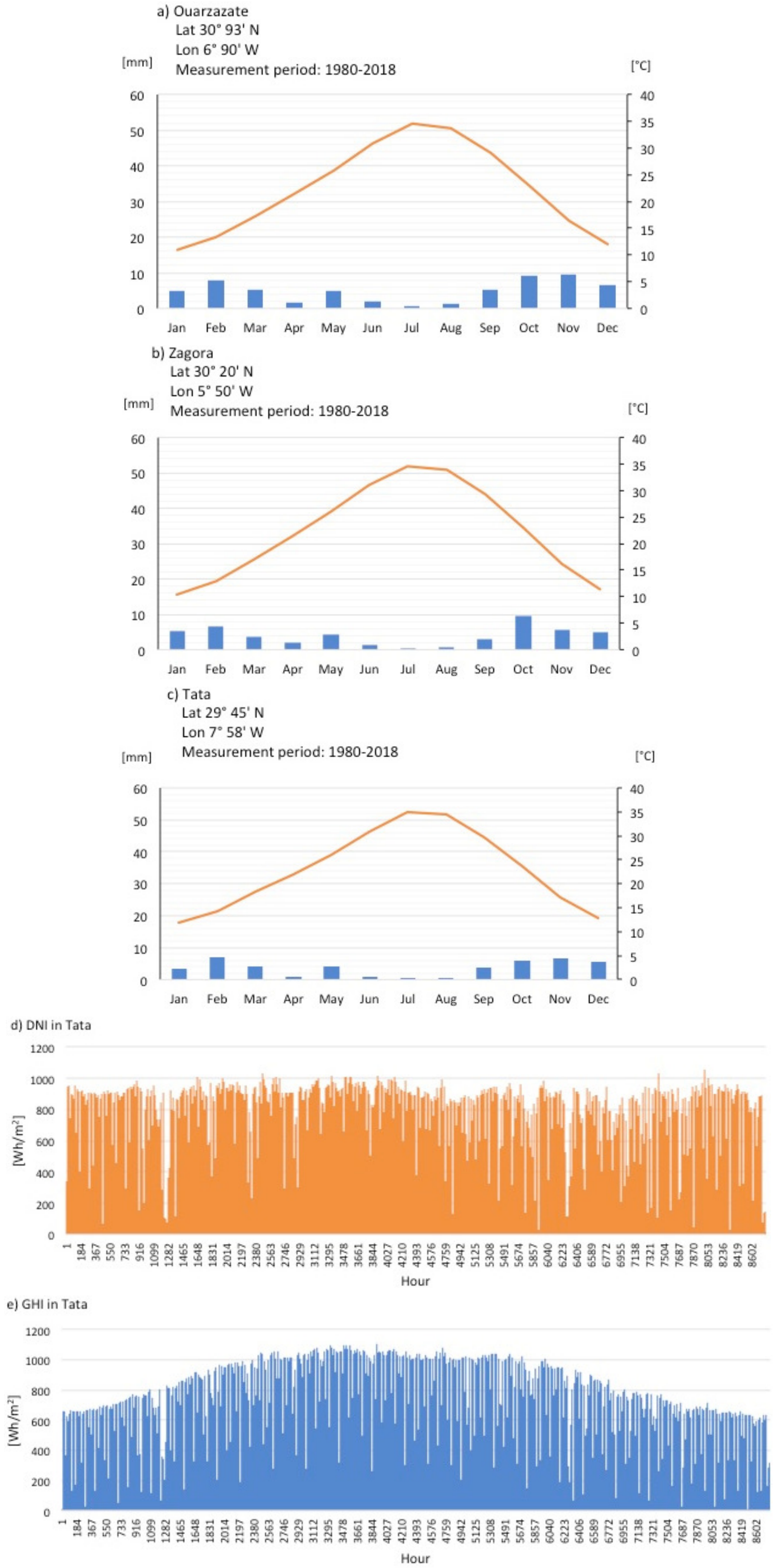


Figure 2. Climate diagram: Ouarzazate (a); Zagora (b); Tata (c); DNI in Tata (d) and GHI in Tata (e)

SCENARIO INITIALIZATIONS AND MODELLING

In this research, scenarios are applied to describe the potential developments of the water supply and demand in the Drâa Valley. The scenarios have been generated by: combining expert interviews to generate qualitative storylines and a WEAP model that simulates the impacts of certain driving forces under the assumptions of the given storylines that results in quantitative responses.

To support the development of the scenarios narratives a total of 10 expert interviews have been conducted that had a semi-structured form. The experts are relevant stakeholders from the water and energy sector or work for development or research institutions in Morocco and Germany. A representative from the province of Tata was also interviewed to identify strategic development pathways on the political level. Some information was also gathered through informal background talks during a two-month research stay in Morocco.

The WEAP model baseline scenario comprises the years 1984-2011, which is the current account year. From the baseline scenario, three main scenarios for the period from 2012-2050 are constructed. The scenarios include different socio-economic changes under the assumption of climate change and the development of renewable energy (Figure 3). In the following, the different scenario components are described in detail.

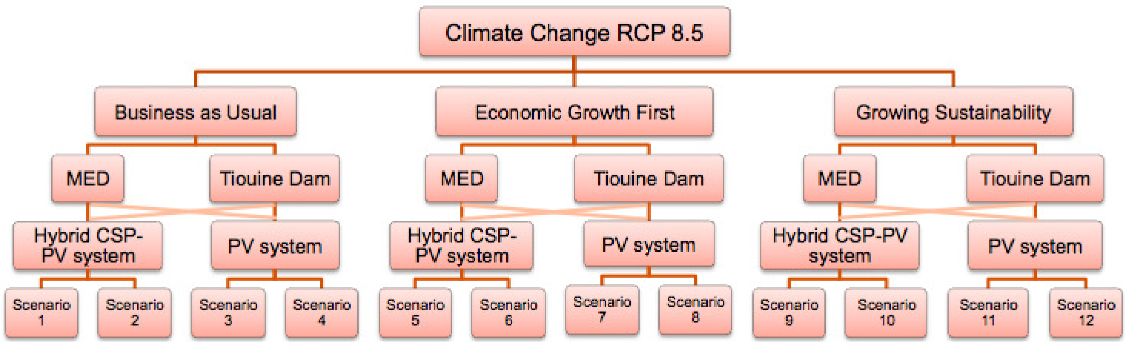


Figure 3. Scenario overview for this research study [Mansour Eddhabi Dam (MED)]

Climate scenario

The model refers to the assumption of climate change according to RCP 8.5 adopted by the Intergovernmental Panel on Climate Change (IPCC) in the fifth Assessment Report (AR5). The RCP describes the GHG concentration in the atmosphere in accordance with possible anthropogenic changes in the future. RCP 8.5 is the worst-case scenario and it assumes a steady rise of GHG emissions until 2100 and a radiative force of 8.5 W/m^2. According to RCP 8.5, under regional extremes it is assumed that the study region will be characterised by a temperature increase of 1.8 °C and a reduction in precipitation of 12% by 2050 compared to the base year 2010 [47]. In the model, the statistical analysis shows that by 2050 the region is characterized by more extremes. Less normal years will occur, instead dry and very dry years will increase with unusual short wet periods.

Socio-economic scenarios

Three socio-economic scenarios have been adapted from the Moroccan case study of the Wuppertal Institute for Climate, Environment and Energy (WANDEL) project [48] and then adjusted based on the evaluation of the expert interviews. Agricultural development, demographic and social changes, economic and political transformations are considered in the different scenarios. Table 1 summarises the characteristics of the socio-economic scenarios.

Table 1. Summary of the socio-economic scenarios

Topic	S1 – Business as Usual	S2 – Economic Growth First	S3 – Growing Sustainability
Population	Urban: 2.25% increase Rural: 0.45% decrease	Urban: 3% increase Rural: 1% increase	Urban: 3% increase Rural: 1% increase
Agriculture	Cultivated area remains the same	Cultivated area: 2% increase	Cultivated area remains the same
Livestock farming	Annual decrease: 0.25%	Annual decrease: 2.5%	Annual decrease: 0.5%
Irrigation efficiency	Irrigation efficiency remains constant at 65%	Irrigation efficiency increases up to 85%	Irrigation efficiency increases up to 95%
Reservoir siltation	Storage capacity: 0.7% decrease	Storage capacity: 1.5% decrease	Storage capacity: 0.5% decrease

Scenario 1: Business as Usual. Scenario 1 (S1), Business as Usual, describes the current socio-economic situation of the Drâa Valley and assumes it will remain constant in the future. As work is scarce, there is constant migration. Many people continue to live off money sent from family members who live abroad. The cities remain as areas of population concentration where the population continues to grow, whereas in the oases the population declines. People's behaviour and awareness of water issues does not change significantly according to Agueniou [49] and Dahan and Grijsen [50]. The tourism sector is concentrated in a few areas and hence, water exploitation remains high and uncontrolled [51]. With respect to agricultural development, the cultivated areas remain constant until water scarcity limits their expansion. The selection of cash crops leads to low water productivity (Figure 4a). As farmers continue to use groundwater for irrigation and the number of groundwater pumps increases moderately, the water quality – which is already low – continues to deteriorate. The irrigation techniques remain the same and, due to a lack of financial opportunities, the efficiency does not change. Livestock farming level, which is analysed as well by FAO [52] and Gleitsman *et al.* [53], decreases reducing alternative income generating activities and food security. Supportive policies and programmes do exist, but are not accessible to the majority. Reasons for this include a lack of funding, unresolved land right questions and a lack of technical know-how. Regional plans continue and the storage volume of the reservoirs continues to decrease at the same rate.

Scenario 2: Economic Growth First. In contrast to S1, Scenario 2 (S2), Economic Growth First, describes a situation of a strong, but unsustainable economic growth. The government and regional authorities invest in supportive programmes where the cash crop production and the tourism sector are prioritised. Due to increased employment opportunities, migration reduces and the rural areas experience a low level of steady growth. The urban areas continue to grow. The cultivation of cash crops leads to higher income for farmers. As a result, multiplier effects such as the services sector start to develop. Higher incomes lead to lifestyle changes, which in turn lead to higher water consumption per capita. Tourism continues to reach its peak in both the urban and oases areas. Water consumption in the tourism sector is high. The agricultural areas increase until water scarcity limits their expansion. The extension of drip irrigation is implemented, resulting in higher irrigation efficiencies. The crop share favours water-intensive cash crops for export, such as watermelons and dates (Figure 4b). This means that the water productivity increases, but the rapid exploitation of groundwater resources also grows significantly. In addition, the groundwater salinity levels become very high, leading in the long term to decreased yields. Livestock farming decreases, because the cash crop market generates more income. The storage volume of the reservoirs decreases faster than in S1, because regional funds now invest more in soil activities that favour the cash crop production rather than in siltation prevention.

Scenario 3: Growing Sustainability. Scenario 3 (S3), Growing Sustainability, describes a scenario that emphasises the valorisation of the local culture and regional heritage. It assumes that the governmental strategy creates programmes and funds to protect the oases and forests. New initiatives boost the productivity, and the region is characterised by less migration due to improved living conditions and information centres. The agricultural sector focuses less on water-intensive crops (Figure 4c) and the government introduces laws for the mandatory introduction of efficient irrigation techniques. Livestock becomes an integrated part of farming, animals provide fertilizer in form of manure. The concept of sustainability becomes an important lifestyle component with the result that water consumption is decoupled from lifestyle changes and remains stable. Water saving measures are an element of a strong resources management strategy, which enhances the water quality in households and in the hotel industry. The tourism sector embraces eco-friendly tourism focusing more on environmentally-sensitive tourists who come to the region to visit, e.g., the solar power plants NOOR. The sedimentation of the reservoir decreases less than in the other two scenarios, because policies invest strategically into sedimentation removal such as, e.g., hydrosuction [54] or inflated dams.

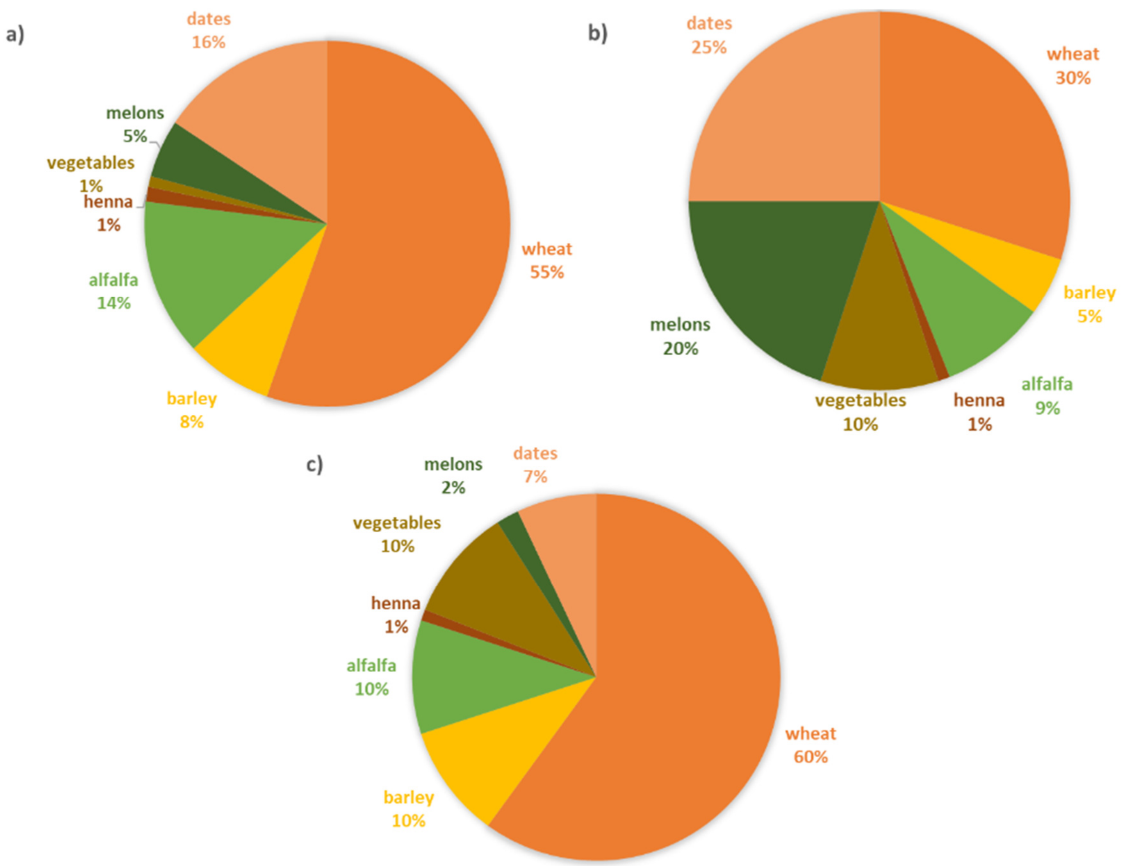


Figure 4. The crop share of the different socio-economic scenarios: S1 (a); S2 (b) and S3 (c)

Energy scenarios

The two energy scenarios: Hybrid CSP-PV system, and PV system – describe hypothetical developments in the study catchment. Different technical configuration options are examined and analysed.

Hybrid CSP-PV system. The hybrid CSP-PV system designed for NOOR Tata consists of a 180 MW CSP and 420 MW PV power plant. According to MASEN, future CSP projects in Morocco are obliged to use air-cooled technologies, owing to lessons learnt from $NOOR_o$ Ouarzazate and the water scarcity in Morocco. Hence, the design of the CSP plant uses an indirect dry cooling system (Heller system). The design opts for a solar tower, as the power block has higher efficiencies and lower specific water consumption (m^3/kWh) than parabolic trough technologies. According to experts, it also has advantageous life cycle costs compared to other CSP technologies.

As the DNI for Tata is 2,488 kWh/m^2 (in 2008) [9], by applying the eq. (1) the annual energy production of NOOR Tata CSP is 788 GWh. The overall efficiency for this configuration is set to 20% considering thermal storage. The PV power plant produces around 1,313 GWh annually, according to eq. (2). It is assumed that NOOR Tata PV uses polycrystalline silicon modules with an efficiency of 18% [55].

PV system. The PV system energy scenario assumes that NOOR Tata will have a capacity of 600 MW, consisting solely of a PV complex. The same modules and efficiencies are used as in the hybrid system scenario. In this configuration, the PV power plant produces with 2,171 kWh/m^2 of GHI (in 2008) [9] 1,875 GWh annually.

Model input data

The WEAP schematic is based on the imported shapefile that has been generated in ArcGIS. Products from SRTM 90m Digital Elevation Model have been projected and masked over the Drâa catchment in southern Morocco [33-35]. The WEAP model consists of seven demand sites for Ouarzazate city and other households in the oases, six agricultural and husbandry sites in the oases and two solar complexes – $NOOR_o$ Ouarzazate (active from 2016 on) and NOOR Tata (active from 2020 on). Seven main crop types are farmed in the oases. The water is supplied by the upstream reservoirs of Tiouine and Mansour Eddhabi and six aquifers at the oasis sites. The six oasis household sites are solely supplied by the aquifers, whereas the city of Ouarzazate is exclusively supplied by the reservoirs. The solar power plant $NOOR_o$ Ouarzazate is supplied by the Mansour Eddhabi dam. NOOR Tata is supplied for different scenarios either by the Mansour Eddhabi or the Tiouine dam. It is assumed that all the water is consumed by the demand sites and does not return into the system. The simulations are run on a monthly basis. The current account year is 2011 and the historical dataset from which the scenarios are created is from 1984-2011.

Climate data. Daily temperature and precipitation data between 1980-2018 for the site of Zagora has been taken from NASA's MERRA 2 Re-Analysis (Modern-Era Retrospective analysis for Research and Application) with a spatial resolution of 50 km [39]. According to RCP 8.5 [47], compared to the base year 2010 by 2050 the temperature will increase by 1.8 °C and precipitation will decrease by 12% for the region of south Morocco which was analyzed as well by De Jong *et al.* [32] and Busche [36]. The data for long-term mean precipitation has been calculated for 2030 and 2050 and then interpolated in WEAP. By applying the Water-Year-Method embedded in the WEAP software [30], a statistical analysis of precipitation data has been carried out to identify the sequence of dry and wet years. The same climate scenario is applied to all socio-economic and energy scenarios.

It must be considered that MERRA 2 is a global reanalysis product that leads to lower climate data accuracies for the study region in this paper.

Households. Population data has been obtained from Haut Commissariat au Plan (HCP) [41]. The data has been extrapolated in a linear manner until 2050. The annual households water demand is defined per capita as 20 litres per day in rural areas and 50 litres per day in urban areas [21].

Agriculture and irrigation. A total irrigated area of 26,118 ha distributed across the six oases has been simulated (Figure 5) [46]. Seven different crop types – wheat, barley, alfalfa, henna, vegetables, melons and dates – are planted on the agricultural sites. The crop factors (K_c values) are taken from Busche [36] and FAO [56].

The irrigation efficiency in the current account year is 65%. According to experts, the Drâa Valley uses in big extension flood irrigation. 35% of the irrigated water cannot be used by the crops and evaporates. In WEAP, the transmission links from the river to the oases represent the irrigation channels and the links from the groundwater nodes to the oases represent the household water supply. The flow requirements reflect the oases in which the oases receive irrigation water. Mhamid, as the last oasis, has top priority and consequently Mezguita, as the first oasis, has the last priority.

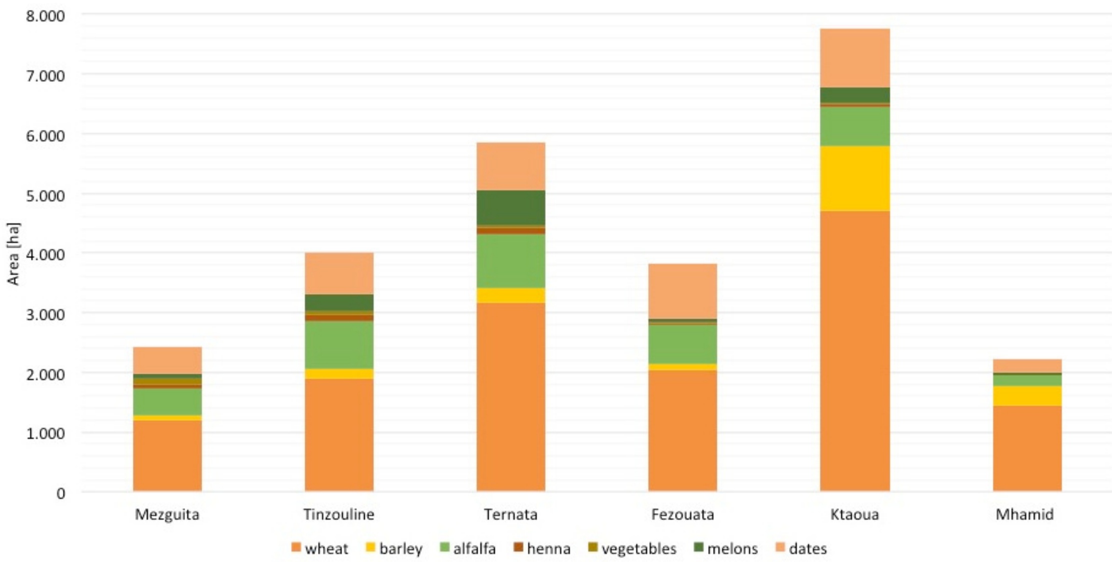


Figure 5. Agricultural area by crop type and six different oases [21]

Hydrologic parameters. As a baseline serves historical data from 1984-2011 provided by Agence du Basin Hydraulique (ABH), Ouarzazate [40] and University of Bonn (IMPETUS project) [28] on river discharge, groundwater resources, reservoir inflow, reservoir evaporation, reservoir volume and dam capacity. The data was used on a monthly basis as a cycle projection until 2050 by assuming a discharge reduction of 20% [57] and an increase in reservoir evaporation of 6%. The reference ET_o was taken from the Food and Agriculture Organization's (FAO) Wapor [38]. By using the Blaney-Criddle-Method [56], the future increase in ET_o could be defined as 6% in 2050 compared to the base year 2010. For simplicity reasons and missing data all catchments are assumed to have the same climate data. For all scenarios the yearly groundwater recharge is set by a reduction of 1% as a consequence of climate change [58].

The reservoir capacity decreases in all scenarios (Figure 6). Compared to a storage capacity in 1972 of 560 million m^3, the Mansour Eddhabi dam will have by 2050 in Scenario 1 (Business as Usual) a capacity of 316 million m^3, in Scenario 2 (Economic Growth First) 216 million m^3 and in Scenario 3 (Growing Sustainability) 347 million m^3 (parameters based on [43, 54, 59, 60]). To guarantee drinking water supply a minimum threshold of 35 million m^3 is assumed in all scenarios [21]. The Tiouine dam, which started its operation in 2015, has an initial storage capacity of 270 million m^3, by 2050 this decreases in Scenario 1 (Business as Usual) to 211 million m^3, in Scenario 2

(Economic Growth First) to 159 million m^3 and in Scenario 3 (Growing Sustainability) to 226 million m^3.

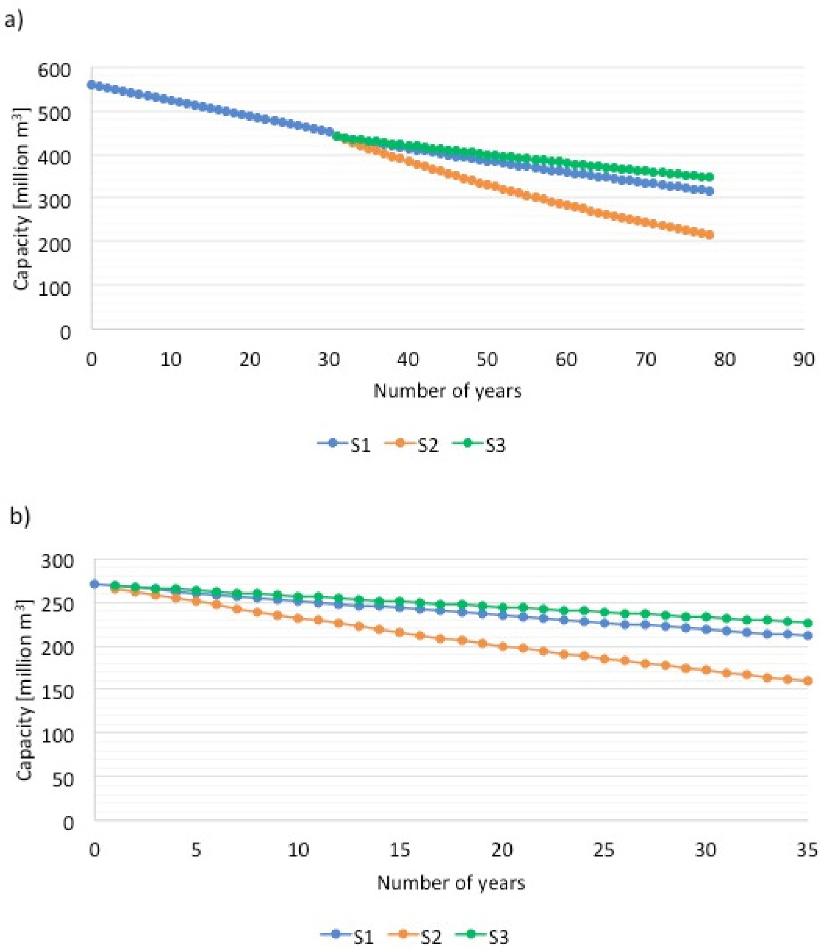


Figure 6. Reservoir storage capacity by number of years: Mansour Eddhabi dam 1972-2050 (a) and Tiouine dam 2015-2050 (b)

Energy parameters. Two power plant demand sites are integrated into WEAP. MASEN's solar complex NOOR$_o$ (Ouarzazate) consists of four power plants: NOOR$_o$ I and II use parabolic troughs, NOOR$_o$ III uses a solar tower and NOOR$_o$ IV is a PV complex. The power plant's capacity is 580 MW. NOOR$_o$ comes into operation in 2016 and is linked to the Mansour Eddhabi dam, which supplies the power plant with 2.19 million m^3 of water annually for cooling and cleaning purposes according to MASEN's [61] and Capitals 5's [55] information.

The configuration of NOOR Tata is still not defined and the supply source is also in the evaluation phase. The model is based on two possible configurations and two supply sources. The configurations assumed are: a hybrid CSP-PV system with 180 MW CSP and 420 MW PV capacity and a 600 MW PV complex. The supply sources assumed are: the Mansour Eddhabi dam and the Tiouine dam. For both power plants, the supply priority for the energy production comes after drinking water (top priority) and irrigation (second priority).

RESULTS AND DISCUSSION

The results section has been separated into five parts: reservoir and groundwater storage, water demand in the oases, households and for potential solar energy system NOOR Tata and the unmet water demand in the oases, households and in NOOR Tata.

Reservoir and groundwater storage

The graph in Figure 7a shows the accumulated monthly storage volume of both reservoirs by scenario. The graph shows a general negative trend, which fits with assumptions made about changing precipitation patterns, discharge reductions and sedimentation in the reservoirs. Although, less precipitation is expected in the future, the variability of precipitation will be more extreme [24].

In the first model decade 2011-2020, the reservoirs' storage is low to empty in the first half – for a simulated drought – and refills after two very unusually wet years. By end of the second model decade (2021-2030) the reservoir's storage is again low to empty due to a simulated sequence of two dry and very dry years that occur in model year 2028 and 2029. Although, the following model year is a normal year, the reservoirs are not able to recover immediately and cannot meet the water demand. The lower storage levels in the reservoir in S2 reflect its higher water demand. The third model decade (2031-2040) is characterised by more normal years where the reservoirs are able to refill, but do not reach peaks such as in the first decade, as wet years do not occur in a sequence. The end of the third model decade and the beginning of the last model decade (2041-2050) are characterised by a simulated drought of four years. S2 with an overall higher water demand shows here the worst conditions regarding the reservoirs' storage: the storage volume remains at lower levels for several years. Only S3, with its more sustainable water use (higher irrigation efficiencies and lower water use per capita), maintains steady storage levels a few longer. The last model decade is characterised by two consecutive wet to very wet years, which are indicated by peaks in the storage graph. These peaks enable the reservoirs to store water, which will then be depleted over the subsequent dry years. S2 shows also in the last model decade the worst conditions due to overall water stress caused by large cultivated areas and high household water demand, whereas the highest storage capacity is simulated in S3.

Figure 7b illustrates the monthly groundwater storage by socio-economic scenario. It shows a negative trend which is found as well in Johannsen *et al.* [21] for the Middle Drâa Valley and in Droogers *et al.* [24] within the whole Middle Eastern and North African region. After a drought period from model years 2014-2015, the water levels in the aquifers decline followed by an improvement in the subsequent wet model years in 2016 and 2017. The model shows that groundwater resources act as a buffer for irrigation purposes when low reservoir inflow impedes irrigation, as found by Johannsen *et al.* [21] as well. The high fluctuations reflect the reservoirs' filling during the wet years. In wet years the aquifers recover well, because the outflow from the Mansour Eddhabi dam enables water infiltration into the aquifers [21]. A sequence of two wet or very wet years, as shown in model years 2016-2017 and 2044-2045, favourably affects the following years: the water levels in the aquifers remain stable for longer compared to the impact that one wet year has (such as in model year 2024 or 2034). S2 puts the greatest pressure on the aquifers, showing them to be depleted by model year 2039, followed by a light recovery before they are finally and fully depleted in model year 2049. In S3 the aquifers reach their limit by model year 2050, whereas in S1 there is still water stored in the aquifers by then. S3, which is supposed to describe the most sustainable socio-economic development, shows a less positive result than S1 for the long-term future. The reasons for this might be found in the geographical conditions [21]. Higher irrigation efficiencies and lower water demand lead to a slower aquifer recharge, because in arid or semi-arid regions the recharge from precipitation is very low. The aquifers mainly recharge through river-bed infiltration or by channel/flood irrigation infiltration. S3 needs in absolute numbers less water, which explains the lower groundwater storage compared to S1, because of lower infiltration rates. In the first half of the second model decade, the aquifers recover the best in S2, because irrigation fields are extended leading on one hand to more water use, but on the other hand to higher infiltration rates. This scenario shifts in the middle of the second decade, as the exploitation of water is higher than the recovery of the groundwater table. S3 shows the best aquifer storage in the second half of the same decade, as the impact of the wet model year 2024 lasts for longer. S1 shows the worst conditions at first, but from the third model decade, the aquifers have the greatest capacity in response to low irrigation efficiencies and low or declining population growth in rural areas, which are supplied by groundwater.

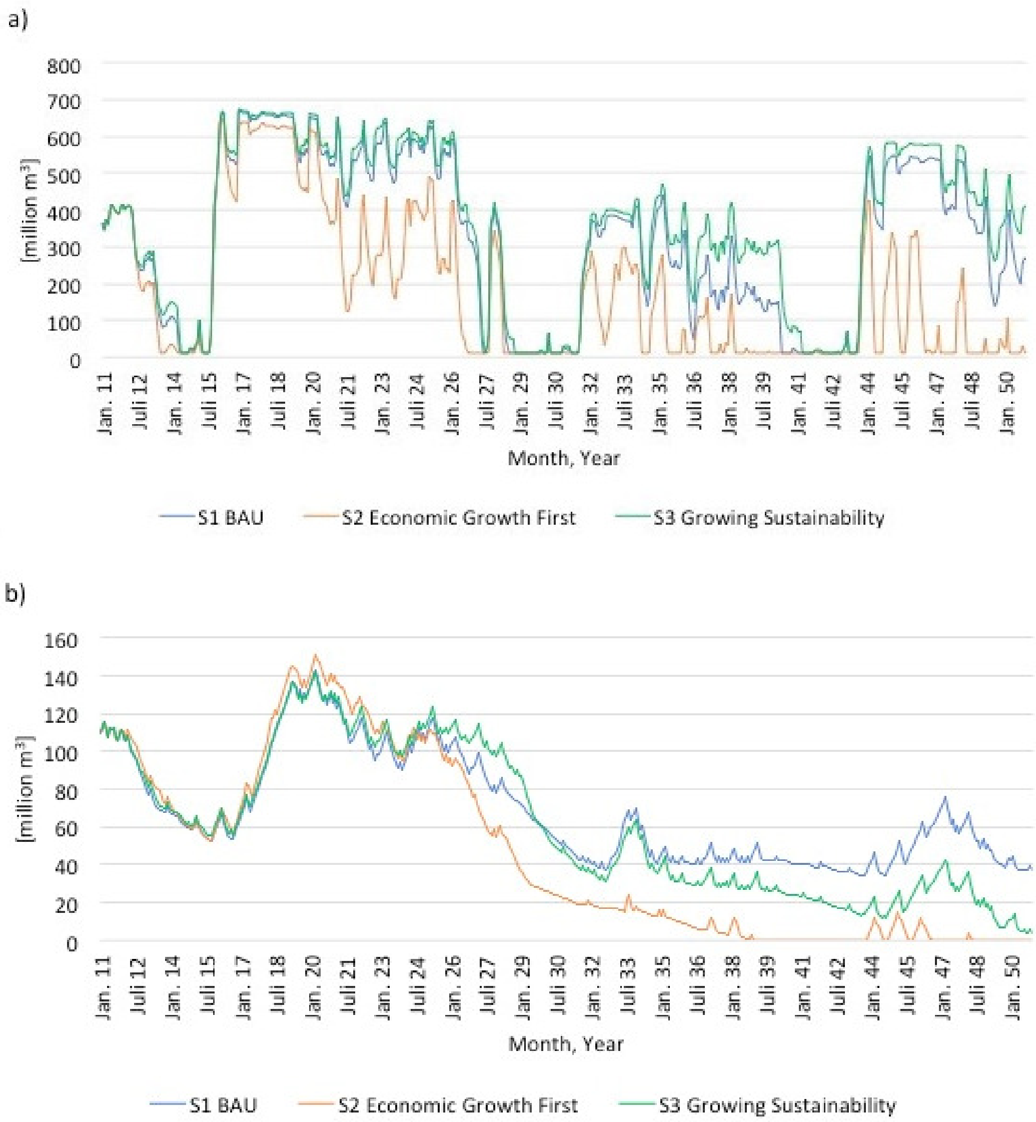


Figure 7. Monthly storage volume by scenario: in the reservoirs (a) and in the groundwater (b)

In summary, none of the scenarios indicate the sustainable use of water. In all scenarios, the aquifers will be depleted in future. To achieve water savings, methods should focus on efficiency in order to cope with dry years in the Drâa Valley. Johannsen *et al.* [21] suggest using only the groundwater in dry years, to give the aquifers time to recover. This could, however, intensify water stress because the given water demand cannot be met by surface water. A measure to tackle this problem, could be cultivated area reduction, as the largest proportion of the water is used by this sector and reasons for the water storage decline are found mainly in the agricultural sector. Also, the crop choice is an important factor to consider. Crops such as watermelons and dates require the most water, however, these crops are intended mostly for the export market. The declining water quality is a decisive factor on the crop choice and dates being highly salt tolerant are being prioritized for the crop cultivation. The crop choice should focus on the one hand on the water productivity and on the other hand on the guarantee of the farmer's income [21]. However, with the majority of farmers being subsistence farmers or rely on their farm to provide for their livelihoods [21], this could have extensive socio-economic consequences, which would need to be assessed by in detail by further research. The integration of farmers in the energy sector by employment in upcoming energy industries could be a measure. The energy sector itself has a low overall impact on the reservoir or groundwater storage levels. However, as the potential for water shortages is high, impacts on the power sector can be expected in the form of unmet demand for cooling or cleaning purposes.

It must be considered that WEAP lacks in groundwater modelling accuracy and is, therefore, bonded with high uncertainties. It cannot be taken into account important parameters such as aquifer characteristics, interactions, soil properties, etc. Thus, in future studies, other models like MODFLOW could be linked to WEAP in order to achieve more certain quantitative analysis which is also suggested by Johannsen *et al.* [21] and by Amin *et al.* [26].

Water demand in the oases and households

The total annual water demand of the Drâa Valley and the city of Ouarzazate by scenario and demand site is shown in Figure 8. Figure 8 points out the future trend of the water resources demand in the Drâa Valley which is similar for the different scenario combinations. Figure 8a shows solely the results for the CSP-PV NOOR Tata system supplied by the Mansour Eddhabi dam, as the water demand percentages of the different sectors show negligible differences in the different scenario combinations. In the model year 2011, around 306 million m^3 of water is required to meet the demand of the Drâa Valley and the city of Ouarzazate. In the first operational year of NOOR$_o$ Ouarzazate (model year 2016) the total water demand is around 318 million m^3 in S1. Of the total water demand, 0.94% is required for domestic use and livestock farming needs 0.2%. The largest proportion (98.18%) of the water demand is used for agricultural purposes other than livestock farming. The energy sector consumes in 2016 0.69% (S1), 0.58% (S2) and 0.78% (S3) of the total water demand. Until model year 2050, the water demand differs hugely in the three different socio-economic scenarios. The largest water demand is shown in S2 where, due to the annual increase in cultivated land, the water-intensive sector consumes 458 million m^3 (out of 467 million m^3 of total water demand) in model year 2030 and 630 million m^3 (out of 643 million m^3 of total water demand) in model year 2050. S1 shows a slight increase in total water demand, because population growth increases at a lower rate in the urban areas and declines in the rural areas. Furthermore, S1 assumes constant irrigation efficiency in the agricultural sector. Hence, in S1 by model year 2050 the total water demand is expected to be almost 340 million m^3. Only S3 shows a steady decline in the total water demand, reducing to 238 million m^3 in model year 2050. This is due to the implementation of irrigation technologies with high efficiencies assuming an annually overall increase in irrigation efficiency of 0.75%. In addition, the crop share in S3 reduces water demand in general, as fewer water-intensive crops are planted (Figure 4). The reduction in date cultivation, which needs more than twice the amount of water than wheat, combined with a significant reduction in watermelon cultivation, reduces the water demand in agriculture. Population growth in the cities has greater impact on water use than in the rural areas. The urban population consumes 50 L/day in S2 and S3, in rural areas the water use is 30 L/day in both scenarios. Nevertheless, the water consumption per capita remains lower in southern Morocco compared to other regions of the country [50] and also lower or at the threshold of 50 and 100 litres of water per person per day which are needed to ensure that most basic needs are met according to the World Health Organisation (WHO) [62].

Figure 8. Annual total water demand by scenario (a); water demand by demand sites for: S1 (b); S2 (c) and S3 (graphs by demand sites do not include demand for NOOR Tata) (d)

Water demand for potential solar energy system NOOR Tata

With regards to the water demand in the energy generation systems, the results show that the proportion of water used in this sector is in general very low, amounting on average to between 0.58% (S1), 0.4% (S2) and 0.74% (S3) of the total water demand. The water authorities have already assigned 1 million m^3 for the water use per year for NOOR Tata to MASEN. In this paper, the system design calculates the water consumption for the average case. However, the power plant's capacity is set in the way that even with higher water consumption the assigned threshold is not passed.

Considering the water demand of the different solar technology option, a solar tower with Air Cooled Condensers (ACC) cooling technology uses around 80% (0.7 L/m^2) of the total water consumption for mirror cleaning [63]. It is assumed that the CSP plant has 61 cleaning cycles and the PV plant 24. The proposed hybrid CSP-PV system with ACC would use 597,434 m^3 of water, which would still be within the assigned threshold. According to experts, the water use range for a solar tower with dry cooling technology in southern Morocco lies between 0.2-1 m^3/MWh with simulation uncertainties of +/–20%. In comparison, a wet cooling technology in CSP plants consumes approximately 90% of the total water consumption only for cooling purposes. Specifically, the water rate in wet cooling technologies ranges between 1.8-5 m^3/MWh depending on the site and CSP technology [1].

The option to implement a PV only complex would save almost 520,000 m^3 of water. The total annual water consumption for cleaning purposes at the PV complex amounts to 80,640 m^3 with the same cleaning cycle assumed. Figure 9 compares annual water consumption and energy production for both hypothetical solar power plant configurations: hybrid CSP-PV system with 180 MW CSP and 420 PV capacity and 600 MW PV system.

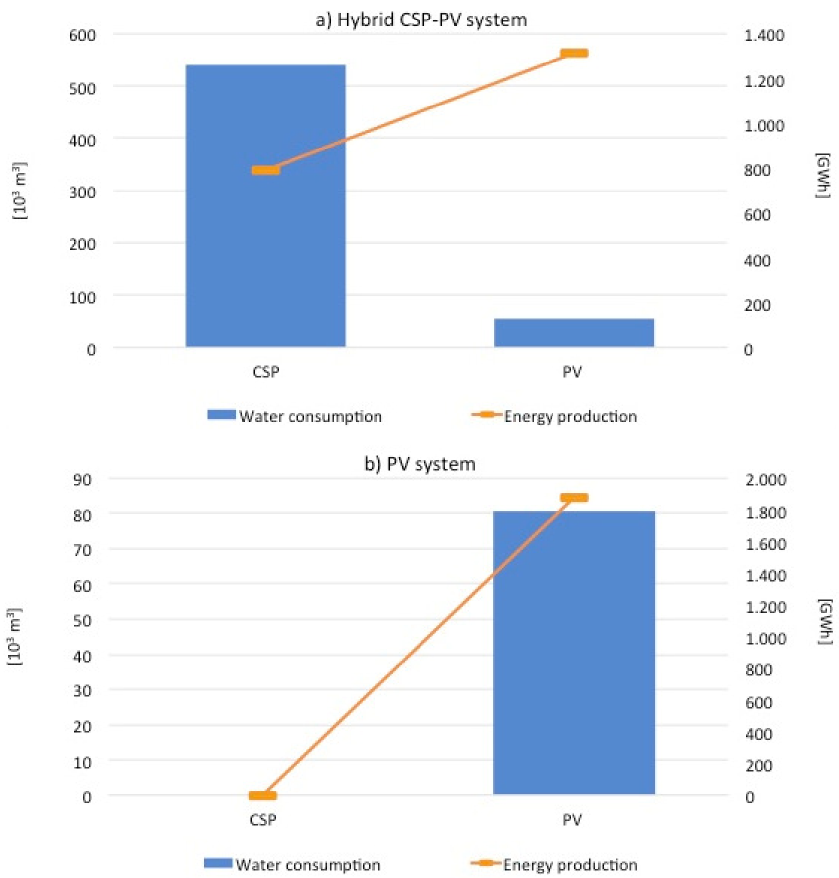


Figure 9. Annual water consumption and energy production of different power plant configurations

The results show that the water demand for the energy production sector has a very small impact on the water demand in the Drâa Valley, compared to the agricultural sector. However, differences are visible in the different cooling technologies of the CSP plants. These differences may seem negligible at first sight, but the implementation of the most water-saving CSP cooling technology can make an impact in very water-scarce regions.

Unmet water demand in the oases and households

Unmet demand is defined as the water amount that cannot be satisfied by water supply sources to cover a water demand site properly. The model results show that the way that water is used now and in the future could result in high unmet demand which can lead to water stress and water scarcity which was found for the region as well in Johannsen *et al.* [21] and in Droogers *et al.* [24]. Figures 10a-d show the results for the case of the hybrid CSP-PV NOOR Tata system and a Mansour Eddhabi dam supply while Figures 10b-d do not include the results of the unmet water demand in rural households and NOOR Tata. In all the model decades, the reservoirs cannot cope with long droughts as their storage volume steadily declines which results in unmet demand (Figure 10). The groundwater reserves are the highest by end of the first model decade and at the beginning of the second model decade, and are capable to buffer water demand for the oases. By the middle of the first model decade (2011-2020) and by end of the second model decade (2021-2030), the unmet demand increases as a consequence of a lack of surface water. The greatest impact can be seen in S2, due to its higher water demand throughout all model decades and its increasing size in irrigation area. The model decade between 2031-2040 is characterised by unmet water demand mainly in S2, in S1 and S3 the last years of the same decade and the beginning of the last decade show some peaks in unmet demand as a result of consecutive dry years that cause stress, in particular in S2.

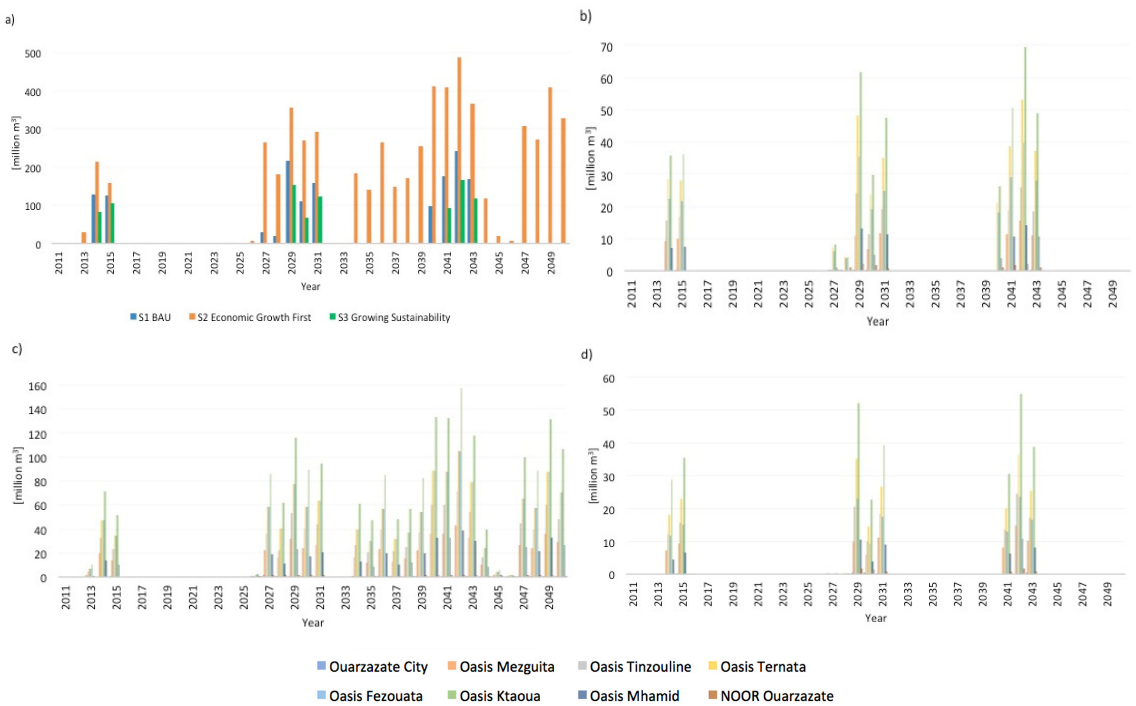


Figure 10. Total unmet demand by scenario (a); unmet demand by demand site for: S1 (b); S2 (c) and S3 (d)

The highest unmet demand (487 million m^3) is in model year 2042 for S2, caused by an extremely low inflow into the reservoir. In this model year, both the groundwater and reservoirs storage areas are empty in S2. After a refill of the reservoir by the middle of the last decade due to large precipitation events, the unmet demand is reduced in all other scenarios, but in S2 the unmet demand shows peaks again.

The unmet demand reflects the high demand in the cities and in the oases. The highest unmet water demand is in the Ktaoua oasis, which is the largest and requires more water for irrigation. Mhamid is the southernmost oasis and its cultivated area is the smallest due to climatic conditions. As a result, it has the lowest unmet water demand in all scenarios. Comparing the ratio between water demand and unmet water demand, for S1 shows 27% of water demand being unmet, for S2 63-66% and for S3 22-24%.

In summary, high unmet demand can be attributed mainly to irrigation in agriculture. The greatest impact is shown by the cultivated area size and its crop share which was found as well in Johannsen *et al.* [21]. In order to tackle the high unmet demand in agriculture, subsidies for the introduction of better irrigation techniques could help to reduce the overall water demand, as seen in S3. El Hwary and Yagoub [64] suggest skipping irrigation at certain plant growth stages and this option should also be studied for the Drâa Valley.

Unmet water demand in NOOR Tata

In the case of the power plants unmet demand would have to be compensated by lower water use in agriculture. In examining the energy scenarios more closely it becomes clear that the probability of unmet water demand differs mainly due to the different solar technologies options. In the assumptions, NOOR Tata could be either a hybrid CSP-PV power plant or a PV only power plant. The supply sources also vary: the power plant is supplied by either the Mansour Eddhabi dam or the Tiouine dam. The results show that there is a negligible difference in unmet demand by supply source. However, variations are clearly shown for the use of different solar energy technologies. The worst-case scenario would be a hybrid CSP-PV system with water supplied by the Tiouine dam.

Figure 11 allows for greater examination of the different supply sources and solar energy technology options. It compares the unmet water of the potential hybrid CSP-PV system (Figure 11.1) for the two different supply sources Mansour Eddhabi or Tiouine dam and three socio-economic scenarios S1 (Figure 11.1a), S2 (Figure 11.1b) and S3 (Figure 11.1c), and the unmet water demand of the PV system under the different supply sources and socio-economic scenarios (Figure 11.2a-c). The blue lines stand for the Mansour Eddhabi dam supply source, the red lines for the Tiouine dam.

The highest unmet demand for NOOR Tata occurs in S2 with 59% when the Tiouine dam supplies the water, whereas a supply by the Mansour Eddhabi dam can lower the unmet demand to 56%. In S1, 22% of the water demand is being unmet for NOOR Tata in both supply source cases. In S3, 20% of the water demand is being unmet in all cases and combinations, except for an implementation of a PV only system and a supply source of the Mansour Eddhabi dam which lowers the unmet demand to 17% and presents itself the best solution. The results show that there will be supply shortages for the energy sector in particular in years where the surface water is low. This is the case for some years in the second and last model decade, which are visible in all three socio-economic scenarios. In addition, a supply by the Tiouine dam increases the number of years of unmet demand as shown in the model years 2033 in S2 and 2028 in S3 for the case PV system and Tiouine dam supply.

The unmet demand for all demand sites, including households, agriculture and energy sector, in S1 is 27%, when NOOR Tata is supplied by the Tiouine or the Mansour Eddhabi dam, in S2 66% of the water demand cannot be met for all demand sites, when the Tiouine dam is the supply source, in S3 24% of the water demand is unmet demand, when NOOR Tata is supplied by the Tiouine dam. If the Mansour Eddhabi dam supplies the water for NOOR Tata, S2 has 63% of unmet demand for all demand sites and S3 22% of unmet demand.

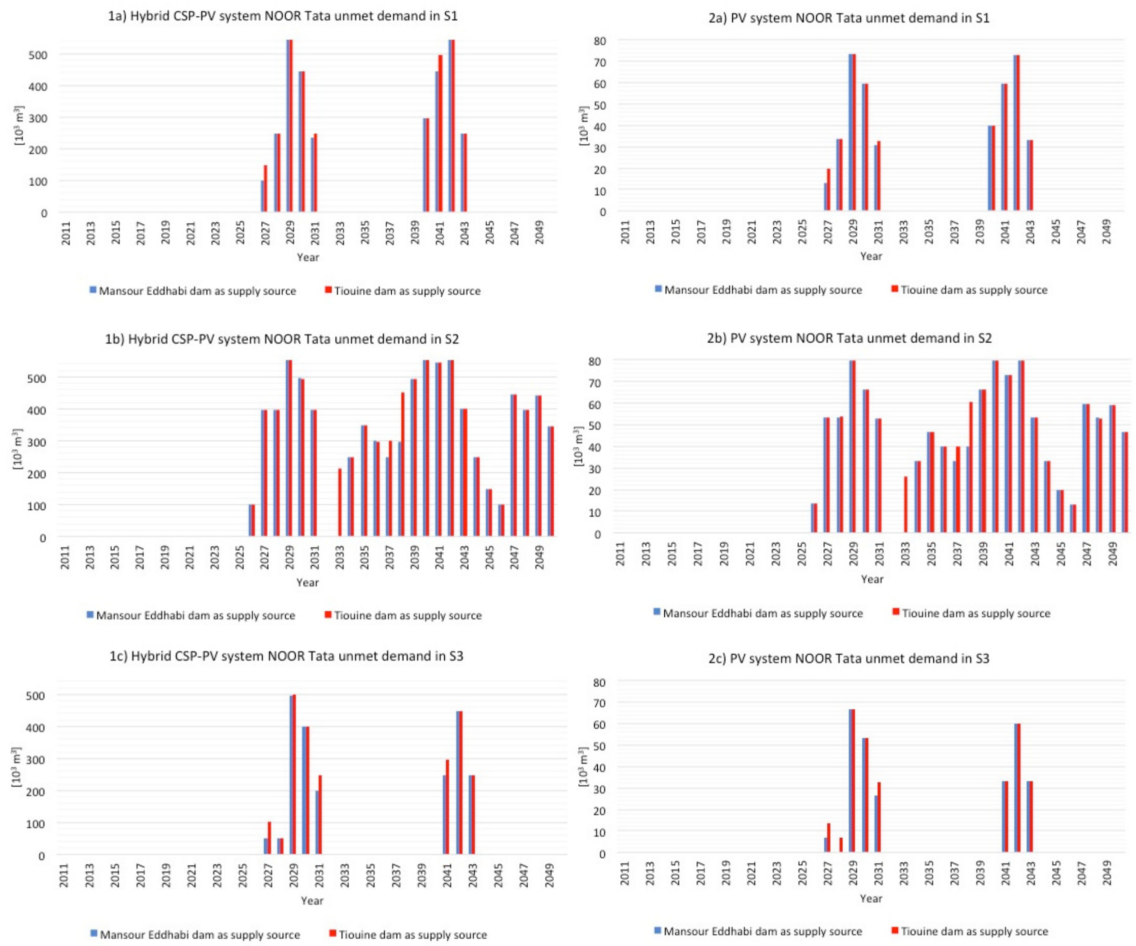


Figure 11. Different water supply options and socio-economic scenarios: 11.1 – Unmet demand for NOOR Tata as a hybrid CSP-PV system and 11.2 – Unmet demand for NOOR Tata as a PV system

From a technology standpoint, the best-case scenario would be the application of a PV only system. However, with the application of a PV system the unmet demand will still occur according to the model results. To tackle water shortages, particularly in dry years, alternative supply sources should be taken into account. According to some experts, one measure could be the transportation of water in tanks from the coast. As the construction of seawater desalination plants are already an element of the Moroccan water strategy, water tanks from these desalination plants could be an option to supply energy sites in water-scarce regions. However, this strategy could generate conflicts as other sectors and, for instance, farmers would also suffer from the water shortages. Therefore, further research in form of a cost-benefit analysis could help to evaluate this option and as well the question, if desalinated water could supply all other remaining sectors as well, could be studied. Further options could be to build PV panels on the reservoirs which could lower evaporation losses of the dams and increase the PV cells efficiency due to a cooling effect of the water or to combine PV with agriculture in form of agrivoltaics which is emphasized as well by Dinesh and Pearce [65], who studied the potential of agrivoltaic systems, by Majumdar and Paqualetti [66] who applied this approach to Phoenix and by Malu *et al.* [67] who analysed this system for an Indian case study. Apart from that agrivoltaic systems have the capacity to increase the land productivity, PV arrays could act as rainwater and irrigation runoff channel. Using PV in conjunction with a sprinkle irrigation system, the water sprinkled on the PV modules could have a cleaning effect and drain off on the crops for irrigation and increase the water usage efficiency [65]. Therefore, on-going and further research on panel and mirror cleaning is essential. It can be expected that the water amount for cleaning will decrease in future, as e.g., electrodynamic screen cleaning methods [68], collecting dust fences and mirror sensors show promising alternative water use-efficient ways according to experts. All these methods could contribute to a successful reduction in unmet demand for future solar power plants in water-scarce regions.

It must be pointed out that certain energy parameters (e.g., temperature increase that affect the solar modules efficiencies and the energy generation output) cannot be considered in WEAP, but have to be integrated exogenously. Therefore, the results for the water consumption in NOOR Tata are subject to high uncertainties. However, the results still give a profound understanding of possible future trends.

CONCLUSIONS

The results show that the development of solar energy in southern Morocco could be put at risk by water scarcity under severe global climate change conditions. In addition, farming in the Drâa catchment, which is already at risk today, could be affected even more severely in the future. The WEAP model shows that the population in the Drâa Valley is strongly dependent on the surface water supply originating from the High Atlas Mountains. Groundwater resources can solely compensate for a short period and will become exhausted, as the groundwater table is declining and recharges cannot compensate for the excess in water pumping.

The results of the model also indicate that the way that water is used now and in the future, either for energy production or farming, could lead to high unmet demand resulting in water stress and water scarcity. According to some experts, these consequences are already leading to tensions within the local population manifested in the form of protests. Implementing a new power plant that consumes water could intensify water problems and alternative supply sources must be assessed to overcome potential conflicts.

The modelled scenarios already include water saving and conservation measures like better irrigation techniques, reservoir siltation control, crop choices and different solar energy technology options with dry cooling technology. Higher irrigation efficiencies such as drip irrigation for example would reduce the overall water demand in agriculture, which is the highest water consumer. Crops such as watermelons or dates intended for the export market, require the most water. Though, dates are a traditional crop and have a higher salt tolerance, which is a decisive factor in a region with decreasing water quality, the choice of crops should focus on water productivity and guaranteeing farmer's income. The option to skip irrigation at certain plant growth stages is suggested as well by experts and should also be examined for the Drâa Valley.

Regarding the development of renewable energy in southern Morocco, where water has a high value, the results show that solar energy uses the least water, if PV technology is applied. However, the highest energy generation outputs are given, if the hybrid CSP-PV technology is implemented. As long as PV cannot meet the energy demand during the evening peak hours and batteries have a high cost, the hybrid CSP-PV systems that is highly dispatchable and able to quickly ramping up presents itself as the better option. With the overall share of water consumption for the energy generation being low independent of the solar technology option technology costs, efficiencies and capacity factors of different technologies will most likely be the decisive factors for the power plant configuration. However, in the future this low water demand for energy production may also compete with other sectors such as agriculture.

In order to show possible solution pathways to reduce the high unmet demand for the different sectors under severe climate change conditions, further research needs to be conducted, for example on bringing desalinated water inland and on what impacts further dam constructions could have on the water system in the Drâa Valley. PV panels on the reservoirs or agrivoltaics could be considered as well, because, these concepts combine the water, energy and agricultural sector, with an integrative approach. However, these PV concepts should be analysed within storage solutions, because, according to experts, PV should be only increased, if storage solutions are added to this concept. These options should be studied for the Drâa Valley following both participative approaches and technical methods. In order to safeguard a sustainable development, the upscale of solar power plant should take the needs of the communities in which they are sited into account and ensure their participation. The results of this study could be transferred to discuss the development in other water-scarce regions in Morocco that could become potential large-scale CSP sites.

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NOMENCLATURE

A	effective aperture area	[m^2]
E	energy	[kWh]
ET_o	actual evapotranspiration	[mm]
G	global irradiation	[kWh/m^{2}y]
I	irradiation	[kWh/m^{2}y]
K_c	crop factor	[-]
P	power	[kW]
Q	quality factor	[-]

Greek letters

η	efficiency	[-]

Abbreviations

ABH	Agence Du Basin Hydraulique
ACC	Air Cooled Condensers
AR5	Assessment Report 5
ArcGIS	Arc Geographic Information System
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiation
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiation
HCP	Haut Commissariat Au Plan
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LEAP	Long-Range Energy Alternatives Planning System
MASEN	Moroccan Agency for Solar Energy

MERRA	Modern-Era Retrospective Analysis for Research and Application
MSP	Moroccan Solar Plan
NOOR	Solar Energy Projects in Morocco (From Arabic: 'Light')
NREL	National Renewable Energy Laboratory
ONEE	Office National De l'Electricité Et De l'Eau Potable
PAREMA	German-Moroccan Energy Partnership
PV	Photovoltaic
RCP	Representative Concentration Pathway
SRTM	Shuttle Radar Topography Mission
STC	Standard Test Conditions
STE	Solar Thermal Energy
WEAP	Water Evaluation and Planning System
WHO	World Health Organization

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