Water Use for Electricity Generation in North Africa - a Meeting Point for Energy and Water Policies

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Key-words: power sector; water for energy; water scarcity; climate mitigation; climate change; water-energy nexus; water withdrawal; water consumption; water usage; electricity production; North Africa

Abstract

Freshwater is a scarce resource in the MENA region and, thus, in North Africa (Morocco, Algeria, Tunisia, Libya, and Egypt). North Africa experiences simultaneously economic and population growth, while the water availability is changing due to climate change. Therefore, electricity generation is expected to increase both per capita and in absolute numbers, which may challenge the freshwater availability even more. This study focuses on the current and future freshwater use for power production in the region (coal, gas, oil, hydropower, wind, solar photovoltaic (PV), and concentrated solar power (CSP)), for the current situation and for the year of 2040 for three energy scenarios (BAU, NEP, SUS). Freshwater use is calculated only for the operating phase of power plants. Furthermore, current and future water stress is calculated at watershed level for each of these countries.

The developed approach starts by characterizing (technology type, capacity, cooling system, etc.) and locating the existing power plants in the 28 considered watersheds in the region. This is followed by the assessment of water usage in each one of the 125 considered plants through water use factors for the currently installed capacity, using a range of minimum and maximum water withdrawal and consumption factors from literature. Future power plants evolution scenarios till 2040 are developed projecting an increase of generated electricity from current values from 306% to 397% for the region, depending on the considered scenario. Finally, water stress (i.e. if water use is higher than 40% of available water) is calculated comparing water volumes used with current and future water availability using both current run off data and future climate change impact scenarios addressing possible changes in water availability. Additionally, a sensitivity analysis is conducted to investigate the importance of future CSP cooling system types, the potential location of new renewable energy sources (RES) installed capacity, and the competition among economic sectors regarding freshwater.

The results show that by 2040 the future water usage for the power sector in the region can vary between -13% to +37% from current values, depending on the energy scenario and, mostly, on the type and efficiency of cooling systems in place (i.e. that affects the water usage factor being considered). Thus, for the BAU scenario the future water usage compared to current usage can vary from an increase of 25-27%, 21-37% for the NEP scenario and -13-36% in the SUS scenario, where the range reflects the range of possible water use factors. The increase in generated power does, hence, not translate in a corresponding increase of water use, since much of the new capacity is expected to be wind and solar. The range in future water use is dependent on the amounts of future installed hydropower and fossil fuels capacity, while other RES do not significantly influence the variation in water use. For the RES power plants (including hydropower), the future water usage in 2040 will vary by -23% to +74% from current values. For fossil power plants the future water use can vary from -22% to +109% from current values, due to the different scenarios regarding the deployment of mainly new tower an dry cooled gas power plants.

It was found that there is no water stress in any of the analyzed watersheds solely caused by water use for power production, both currently and by 2040. However, the power production in the watersheds in the Atlas Mountain range and in the Sinai Peninsula use substantial amounts of water for power production (up to 18.75% of run-off). The more sustainable electricity scenarios do not necessary lead to lower water stress, since they can consider an increase of hydropower which uses substantial amounts of water. Potential future water stress levels could, moreover, be decreased through the allocation of new RES plants in less water scarce areas. By considering also water withdrawal in other economic sectors, electricity generation increase could contribute to water stress in all countries except for Tunisia. The main limitations of the analysis are the need for more precise data on available water in the region, the water consumption and withdrawal of individual power plants, and the uncertainties associated to the developed power sector scenarios per country. Moreover, if climate change impacts regarding water availability are higher than what was considered in this report and/or the electricity generation growth is higher, the potential future water stress will be further exacerbated. Finally, the consideration of water use in hydropower could be debated, especially because no detailed information was available on the type of hydropower plants (reservoir or run-of-river). Nonetheless, this analysis can be expanded, improved, and replicated.

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Abbreviations list

BAU – *Business-As-Usual*
CII – *Climate impact indicators*
CSP – *Concentrated Solar Power*
EIA – *Energy Information Administration*
GDP – G*ross Domestic Product*
GHG – *Greenhouse Gases*
GIS – *Geographical Information System*
HYPE – *Hydrological Predictions for the Environment*
IEA – *International Energy Agency*
MOEE – *Ministry of Electricity & Energy*
NEP – *New Policies*
NREA – *New & Renewable Energy Authority*
OECD – *Organisation for Economic Co-operation and Development*
PV – *Photovoltaic*
RCP – *Representative Concentration Pathway*
RCREEE – *Regional Center for Renewable Energy and Energy Efficiency*
RES – *Renewable Energy Sources*
RES4MED – *Renewable Energy Solutions for the Mediterranean*
SMHI – *Swedish Meteorological and Hydrological Institute*
SUS – *Sustainability*
TREC – *Trans-Mediterranean Renewable Energy Cooperation*
USGS - *United States Geological Survey*
WNA – *World Nuclear Association*
WPR – *World Population Review*
WRI – *World Resources institute*
WWF – *World Wildlife Found*

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1 Introduction - The North African Part of the MENA region

The Middle East and North Africa (MENA) region is using water in an unsustainable way which will be exacerbated in the future by a growing electricity and water demand in absolute terms and per capita (Farid, Lubega, & Hickman, 2016). Without water security, the security of other sectors is also in danger, as well as a sustainable economic growth. This region is generally water poor and is facing a projected decrease in its economic growth rate (Aawsat, 2019).

1.1 Setting the scene – energy and water in North of Africa

A secure energy supply has been a fundamental factor to enable economic growth (Pappis et al., 2019). Roughly 97% of the population in North Africa in 2017 (excluding Egypt) had access to electricity. However, for a large share of this population electricity access unstable access and facing frequent outages. Moreover, restricted access to energy could potentially affect water pumping leading to negative effects on agricultural production and drinking water supply (Pappis et al., 2019).

Africa possesses multiple energy resources in fossil fuels and renewable energy sources (RES). Despite that, the total installed capacity of electricity in the continent (i.e. 165 GW in 2015) is about nine times less than the one of Europe (i.e. 1,519 GW in 2015) (Pappis et al., 2019). In many areas of the Earth, power sector regulations promote the clean energy transition. In particular, Africa aims to provide affordable electricity from solar, wind, and hydro (i.e. about more than 60 GW by 2040) resources (IEA, 2018).

A specific innovative project that aims at the valorization of the potential energy resources of Africa (and particularly, North Africa) is DESERTECH (TREC, 2007). This project aims for decarbonisation through the production of power by concentrated solar thermal power plants (CSP) in the desertic areas of the MENA region and transmit it with low losses by High Voltage Direct Current (HVDC) lines to up to 90% of the global population. This also represents an opportunity for Mediterranean regions of Europe, the Middle East and North Africa (EUMENA) to constitute a united group of nations for energy, water, and climate security, with the goal of a harmonious and peaceful future (TREC, 2007).

On the other hand, water issues are a serious issue in the MENA region. Many problems have arisen due to the increasing demand for water, competition for water across economic sectors (e.g. agriculture *versus* industry), inadequate adjusted policies, and the potential decrease of water run-off caused by climate change (FAO, 2018).

Already now, the MENA region is one of the most water scarce regions in the world, with most of the area receiving less than 300 mm in annual precipitation (Pathirana, Perera, & Hobeichi, 2015). It should also be underlined that the average global water availability per capita is approximately 7,000 m^3/person/year. However, in MENA countries this value is around one seventh, (1,200 m^3/person/year) (Pathirana et al., 2015). Climate change will further exacerbate dry seasons and extreme events in MENA, with possible decreases in precipitation from 15% – 45% for a temperature increase of 2 °C by 2100 and up to less 75% precipitation for a temperature increase of 4 °C by 2100 (Waha et al., 2017). Currently there is already a moderate to severe water scarcity in North Africa for more than half of the year (Mekonnen & Hoekstra, 2016).

Additionally, according to (Pathirana et al., 2015), approximately half of the countries use more water than they accumulate in the MENA region. Irrigation alone consumes about 85% of the water available. This is in contrast with the concept of natural renewable water, which is considered as the quantity of a country's water resources produced through the hydrological cycle with the inclusion of surface water and groundwater (FAO, 2003).

Despite the high share of water used for agriculture, the MENA region is currently very dependent on food imports, which makes its countries vulnerable to food prices (Pathirana et al., 2015).

1.2 Importance of water-energy nexus in North Africa

This highlights the importance of both, water and energy in North Africa. A framework for environmental management and policymaking which is getting increasing attention is the water-energy nexus (Howells et al., 2013). The urgency of a nexus thinking comes primarily from the fact that interlinks make it easier to deal with rising resources scarcity and supply crises, but also because of the failure of sector driven management planning (Al-Saidi & Elagib, 2017). The fundament of the nexus is to analyze the interdependent resource issues of water and energy by an integrated framework. Currently, this is not standardized, and the integration process depends on the context. Therefore, the nexus can be developed differently according to the existing resource connections in a certain geographical area and the purpose of the respective analysis (Al-Saidi & Elagib, 2017). However, Farid et al. (2016) (p. 1) attempted a definition of water-energy nexus as "a system-of-systems composed of one infrastructure system with the artifacts necessary to describe a full energy value chain and another infrastructure system with the artifacts necessary to describe a full water value chain".

Therefore, an important tool to analyze water systems is the zonation of an area into watersheds. The term watershed has been defined by Goenenc, Vadineanu, Wolflin, and Russo (2007) (p. 5) as an "area of land, a bounded hydrologic system, within which all living things are inextricably linked by their common water course and where, as humans settled, simple logic demanded that they become part of a community".

This approach helps in the coordination of environmental management for public and private sectors on how to prioritize and solve issues within defined hydrogeological areas or watersheds. Furthermore, aquatic ecosystem problems are not connected to an individual anthropogenic activity near a river or lake, but to several single activities in every part of a water body's drainage area, catchment area, or watershed (Goenenc et al., 2007). This is the approach used in this report to study water use for power production in North Africa.

1.3 Research Questions and Scope

The overarching objective of this study is to assess the current and future water use for electricity generation in North Africa. To do so, the following research questions were developed and addressed in this report:

- Which technologies are currently used to generate electricity and how can future power plants capacity be located across watersheds in North Africa?
- How does the water usage pattern for operation of power plants currently look like and how will it evolve?
- How will the water stress level evolve in the future due to climate change and expansion of the power sector?
- To which amount can the possible future water use for power generation scenarios be affected by certain assumptions?

These questions were applied over the five North African countries of Algeria, Egypt, Libya, Morocco, and Tunisia for the current situation and the future (year of 2040, starting from existing energy scenarios from the International Energy Agency or IEA combined with national strategies). It should be mentioned that the "current situation" is a combination of data from 2012 to 2019, with substantial power plant data from 2017.
The questions are of extreme relevance because of an ongoing population growth, an expected economic growth, a subsequent large expansion of the power sector, and severe climate change impacts, while water is already a very rare commodity in this region.

Furthermore, power generation in North Africa is a debated and complex issue (IEA, 2018; Pappis et al., 2019; TREC, 2007). To reach a steady economic growth, the availability of a stable energy supply is fundamental, which is not yet reached in North Africa. For example, as mentioned by Farid et al. (2016), power plant output had to be reduced in the past because of heat wave episodes; creating a gap between electricity demand and the available energy supply. This highlights the vulnerability of the current (and planned) North African power supply infrastructure to climate change and water use for cooling.

Finally, this report is only focusing on assessing water use for power generation during the operation phase (thus, water footprint for example from fossil fuel extraction is not considered) and only for electricity generated with surface freshwater. Many of the North African power plants are located at the coast. Coastal power generation facilities often utilize sea water and are, hence, not considered here as vulnerable to water scarcity.

1.4 Outline of the report

This report is structured in five sections besides this introduction. The following section presents a review of relevant literature regarding the region's power sector and most relevant studies on water use for power generation. This is followed by the methods section outlining the approach developed in this work. Section 4 presents the obtained results regarding characteristics of current and future power plants, current and future water use and water stress per watershed, and a sensitivity analysis. Section 5 concludes and discusses the limitations of the performed analysis.

2 Literature Review

This section gives an overview on related research, the definition of terms used regarding the calculation of water stress, and electricity production in the North African region, as well as a short outline on the studied area.

2.1 North Africa and electricity production

The assessed area includes the five countries of Morocco (including Western Sahara), Algeria, Tunisia, Egypt, and Libya, see Figure 1 below.

Figure 1 – The five North African countries analyzed in this study.

Table 1 presents general information on these five nations in 2017 (The World Bank, 2019a), their electricity production in 2017, according to the IEA (2019), and their GDP in 2018 (The World Bank, 2019b). The population density is, in some countries, rather low because the Sahara Desert occupies a big share of land in North Africa.

Table 1 – General information on the countries included in this report. Data are from IEA (2019); The World Bank (2019a, 2019b).

Country	**Area [thousand km^2]**	**Inhabitants in 2017 [million]**	**Population density in 2017 [inhabitants/km^2]**	**Electricity production in 2017 [TWh]**	**Electricity production per capita in 2017 [kWh/ inhabitant]**	**GDP in 2018 [billion US$]**
Algeria	2’380	41.4	17.4	76.0	1’836.2	180.7
Egypt	1’002	96.5	96.3	188	1’948.6	250.9
Libya	1’760	6.6	3.7	36.8	5’592.7	48.32
Morocco & Western Sahara	713	35.6	49.9	33.2	933.1	118.5
Tunisia	164	11.4	69.7	20.6	1’802.3	39.9

Egypt is the country in North Africa with the most densely populated area (i.e. 96.3 inhabitants/km^2), the highest GDP, and the country with the highest electricity generation (even if Libya has the highest electricity generation per capita). Libya is the least densely populated with the Sahara desert occupying almost the entire country. Morocco produces the least electricity, although the population was 5.4 times the one of Libya in 2017 (i.e. 33.2 TWh in 2017).

All the five considered North African countries are developing countries (Pappis et al., 2019), therefore, it was challenging to retrieve transparent and accurate information on statistics in this region, especially with regards to the power sector and water use. This is especially the case in Libya which is since 2011 in very unstable conditions, as it was in a civil war (Zambakari, 2016).

2.2 State of the art research

There are already some studies addressing water usage for the energy sector with a special emphasis in North Africa and the entire MENA region. Table 2 shows the most relevant scientific literature regarding this topic, detailing their objectives, methods, and main results. Additionally, a comparison with the approach in this report is included.

Table 2 – Brief summary of aim, method, main results, and the difference to this report of relevant reviewed papers on water use for the energy sector mainly in the MENA region.

Source	Aim and method	Results	Difference to this report
Damerau, Van Vliet, and Patt (2015)	Analysis of current (2010) and future (2100) freshwater demand for energy extraction and conversion technologies in the MENA region. For the future assessment, three scenarios were considered.	Share of the region's renewable water resources that the energy sector currently demands is about 2%. This share increases to 11 % with RCP[1] 8.5 scenario due to a rise of unconventional fossil fuels extraction. The results from the scenario RCP 2.6 show no stress in freshwater demand for the energy sector. However, the MENA region is characterized by water scarcity and there is competition over freshwater within the economic sectors.	● No water-energy nexus analysis at country level ● Water withdrawal factors not considered ● All MENA region countries are included ● Different approach to formulate future projections ● Focus on total energy sector of the MENA region
Siddiqi and Anadon (2011)	Country level assessment of the energy-water nexus in the MENA region. Electricity requirements for water extraction, delivery, and disposal are of interest, as well as the water demand for electricity production.	Electricity generation in the MENA region is largely decoupled from freshwater use. Based on the coastal siting and the intense usage of seawater for cooling systems in power plants, the marine environment is affected. On the contrary, substantial energy is needed to supply water.	● Water consumption is considered but not water withdrawal ● No classification into watersheds ● No future scenarios ● Available freshwater is defined as annual renewable water supply, whereby groundwater is also included
Farid et al. (2016)	Investigation of pros and cons of holistic models that interface electricity systems and water systems, enabling an integrated management of the water-energy nexus in the MENA region. A more socio-economical approach is undertaken	The results include generic suggestions, such as reducing water leakages through embedded energy and the associated economic and environmental costs of these leakages. Also considered is an increase of water recycling to reduce the energy footprint of water supply, and the promotion of public-private partnerships to coordinate coupling points of both, power and water.	● No future scenarios available ● Inclusion of all water sector (i.e. wastewater, desalination of water) ● No water stress calculation ● Water withdrawal and consumption factor not utilized
Davies, Kyle, and Edmonds (2013)	Assessment model applied to estimate lower-, median-, and upper-bound withdrawal and consumption of water for the global electricity generation. Authors compare the used water with the available water in 14 created geopolitical regions in 10 Scenarios.	The shares of the different power generation technologies are defined until 2095. The total water withdrawal is in nine out of ten scenarios, in total numbers, similar to today's withdrawal. The water intensity (m^3/MWh), however, is decreasing in all the scenarios. This is mainly because of the shift in electricity technologies and the shift from once-through cooling systems into wet tower systems. Water consumption increases in all scenarios.	● Worldwide assessment with no further explanation within the regions ● No water stress calculation ● No analysis of watersheds
Klabucar and Simoes (2018)	Estimation of the water use by the power sector in Brazil in 2017 and in	Water withdrawal and water consumption per defined watershed are presented. It is estimated that in 2017 power plants consumed	● For Brazil only ● No adjustment of the water availability in the future

[1] RCP are representative concentration pathways scenarios. RCP4.5 translates an intermediate climate stabilisation pathways in which radiative forcing is stabilised at approximately 4.5 W m-2 by 2100, whereas RCP8.5 translates a pathway for which radiative forcing reaches greater than 8.5 W m-2 by 2100 (source: Stocker_2013)

	future scenarios for 2030 and 2050. In particular, the future scenarios are based on an increase of the average global temperature of 2°C, 4°C, and 6°C.	4,611 hm^3 and withdrew 10,787 hm^3 of fresh water. Since hydropower generated 75% (394.2 TWh) of electricity, they also represent the major category of water use. Water usage of the power sector is not exposing the country to water stress.	● No mathematical definition of the term water stress ● Water withdrawal of hydropower are considered
Simoes, Marogna, and Fortes (2017)	Assessment of water use for electricity production per watershed in the Iberian peninsula currently (2015) and in a conservative and optimistic scenario for 2050. Moreover, an investigation of potential water stress is done.	In 2015 it is estimated that 3,012 - 6,515 hm^3 and 424 - 2,984 hm^3 of water were withdrawn and consumed, respectively, for electricity generation. The first is due to operation of coal and nuclear power plants in Spain. In the future projections, the water withdrawn is half in both 2050 scenarios. At the same time, the water consumed can decrease of 5% or rise of 8% due to an increase of CSP and new hydropower plants in the area. Other than that, there is no water stress due to power sector.	● Water withdrawal of hydropower are considered ● For the Iberian peninsula only ● Different approach to collect data for water availability in future climate scenarios ● Different approach to retrieve data of annual average run-off ● No inclusion of water consumption factor in water stress quantification
Vassolo and Döll (2005)	Estimation of the global water usage of 63’590 thermoelectric power plants and industrial manufacturing in 1995. They used data for installed capacities with details on the cooling system for only 11% of the power plants.	Water usage is presented in a world map with a spatial resolution of 0.5° by 0.5°.	● Integration of manufacturing water use ● No comparison with available water ● No data about countries in North Africa ● Only two values for water withdrawal and water consumption, respectively, based on the cooling system (once through or wet tower) ● Results for 1995 ● No water stress calculation
Pappis et al. (2019)	Assessment of the water-energy nexus of African countries in order for them to reach the target global average temperature increase of only 1.5°C or 2.0°C. The reference scenario is based on population projections from the United Nations and the respective GDP projections. The existing energy demand was further calibrated with the historical energy demand. The considered years are: 2015, 2030, 2050, 2065.	The study forecasts that the total installed capacity in Africa will be ten times higher than now by 2065 and will reach 1,834 GW. It is projected that, in the reference scenario in 2065, the African energy system will withdraw about 4% of the total renewable water resources in Africa. If this number is taken into account together with the nexus between water for food, energy, household uses, etc.., this proportion is considered to be alarming. The 4% share is projected to be reduced up to 1.2% and 1.6% in the 2.0°C and 1.5°C scenarios, respectively.	● Average values for water withdrawal and consumption factors are used ● No water stress calculation ● Future projections of climate change are based on average global temperature and radiative forcing ● No country level ● No GIS maps ● Mauritania is included in results for North Africa ● No water consumption of hydropower ● Climate-induced changes in water availability are excluded

Overall, we conclude that approaches to assess water use for the power sector can vary substantially. Approaches can differ from socio-economic studies (e.g. Farid et al. (2016)) to quantitative evaluations including water withdrawal and consumption factors (e.g. Siddiqi and Anadon (2011)). The presented studies assessed the water usage in a comprehensive way, with more aspects of water usage than electricity production only, but on a country level or region level approach. Moreover, literature about the water use of electricity production on a watershed level in the North African country is missing. North Africa was investigated often as one region, within the MENA region, or defined with other countries than Morocco, Algeria, Tunisia, Libya, and Morocco, which is the approach of this report.

Furthermore, the approach undertaken in this report is a quantitative analysis. The water-energy nexus of North Africa, here presented, includes an analysis based on literature of water withdrawal and consumption factors for power production. Another relevant difference with respect to previous studies is that future scenarios are considered. In particular, the scenarios will include both, the evolution of the North African energy system and water availability changes according to climate change models.

2.3 The concepts of water withdrawal, water consumption, and water usage

The aim of this report is to assess how water used for power production could be affected by (or affect) concurrent water uses, both in the current situation and considering climate change. To do so, water withdrawal for power production is compared with available surface water run-off, since water withdrawal is generically defined in the literature "as freshwater taken from ground or surface water sources, either permanently or temporarily, and conveyed to a place of use" (OECD, 2018). In the specific literature on water use for power production, besides considering water withdrawal, the concept of water consumption is also explained. Water consumption refers to: "the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment " (Macknick, Newmark, Heath, and Hallett (2012), p. 2). Thus, water withdrawal should also encompass water consumption, although this is only clearly stated by (Medarac, Magagna, & Hidalgo González, 2018). This articulation of the two concepts is somewhat inconsistent for hydropower production, since literature sources report that hydropower has water consumption but no water withdrawal (Damerau et al., 2015; Davies et al., 2013; Macknick et al., 2012; Medarac et al., 2018).

Nonetheless, in this report, the authors assess water use for hydropower production, as the goal is to address possible water stress and thus, all types of uses of water for power production need to be included. According to (Wada et al., 2011), water stress occurs if more than 40% of the available water is demanded. However, already values between 20% and 40% can be a sign of looming water scarcity (Wada et al., 2011).

Therefore, the fact that the literature is somewhat unclear on the articulation of water withdrawal and consumption for hydropower, led us to assume here a hybrid approach, where we consider water use as all water withdrawal plus water consumption associated to hydropower production. This allows us to take into account water evaporation in hydropower reservoirs which is a relevant fraction of the water use. Water use factors vary, according to Macknick et al. (2012), with the type of plant, type of cooling system, the thermal efficiency, the water source, and the age of the plant and the cooling system.

Water withdrawal and water consumption are not only important regarding electricity production, but also for other sectors such as housing or agriculture. In the year 2000, water withdrawal in Africa was distributed across the following uses, according to Wada et al. (2011): agriculture with 83.1%, industry with 4.3%, and the domestic sector with 12.6%. This is a significantly higher share of withdrawn water in agriculture than in Europe at that time (agriculture: 29.3%, industry: 48.5%, and domestic sector: 22.2%).

Siddiqi and Anadon (2011) stated in 2011, that renewable water consumption in most parts of the MENA region caused by electricity production would be negligible and that electricity production in general is not dependent on freshwater in this region. However, they did not consider climate change and possible changes in the future power production in their analysis.

2.4 Evolution of the power sector in North Africa

Official strategies for the future electricity production in North Africa show the target years of 2025, 2030, or 2035, as in the found literature and on governmental platforms. A comprehensive overview with the main objectives for RES for each North African country is reported below in

Table 3. Therefore, national energy plans were reviewed but information about future energy plants are only scarce available.

Table 3 – North Africa RES and fossil strategies and targets for the future at country level from official energy plans.

Country	Strategy and goals	Source
Algeria	Goal of having a RES share in electricity production of 40% or 12’000 MW in 2035. ● Wind: 17% or 2’000 MW ● Solar PV: 23% or 2’800 MW ● CSP: 60% or 7’200 MW The other 60% of electricity will be fossil fuel based thermal power	RCREEE (2012a)
Egypt	Goal of having the following shares in electricity production in 2035: ● Fossil fuels: 55% ● Solar PV: 22% ● Wind: 14% ● CSP: 3% ● Nuclear: 3% ● Hydro 2% 42% (52 GW) of electricity is expected to come from RES	IRENA, Miketa, and Saadi (2015); ITA (2019); NREA (2019); WNA (2019)
Libya	Goal of having a RES share in electricity production of 10% or 2’219 MW in 2025. ● Wind: 45% ● Solar PV: 38% ● CSP: 17% The other 90% of electricity will be fossil fuel based thermal power	IRENA (2014); RCREEE (2012b)
Morocco & Western Sahara	Goal of an increase of RES in 2030 (4’875 MW) with a renewable installation of 52% of the total installation: ● Hydro: 17.9% (+ 875 MW) ● Wind: 41.0% (+ 2’000 MW) ● Solar PV: 20.5% (+ 1’000 MW) ● CSP: 20.5% (+ 1’000 MW) Biomass currently and in the future is used as biofuel	Ministère Maroc (2016b)
Tunisia	Goal of having a renewable share in electricity production of 30% in 2030. Installed capacities of RES in 2030 is 3’725 MW: ● Wind: 1‘755 MW (47%) ● Solar PV: 1‘510 MW (41%) ● CSP: 460 MW (12%)	ANME (2012); Baccari (2017); RES4MED (2016)

Table 3 considers mainly RES, as information about future strategies in the studied countries about thermal power plants is hard to find. RES capacity is planned to increase in all countries with a significant amount of new installation. This could lead to a big change in the power sector with up to 52% (Morocco) of the total installation in RES. Especially the potential new installation in Egypt would replace or avoid fossil technologies to a large extent. The IEA published their World Energy Outlook (IEA, 2018) with shares of each energy technology worldwide in 2018 and future in future scenarios for 2040. Shares for Africa are, therefore, also included but no shares for the region of North Africa or the five countries separately.

3 Methodology

This section presents the developed approach to address the research questions. Firstly we present how the electricity production in North Africa was characterized, followed by a characterization of the watersheds. To assess the used water regarding electricity production in each watershed, the used water withdrawal and consumption factors of each technology are presented in a further step. The approach for water stress calculation is then explained. In a last step, this section focuses on the considered future scenarios for both the power sector and water availability.

The overall methodological approach used can be summarized with the two following figures:

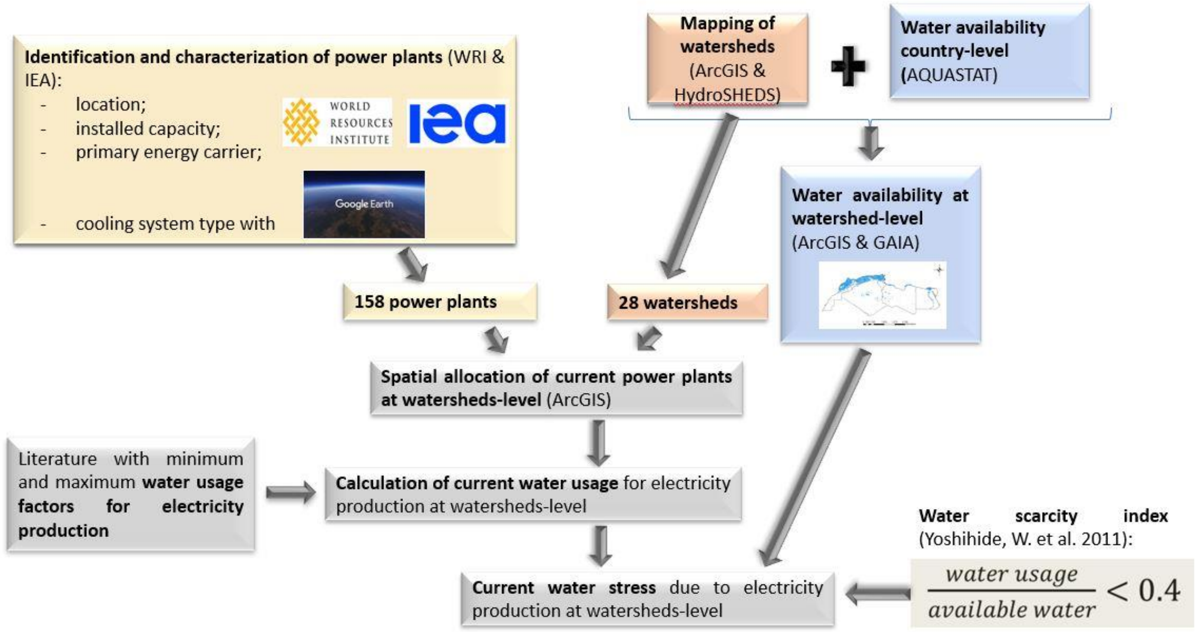

Figure 2 – Flow chart of the method applied to investigate current water usage for electricity production in North Africa.

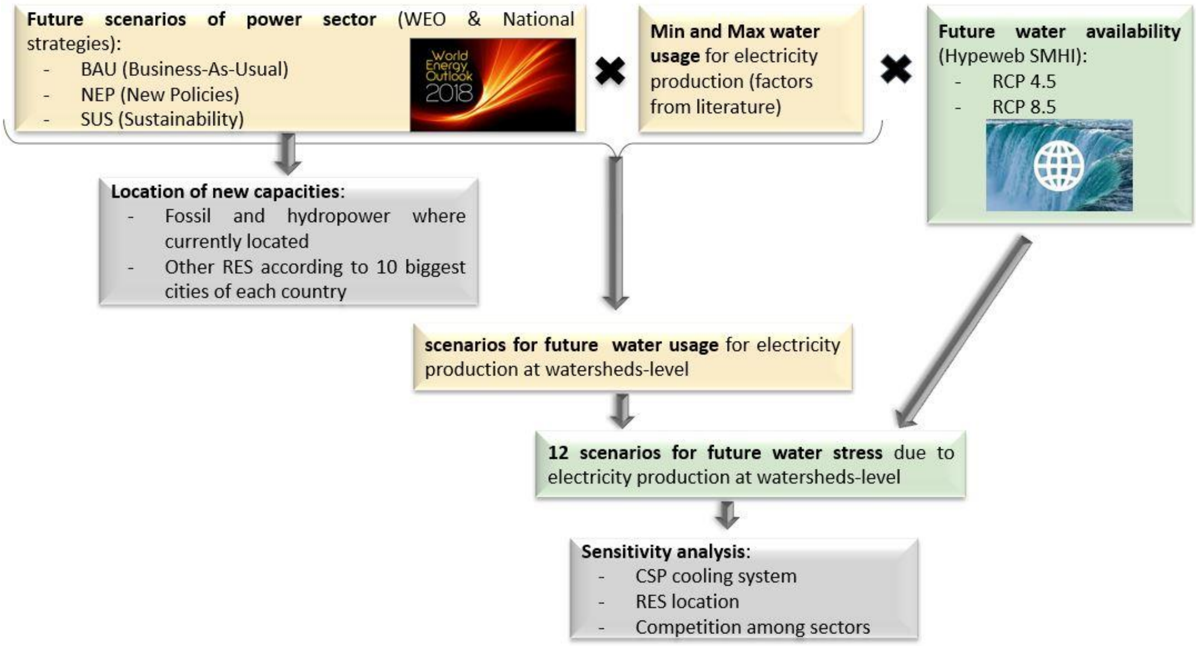

Figure 3 – Flow charts of the method applied to investigate future (2040) water usage for electricity production in North Africa.

Overall, the global approach is the following:

- Characterization of current power production technologies (location, type of plan, size, generate electricity and type of cooling system);
- Mapping the watersheds to be considered in the analysis and identification of current water availability;
- Allocation of the power plants within the mapped watersheds;
- Estimate of current annual water use for electricity generation per country and watershed based on water withdrawal and consumption factors from literature (surface freshwater use only) for both minimum and maximum literature ranges;
- Calculation of current water stress due to the power sector per watershed;
- Development of future scenarios for power sector evolution per country and type of plant for the year of 2040 (Business as Usual, New Policies, and Sustainability);
- Allocation of new future installed capacity for each scenario across the mapped watersheds;
- Systematization of future (2040) water availability per watershed for RCP 4.5 and RCP 8.5;
- Calculation of future water stress per watershed for future power and water availability scenarios in 2040;
- Sensitivity analysis regarding: (i) change in type of cooling systems of CSP plants; (ii) allocation of future RES power plants across watershed, and (iii) consideration of water usage in other sectors

3.1 North African electricity production

Power plant data, used for further calculations, was obtained by the open source database of the World Resources Institute (WRI, 2019), including information on the name, fuel, latitude, longitude, installed capacity, and the estimated power generation. A total of 158 power plants was characterized, of which 33 use seawater for cooling (for more information please see Supplementary Information). The estimated power generation data was not always available or complete with missing or inaccurate data for ten power plants in Egypt and three power plants in Morocco. For these power plants, we applied an estimated capacity factor of the different power plant types, which was multiplied with the individual installed capacity. Where necessary, runtime estimations are 6’319 h/year for coal power plants (EIA, 2011), 1’586 h/year for oil power plants (EIA, 2011), and 2’782 h/year for CSP plants (IEA, 2010). The resulting summed up power generation per country is presented in

Table 4.

Additionally,

Table 4 includes the assessed amount of generated electricity by the IEA in 2017 (source: IEA). Data from few Egyptian power plants (El-Seiuf, Banha, October 6th, Assiut, High Dam, and Ain Sokhna) and for the West Tripoli power plant in Libya were modified based on the source (MOEE, 2013) and (Auptde, 2016), respectively. The Al Wahda Thermal Power Plant in Morocco was excluded because there is no evidence for its current existence, but there is a plan to build it, according to Dr. Abdelkader Amara (Minister of Energy, Mines, Water and Environment) in 2025.[2]

According to Global Energy Observatory (GEO, 2019), the energy carrier in power plants in Libya is interchangeable between oil and gas. Furthermore, some data of the WRI (2019) in Libya show inconsistencies with the GEO (2019). For example the oil power plant in West Tripoli is reported as having only 185 MW in the database of WRI (2019) instead of 565 MW as in GEO (2019). Here, the value of the GEO (2019) was assumed. As all of the installed power in Libya is in one single watershed (detailed in the next section) and the overall generated electricity is very similar to data of the IEA, the generated electricity of the WRI (2019) is assumed for further calculations with the mentioned exception.

The highest difference of total estimated electricity generation, comparing data for 2017 from the IEA and the WRI (2019), occurs in Algeria with a disparity of 17%, followed by Morocco (16.7%) and Tunisia (10.2%), and the other two countries with values below 10%.

[2]http://www.mem.gov.ma/SitePages/Discours/GNLPoint%20de%20presseduDrAbdelkaderAMARA16dec2014.pdf

Table 4 – Generated electricity at country level for North Africa according to the WRI (2019) database for 2019 and the IEA (2019) for 2017.

Country	Electricity production based on analyzed data from the WRI [GWh]	Electricity production in 2017 from the IEA [GWh]	Difference of analyzed data and the IEA value [%]
Algeria	63’079	76’018	17.0
Egypt	178’479	188’159	5.1
Libya	37’731	36’797	-2.5
Morocco & Western Sahara	27’858	33’192	16.1
Tunisia	18’483	20’589	10.2

The electricity generation of RES (E_r), can be calculated as:

$$E_r = E_i \times c$$

where E_i and c are the installed capacity in MW and a capacity factor in hours/year, respectively. Each technology has a different capacity factor.

Regarding **hydropower**, the average of the current runtime in Morocco (1’205 hours/year) and in Egypt (6’243 hours/year) are used in the respective country (WRI, 2019). This is assumed to be also the case in 2040 for this report. The other countries have no hydropower plants in 2040 (

Table 3). According to IRENA et al. (2015), the wind capacity factor in Africa lies between 20% and 40%. Therefore, 30% or 2’628 hours/year is seen as an acceptable value. The U.S. Energy Information Administration (EIA, 2019) gives a performance of solar PV of 25.72% or 2’253 hours/year as an average value in the years from 2013 to 2018. A capacity factor for CSP is calculated based on (IEA, 2010) with data for the Middle East which results in 3’912 hours/year. Thereby, the generated electricity of CSP of 356 TWh in the Middle East in 2040, obtained from the IEA (2010), is divided through the installed projected capacity of 91 GW. All of these values are also taken into account for further calculation.

According to the IEA (2019), all countries besides Morocco had an electricity generation of solar PV greater than 1 GWh in 2017. Together with the assumed capacity factor of 2’253 hours/year, the following **solar PV** installed capacities are calculated: Algeria 254 MW (572 GWh generated electricity), Egypt 172 MW (NREA, 2018), Libya 5 MW (RCREEE, 2012b), Tunisia 59 MW (133 GWh electricity generation), whereas the data for Algeria and Tunisia are from the (IEA, 2019).

Table 5 shows the current considered capacity in each country for each technology type.

Table 5 – Installed capacity and number of power plants by primary energy source in each Northern African country. Data from the WRI (2019)and the IEA (2019).

	ALGERIA		EGYPT		LIBYA		MOROCCO		TUNISIA	
	Installed capacity [MW]	No. plants	Installed capacity [MW]	No. plants	Installed capacity [MW]	No. plants	Installed capacity [MW]	No. plants	Installed capacity [MW]	No. plants
Coal	0	0	0	0	0	0	2’835	3	0	0
Gas	15’179	31	31’060	34	5’916	9	866	3	4’856	19
Oil	0	0	2’010	5	315	3	777.3	5	0	0
Hydro	24	1	2’800	4	0	0	1’676.5	18	54.2	6
Wind	0	0	547	1	0	0	1’209.76	11	142	2
Solar PV	254	-	172	-	5	-	-	-	59	-
CSP	0	0	0	0	0	0	510	3	0	0

As the water consumption of power plants is depending on the used cooling system, each cooling system was investigated separately through Google Earth with help of the report of the United States Geological Survey (USGS, 2007). Power plants using a wet tower or a once through cooling system and are located at the sea, were assumed to rely on seawater and are therefore excluded in the results of this analysis, since only renewable freshwater is considered.

3.2 Watersheds per country

The consideration of watersheds in each one of the countries is useful in this type of assessment, as it allows to have a precise location of the power plants to the watersheds from which the *total surface water* is used. It is also important for the future allocation of power plants to specific watersheds. This enables a more precise picture about the water usage within the countries.

GIS (Geographical Information System, i.e. ArcMap) was used to locate the power plants across the relevant watersheds. The shape files of the countries’ borders were taken from GADM (2018), provided by the University of California. Shape files of the watersheds were retrieved from WWF (2019) on Pfafstetter level 4 (Lehner, 2014). However, if there were no power plants located in the hydrographic areas, the watersheds were considered as one (see for more information Table 14 in *Annex A – Watersheds and ten biggest cities per country*). In Egypt, the entire Nile drainage area was considered as one watershed.

The methodology used to estimate the average annual run-off in this project involves a combination of a rivers bankfull shape file retrieved from K. Andreadis, G. Schumann, and T. Pavelsky (2013) with the watersheds (WWF, 2019) in each country’s shape file. This proportion was estimated based on the share of the sum of the river discharge per watershed. Other water bodies were neglected as the GIS layer includes also the streams through reservoirs. In Egypt, the allocation of average annual run-off was not possible with the discharge because the river layer, provided by K. M. Andreadis, G. J. P. Schumann, and T. Pavelsky (2013), does not include discharge on the Sinai peninsula. Therefore, the average annual run-off is distributed proportionally to the area of the rivers. In this way it was possible to assign a proportion of the freshwater discharge per created watershed.

To our knowledge, the average annual flow of surface freshwater is not available for each watershed in the considered countries, even though research was conducted on several official environmental and water governmental platforms of the countries.

Data found for Morocco (Ministère Maroc, 2016a) were not assignable to our created watersheds and, thus, the same method was used for Morocco like for the other countries. However, it was possible to find values of *surface water produced internally* and also *surface water entering the country (total)* for 2017 for each of the analyzed nations (FAO, 2016). Where *surface water produced internally* is defined as "long-term average annual volume of surface water generated by direct run-off from endogenous precipitation (surface run-off) and groundwater contributions" and *surface water entering the country (total)* is "long-term average quantity of water annually entering the country through transboundary flow (rivers, canals, pipes)" (FAO, 2016). The sum of these two values for each country is considered as *total surface water* (Table 6).

Table 6 – North African countries and their respective total surface water (FAO, 2016) considered for the current situation.

	Algeria	**Egypt**	**Libya**	**Morocco & Western Sahara***	**Tunisia**
Total surface water [hm^3/year]	9'650	84'500	200	22'000	3'420

*the inland freshwater of Western Sahara is so small compared to Morocco that it is neglected.

Then, to allocate the *total surface water* to each of the analyzed countries' watersheds, the estimated share of surface freshwater per watershed was applied.

Figure 4 shows the created watersheds within the countries of Morocco with Western Sahara, Algeria, and Tunisia, while Figure 5 shows the same for Libya and Egypt, and the power plants.

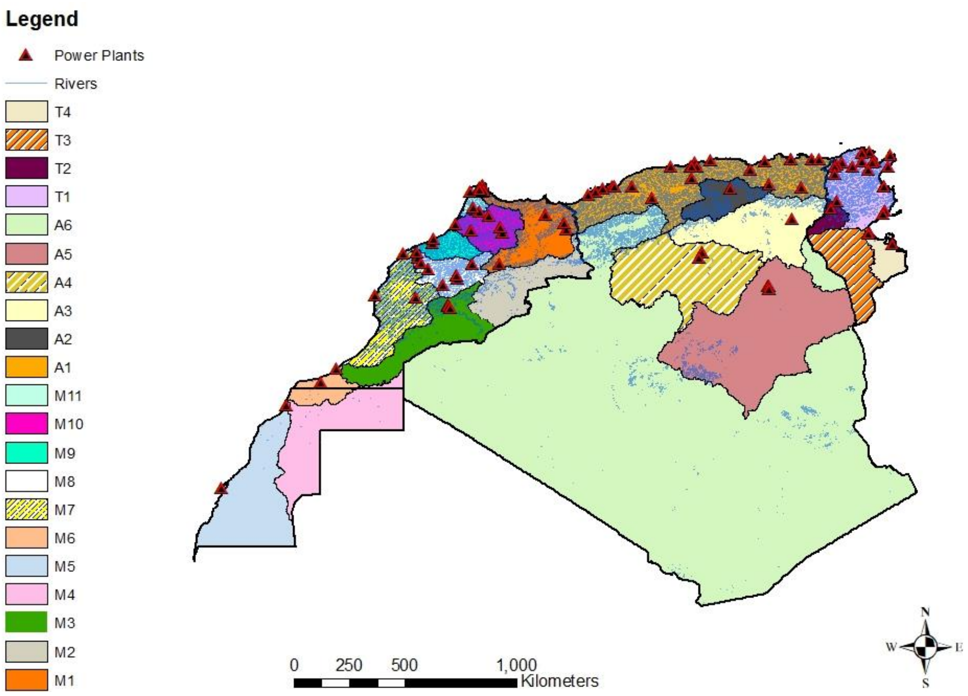

Figure 4 – Considered watersheds in Morocco, Western Sahara, Algeria, and Tunisia with surface water in blue and all power plants in red and black triangles. The first letter represents the country with the following coding: M = Morocco, A = Algeria, T = Tunisia.

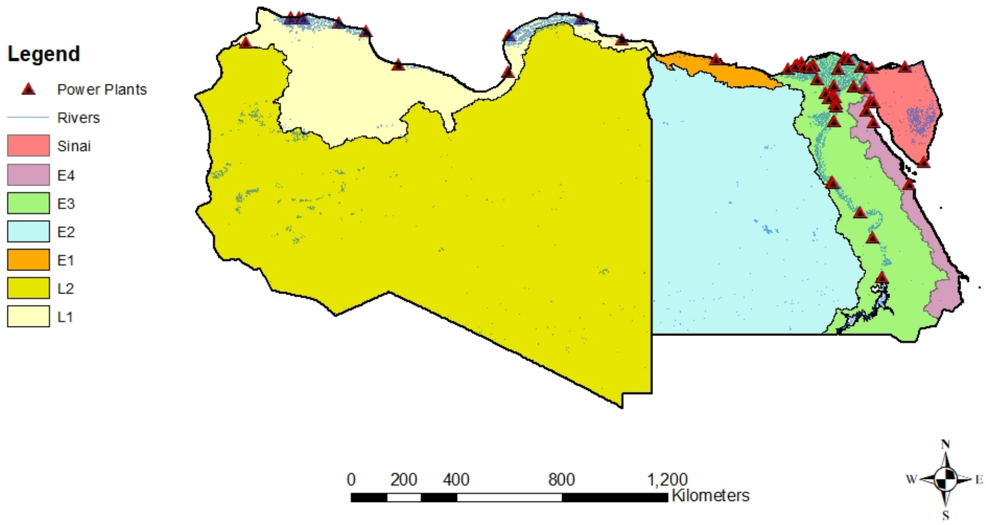

Figure 5 – Considered watersheds in Libya and Egypt with surface water in blue and power plants in red and black triangles. The first letter represents the country with the following coding: L = Libya, E = Egypt.

Regarding Libya, we excluded all the water sources in watershed L2 because with the layer of K. Andreadis et al. (2013), the perception arises of having a big proportion of water in the southern part of Libya which according to Brika (2018) is not the case.

3.3 Water use factors of power plants

Water use factors for electricity production allow to evaluate how water use for electricity production currently and in the future could influence other existing water uses. In particular, to estimate this as precisely as possible, power plants are classified according to the type of primary energy carrier they consume (e.g. natural gas, oil, coal) and per type of cooling system (e.g. once-through). Moreover, as explained in *2.3 The concepts of water withdrawal, water consumption, and water usage,* in this report water withdrawal and consumption for power production are considered separately. The considered factors are shown in Table 7. It should be noted that in the Table 7 maximum and minimum values are provided. This is because the values of water withdrawal and consumption factors differ per power plant. For example, the running time of the plants affect its cooling needs. To have exact values for water use factors and not ranges it would be necessary to obtain the individual plants' factor.

These factors are necessary for calculating the water usage and stress with the definition of *2.3 The concepts of water withdrawal, water consumption, and water usage.* In particular, the hybrid approach adopted in this project to evaluate water usage is the sum of all water withdrawn plus water consumed due to hydropower plants:

$$total\ water\ usage\ =\ total\ water\ withdrawal\ +\ total\ hydropower\ water\ consumption$$

The water usage "hybrid" concept was only used to assess water stress.

Table 7 – Minimum and maximum water consumption and withdrawal factors according to primary energy carrier and cooling type.

		Water consumption [m³/GWh]		**Water withdrawal [m³/GWh]**	
ENERGY CARRIER	**Cooling type**	**Min**	**Max**	**Min**	**Max**
COAL	Once through	242	1'200	75'708	189'270
	Tower	1'204	4'164	1'355	5'031
	Dry∇	1	15	1	15
OIL*	Once through	341	341	86'080	86'080
	Tower	606	606	946	946
	Dry∇	1	15	1	15
NATURAL GAS	Once through	76	1'102	28'391	227'124
	Tower	492	4429	568	5'527
	Dry	1	15	1	15
	Pond	908	1'022	1'022	22'712
CSP	Tower	2'744	4'001	2'744	4'001
	Dry	98	299	98	299
SOLAR PV	N/A	4	356	4	356
WIND	N/A	1	42	53	318
HYDROPOWER	N/A	5'394	68'137	-	-

* Feeley et al. (2008)

∇ Same assumption as for dry cooled natural gas power plants

All factors, with a few exceptions, indicated in the table, are obtained by Halstead, Simoes, Selosse, Kang, and Assoumou (2017). This source refers mainly to work of Macknick et al. (2012). The withdrawal and consumption factors for oil power plants can be received from Feeley et al. (2008), while there is no minimum and maximum value for oil with once-through and tower. Therefore, we apply the average factors in both cases. Hydropower minimum and maximum values regarding water consumption can be obtained by Macknick et al. (2012). As Halstead et al. (2017) provide no numbers for dry cooled coal and oil power plants, a further assumption is the same water usage as reported for natural gas power plants.

Currently installed capacities of solar PV are not included in the database of the WRI (2019). As research into data of the IEA showed in *3.1 North African electricity production*, all countries besides Morocco have a generated electricity of solar PV greater than 1 GWh which is our threshold to be included in the representation of the current water use per technology. However, this is not included in the analysis of water use per watershed as the IEA gives no information on the exact location of these capacities.

3.4 Water stress calculation

Water stress is an important index in order to correlate the water used for a certain purpose to the water available in a specific area as it is described in *2.3 The concepts of water withdrawal, water consumption, and water* usage.

In this report, water stress was defined to occur if the used water exceeds 40% of the total available water in the analyzed area (Wada et al., 2011), in this case each of the watersheds mentioned in the previous section. Water stress can be calculated by dividing the total water demand, in this context the water usage, by the total water availability, in this case the *total surface water*. As a result, the following inequality must hold true for a system to not experiencing water stress:

$$\frac{water\ usage}{available\ water} < 0.4$$

Water stress was calculated for the current situation and the future power and water availability scenarios to investigate in a quantitative way the influence of the used energy carrier in their environment.

3.5 Future power generation and water availability scenarios

The future scenarios deal on the one hand with the evolution of the power sector in the five countries up to 2040. On the other hand, there are also scenarios for future water availability considering effects of climate change. In this section are presented: (i) three different scenarios for expansion of the power of the five countries regarding future electricity production; (ii) two scenarios for future water availability, and (iii) different scenarios regarding the location of future RES power plants. Moreover, minimum and maximum values for water withdrawal and consumption factors from literature were used. Therefore, by combining three scenarios regarding evolution of electricity generation, two scenarios regarding climate change, and the assessment of water usage with minimum and maximum water use factors, in total twelve scenarios were developed.

The following Table 8 describes the power sector evolution scenarios. Scenarios are named according to their strategy regarding RES and conventional energy technologies. The names and some of the features of the scenarios are based World Energy Outlook 2018 by the IEA (2018).

Table 8 – Considered power generation scenarios for 2040 with their abbreviation.

Scenario name	Description	Abbreviation
Business as usual	RES power technologies are considered in the future, but the installed capacity of conventional technologies is still increasing.	BAU
New policies	RES power technologies are strongly fostered than in the BAU scenario, but the installed capacity of conventional technologies are partially still growing.	NEP
Sustainability	RES power technologies are built on a big scale, while installed capacity of conventional technologies is decreasing.	SUS

3.5.1 Electricity generation

Future scenarios of electricity production in North Africa are all based on the value of the currently installed capacity calculated with data from WRI (2019), listed in

Table 4.

National power sector strategies, shown in

Table 3, are also considered in the development of the scenarios for 2040 regarding the respective share of each RES technology within the share (wind, solar, and hydropower) for total RES of the total installed capacity. It should be mentioned that the national strategies targets are addressing the years of 2025 (Libya), 2030 (Morocco and Tunisia), or 2035 (Algeria and Egypt), but not 2040. Installed capacities of RES power in absolute numbers are taken from the aforementioned table, also considering the respective national strategy's share of RES of the total installed capacity. Absolute numbers of the existing RES capacity are then changed to match the future values of the share of RES of the total installed capacity according to scenarios of the IEA (2018). The RES shares of the IEA (2018) scenarios are different for BAU, NEP, and SUS. They have also done projections in three scenarios for power generation in the entire African continent. Data of the IEA current policies scenario are used in our BAU scenario, data of the New Policies scenario are used in the named alike NEP scenario, and data of the Sustainability scenario are used in the SUS scenario. The RES share of the total generated electricity is, thus, in the BAU scenario at 32%, in the NEP scenario at 46%, and in the SUS scenario at 76%.

Non-renewable electricity generation technologies, or fossil technologies, and the total share of RES are assumed to follow the anticipated increase or decrease for total Africa in 2040, in comparison to 2017 values. The variation in installed capacity of conventional technologies, i.e. coal, oil, and natural gas, are directly applied to each of the current power plants individually.

Egypt has officially the plan to install a certain amount of nuclear capacity (NREA, 2019) on the coast at Dabaa (WNA, 2019). As this nuclear power plant will be very likely cooled with desalinated sea water, it is not considered in our assessment.

Future fossil technologies new capacity is assumed to be installed at the exact same location as capacities of today. For the location of new RES power plants across watersheds, a simple allocation is done in a default setting assuming that the new RES power plants will be placed according to the distribution of the population of the ten biggest cities of each country. These cities are shown in

Table 16 in *Annex A – Watersheds and ten biggest cities per country*. Different assumptions of this location criterion are further investigated in the sensitivity analysis. Regarding Morocco and Egypt, a slightly different approach was adopted. In these two countries, hydropower plants and wind power plants in Morocco are assumed to be built in watersheds where there are currently wind and hydro power plants. Finally, wind power plants in Egypt, and CSP and solar PV plants in both countries, are also distributed across watersheds according to the population in the ten biggest cities. Data given for Morocco in

Table 3 are modelled to be added to the current renewable capacity, as this is the assumption of the Moroccan strategy.

Libya has under our standard assumption no *total surface water* in L2. However, there is one out of the ten biggest cities, Sabha, in Libya in L2 with 3.8% of the population within these ten cities. This will result in some of the future RES installed capacity in this watershed. The freshwater used in this city is probably coming from groundwater sources which are not considered in this report. Projects like the great manmade river (Sternberg, 2015) foster the exploitation of non-renewable groundwater from big aquifers in the Sahara desert (Foster & Loucks, 2006). Watershed L2 is therefore considered regarding electricity generation but not for water stress calculation.

Water needs for cooling of CSP depend heavily on the cooling system used (Table 7). Less water has to be withdrawn in dry cooled CSP plants in comparison to tower cooled CSP. A disadvantage of using dry cooling are efficiency losses (Poullikkas, Kourtis, & Hadjipaschalis, 2011). However, in water scarce regions like North Africa, the assumption of dry cooling makes sense and was therefore used in all scenarios. In a sensitivity analysis, this default setting was changed to tower cooled CSP plants.

Table 9 shows the generated electricity in each watershed and scenario. There is an increase of the generated electricity in a range of 306% to 397% in the entire region. Therefore, in all scenarios and in all countries, an increase is assumed. In fact, there is only one watershed in one scenario (BAU), M8 in Morocco, which shows a decrease in generated electricity. The decrease is possible because hydropower has a lower installed capacity in the BAU scenario in Morocco than currently installed and no other RES are planned to be built there.

Table 9 – Generated electricity in each watershed and in the entire region.

	Currently [TWh/year]	**BAU [TWh/year]**	**NEP [TWh/year]**	**SUS [TWh/year]**
A1	19.44	165.78	166.66	134.29
A2	4.06	13.81	12.92	7.75
A3	1.64	7.36	7.63	7.10
A4	3.93	13.39	12.52	7.51
A5	5.65	19.22	17.98	10.79
A6	0.00	0.00	0.00	0.00
Total Algeria	34.72	219.55	217.71	167.44
E1	0.35	1.19	1.11	0.67
E2	0.00	0.00	0.00	0.00
E3	138.77	538.58	546.82	473.93
E4	0.50	25.46	23.16	9.91
Sinai	4.06	45.11	43.83	30.46
Total Egypt	143.67	610.33	614.93	514.97
L1	12.15	101.18	101.01	81.85
L2	0.00	0.78	1.06	1.75
Total Libya	12.15	101.97	102.07	83.61
M1	6.37	18.16	16.86	15.91
M2	0.00	0.00	0.00	0.00

M3	1.42	1.42	1.42	1.43
M4	0.00	0.00	0.00	0.00
M5	0.19	0.46	0.52	0.64
M6	0.89	2.10	2.32	2.73
M7	0.11	19.88	11.84	5.92
M8	1.30	1.28	1.73	2.87
M9	1.25	7.40	7.15	8.42
M10	1.80	4.10	4.28	4.40
M11	1.59	5.41	5.47	4.67
Total Morocco	14.91	60.20	51.60	46.98
T1	4.77	48.80	48.93	38.60
T2	0.87	3.96	4.12	3.89
T3	0.00	0.00	0.00	0.00
T4	0.81	7.30	7.01	4.51
Total Tunisia	6.45	60.06	60.05	47.00
Total North Africa	211.9038	1’052.118	1’046.355	859.9926

3.5.2 Water availability

In order to integrate the future water availability for the considered watersheds in North Africa, the climate impact results from the Swedish Meteorological and Hydrological Institute were applied (SMHI, 2019a). Water and streams, from precipitation to catchment and storage areas, are simulated and considered in this model. In particular, the HYPE model provides essential climate variables and associated climate impact indicators (CIIs) considering different future global climate scenarios. In this report, only the CII *water discharge* was considered. This parameter considers monthly mean values of daily water discharge in a 30 years period. It is calculated as:

$$CII_{WD}[\%] = 100 \times \frac{(WD_{future\ period} - WD_{reference\ period})}{WD_{reference\ period}}$$

Where WD stands for water discharge. In order to obtain the proportion of increase (or decrease) of water discharge in each watershed created with ArcGIS, multiple smaller watersheds (i.e. 3-10) in the HYPE model were selected. It should be highlighted that the watersheds created with ArcGIS are bigger than the ones of the HYPE model. The median value of the monthly water discharge for 2040 was calculated based on 18 different climate change models (SMHI, 2019b). After that, the mean was calculated to find the annual water discharge. Afterwards, the water discharge mean of all the HYPE model watersheds within each of the watersheds created with ArcGIS was investigated (Table 10). Finally, this value was multiplied to the current *total surface water* in order to find the water availability at watershed-level in 2040.

In addition to that, the considered future climate change scenarios in the project are the Representative Concentration Pathway (RCP) 4.5 and 8.5 from 2011 to 2040. This framework includes time series of greenhouse gases (GHGs) and other environmentally harmful gas concentrations, but also land use/land cover. Each RCP proposes a possible outline of consequences of the specific radiative forcing characteristics. For example RCP 4.5 and RCP 8.5 consider frameworks in which radiative forcing is stabilized at approximately 4.5 W m^{-2} and 8.5 W m^{-2}, respectively (IPCC, 2019).

Moreover, for one watershed in Tunisia (T2) the water discharge is forecasted to decrease more for the scenario that considers RCP 4.5 than RCP 8.5. This is unexpected since RCP 8.5 is the more severe scenario. The water availability in watershed E3 in Egypt, the Nile basin, is the only watershed in North Africa with an increase of water discharge according to this model. Indeed, the future projections for the Nile are quite uncertain, with both signs of increases and decreases in discharge. Some articles discuss the possibility that the Nile could increase its discharge during the first half of this century (Di Baldassarre et al., 2011; Niang et al., 2014). Through firsthand contact to an expert of the SMHI, this can be explained by a delay in the effect of the emissions on global/local temperature, and considerable natural variability, especially at a local focus. Furthermore, the expert explained, discharge should be seen as a complex product of both changes in precipitation and evapotranspiration.

Table 10 shows the decrease or increase of water discharge per watershed with respect to the two climate change scenarios. Highest changed in discharge will occur in Morocco with up to 61.46% (M8 in RCP 8.5) less water discharge. This is especial problematic because Morocco has 64% of the currently installed hydropower plants in this watershed.

Table 10 – Projected total surface water per watershed [hm^3/year] according to Climate Change scenario RCP 4.5 and RCP 8.5.

Country	Watershed	RCP 4.5		RCP 8.5	
		Changed water discharge [%]	Projected total surface water per watershed [hm^3/year]	Changed water discharge [%]	Projected total surface water per watershed [hm^3/year]
Algeria	A1	-15.59	4,568.58	-18.15	4,429.86
	A2	-15.62	548.75	-16.56	542.68
	A3	-20.01	732.16	-22.65	707.94
	A4	-24.72	117.65	-48.65	80.25
	A5	-2.41	689.41	-23.73	538.77
	A6	-11.57	1,599.92	-56.55	786.07
Egypt	E1	-20.79	1.34	-22.60	1.31
	E2	-1.04	45.99	-1.04	45.99
	E3	10.74	93,489.90	8.69	91,757.51
	E4	-15.90	1.42	-27.29	1.23
	Sinai	-8.17	26.38	-17.53	23.69
Libya	L1	-14.47	171.06	-15.20	169.60
	L2	0.00	0.00	0.00	0.00
Morocco	M1	-22.61	2,884.29	-26.80	2,728.00
	M2	-47.28	1,112.00	-47.71	1,102.87
	M3	-16.03	1,820.98	-60.42	858.36
	M4	-38.61	66.65	-61.21	42.12
	M5	0.00	15.03	-36.35	9.57
	M6	-35.48	28.00	-39.40	26.30
	M7	-37.90	3,066.24	-39.75	2,974.66

	M8	-51.76	1,632.82	-61.46	1,304.31
	M9	-36.07	501.44	-40.07	470.10
	M10	-26.97	3,256.04	-38.00	2,764.59
	M11	-30.46	183.33	-39.86	158.54
Tunisia	T1	-1.40	2,827.62	-2.97	2,782.46
	T2	-24.46	368.97	-15.72	411.70
	T3	-2.11	42.46	-14.86	36.93
	T4	-14.87	17.44	-19.29	16.54

3.5.3 Sensitivity analysis

The assumptions tested in the sensitivity analyses are three: (i) the type of CSP cooling system, (ii) the allocation of future RES electricity technologies across watersheds, and (iii) the consideration of the share of industrial water withdrawal on the total water usage per country.

First of all, the cooling system of CSP has, as already mentioned in *3.5.1 Electricity generation*, an influence on the withdrawn water. This factor is tested in a sensitivity analysis to investigate if the change from dry cooled power plants to tower cooling systems could have a big impact on the water stress calculation. All other factors remain unchanged.

The allocation of RES power plants across watershed is changed twice to test the variation of results on this assumption. In one alternative option, the new RES capacity is distributed according to the share of available water in each watershed. This could represent an optimal distribution from a water management point of view because water is withdrawn in watersheds where water is available. The second approach is a distribution of future RES capacities based on a simple split of the planned capacity into an equal share of capacity for each watershed. As a consequence, hydropower capacity is for example modelled to exist in very dry areas like M4 in Morocco.

The last sensitivity analysis should emphasize the importance of water use of other sectors. The FAO (2016) has recent data at the country level considering the share of water withdrawal by splitting it into the three sectors of agriculture, industry, and municipality. Shares of withdrawn water take thereby all water, not only renewable water, into account. The largest share of withdrawn water is in all the countries coming from agriculture. For the sensitivity analysis, it is assumed that the water use for electricity generation is included in the share of industrial water withdrawal in 2040. The current water use share for industry in each country is thus the following: Morocco 2.033% (2010), Algeria 1.884% (2016), Tunisia 19.79% (2017), Libya 4.803% (2012), and Egypt 6.968% (2017) (FAO, 2016).

4 Results

In this section, results are presented starting with information about current and future power plants, followed by the estimates of current water use due to these power plants. Finally, results for future water use and water stress are presented, while the topic of sensitivity is covered last.

In this report, 158 power plants from the database of the WRI (2019) were considered (33 use seawater for cooling) for the assessment of the current situation. These power plants are located in 28 watersheds in North Africa.

4.1 Current and future power plants per country and watershed

Water use for electricity generation is dependent on the installed capacity here presented. Figure 6 – Installed capacity per primary energy source at country level and for the entire North African region currently and for the 2040 power scenarios. Shares per energy source at country level and of the entire region are in Figure 13 and Figure 14 in *Annex C - Technology per country*.Figure 6 depicts the current and future installed capacity for each technology in each power scenario and country. Additionally, the installed capacity for all five countries together can be observed.

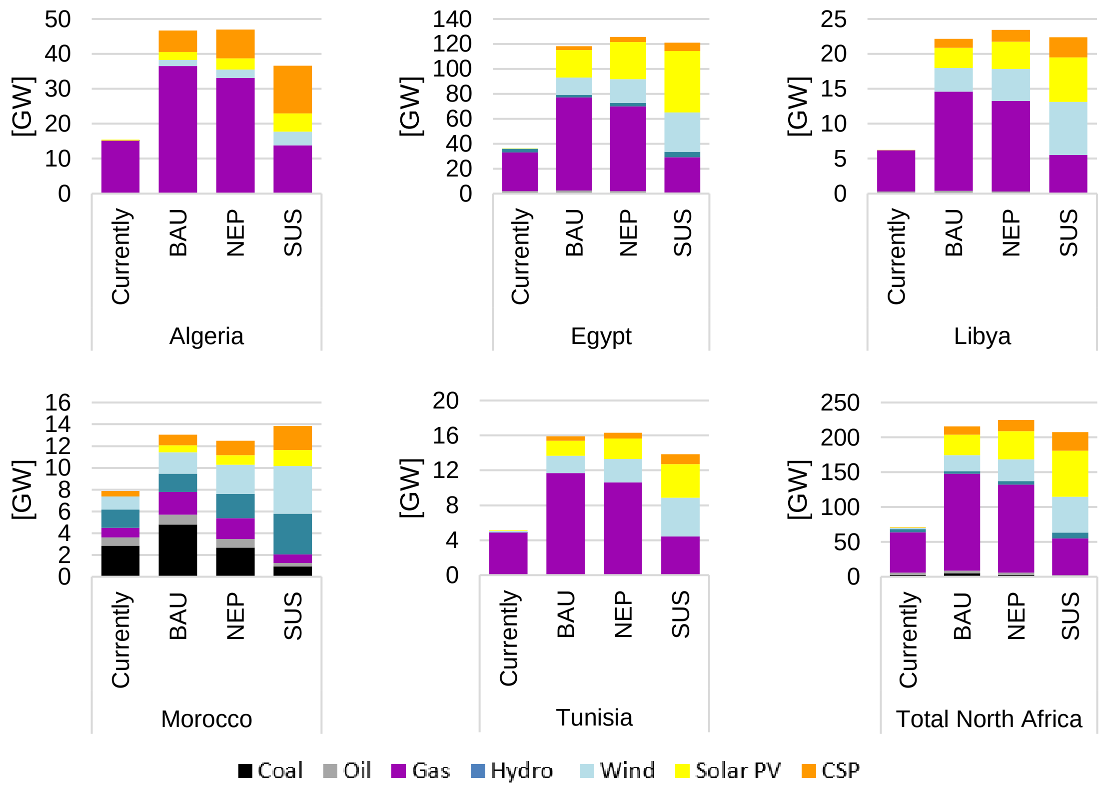

Figure 6 – Installed capacity per primary energy source at country level and for the entire North African region currently and for the 2040 power scenarios. Shares per energy source at country level and of the entire region are in Figure 13 and Figure 14 in *Annex C - Technology per country*.

In comparison to the current installed capacity, all countries show in each scenario an increase. Scenario BAU and NEP show a more similar capacity portfolio than SUS. Egypt has the highest installed capacity in total with more capacity than all of the remaining countries together. Fossil power technologies are still increasing in the BAU and the NEP scenarios (except for coal in NEP). A decrease of fossil technologies can only be observed in the SUS scenario. Egypt and Morocco are the only countries with hydropower production, while all of the other countries do not rely on hydropower in 2040, according to their national strategies (

Table 3). Wind power and solar PV are considered in all scenarios and countries. In some countries in the SUS scenario (Libya, Tunisia, Egypt) they represent more than 50% of the total installed capacity. CSP increases in all countries and scenarios but with a varying intenseness. In Figure 13 in *Annex B - Technology per country*, it is further detailed the share of each technology in each country and scenario.

4.2 Current water use for electricity generation

The current water use for power production is depicted in Figure 7 which shows the water use per watershed for minimum and maximum water usage factor. These two maps do not give the information on how much water is available. Additionally to the used water, the generated electricity per watershed is clustered into three different classes (0.01-10.00 TWh/year, 10.01-100.00 TWh/year and 101.00-1000.00 TWh/year). Power plants operating with desalinated seawater are not included in the depiction of the generated electricity.

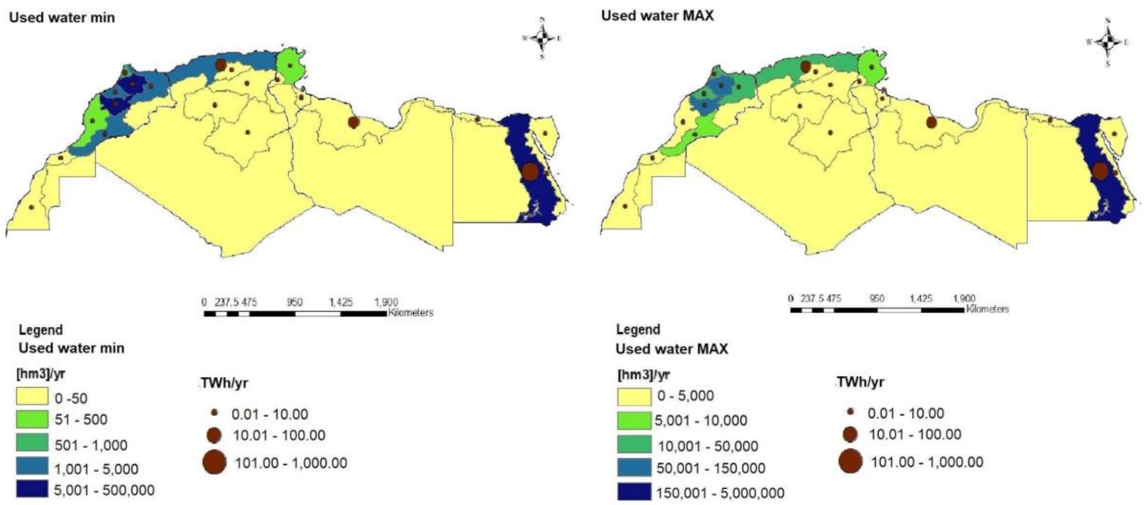

Figure 7 – Current water use and generated electricity per watersheds in North Africa for both minimum (left) and maximum (right) water use factors.

Most water is used in the coastal regions where most of the population is located. Some watersheds in Morocco (M1, M3, M7, M8, M9, M10, and M11), which are on the coast and the Atlas Mountains, have a higher water usage because of the water consumption of hydropower. Egypt has most of its power plants located next to the Nile river which is why the water use in this area is in the highest class. L1 in Libya has a generated electricity of 12’153 GWh/year but is still in the lowest water use class because all of the power plants use dry cooled systems.

Table 11 shows the current water use for electricity generation as well as the water use for the scenarios explained in more detail in the next section.

Table 11 – Water usage for electricity generation per watershed, currently and in the future scenarios in hm^3 (or million m^3).

Watershed	Current		BAU		NEP		SUS	
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
A1	3.9	42.2	8.60	69.71	8.91	67.77	7.84	44.85
A2	0.0	0.1	0.01	0.15	0.01	0.13	0.00	0.06
A3	0.0	0.0	0.14	0.61	0.19	0.80	0.31	1.26
A4	0.0	0.1	0.01	0.14	0.01	0.13	0.00	0.05
A5	0.0	0.1	0.01	0.20	0.01	0.19	0.01	0.08
A6	0.0	0.0	-	-	0.00	0.00	0.00	0.00
Total Algeria	**3.9**	**42.4**	**8.77**	**70.82**	**9.13**	**69.02**	**8.16**	**46.29**
E1	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00
E2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E3	244.33	1876.83	315.31	2416.51	313.72	2584.43	248.14	2553.20
E4	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02
Sinai	0.00	0.06	0.20	2.06	0.27	2.74	0.45	4.44
Total Egypt	**244.33**	**1876.92**	**315.52**	**2418.60**	**314.00**	**2587.21**	**248.58**	**2557.66**
L1	0.01	0.18	0.98	6.75	1.31	8.97	2.14	14.41
L2	0.00	0.00	0.04	0.26	0.05	0.35	0.09	0.71
Total Libya	**0.01**	**0.18**	**1.02**	**7.01**	**1.36**	**9.32**	**2.22**	**15.12**
M1	1.12	11.11	2.52	5.20	2.44	23.31	1.60	14.77
M2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M3	3.92	6.45	0.06	0.97	0.14	1.26	0.19	1.98
M4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M5	0.00	0.03	0.01	0.07	0.02	0.09	0.03	0.15
M6	0.02	0.11	0.05	0.27	0.06	0.38	0.10	0.62
M7	0.06	0.76	0.12	1.03	0.17	1.40	0.28	2.33
M8	7.00	88.39	6.92	87.35	9.36	118.19	15.46	195.26
M9	1.57	19.84	1.74	20.45	2.36	27.71	3.92	45.82
M10	127.04	149.02	150.19	172.09	131.83	161.46	57.35	106.31
M11	1.00	10.37	2.10	5.04	2.03	20.37	1.33	13.90
Total Morocco	**141.73**	**286.07**	**163.70**	**292.47**	**148.40**	**354.16**	**80.25**	**381.15**
T1	0.50	7.73	0.82	12.11	0.93	12.38	1.08	10.33
T2	0.00	0.01	0.05	0.36	0.06	0.47	0.10	0.74
T3	0.00	0.00	-	-	0.00	0.00	0.00	0.00
T4	0.00	0.01	0.03	0.25	0.04	0.32	0.07	0.50
Total Tunisia	**0.50**	**7.75**	**0.90**	**12.71**	**1.03**	**13.17**	**1.24**	**11.57**
Total North Africa	**390.51**	**2’213.33**	**489.90**	**2’801.61**	**473.92**	**3’032.88**	**340.47**	**3’011.79**

Results of water stress for the current situation are reported in the *Supplementary information* and not here, because the values are below 5%. Therefore, there is no water stress and it was considered not relevant to illustrate them in the main report.

4.3 Water use and water stress in the future

In this section, the results for the assessment of water use due to electricity production only and water stress in the future scenarios are reported.

In Table 11, it is possible to see the minimum and maximum numbers of water usage in the three scenarios (BAU, NEP, and SUS). Water withdrawal and water consumption are separately illustrated in *Annex C - Water usage* for each scenario and country. In addition to that, the shares of the contributions of all considered types of primary energy carrier to the water usage per country and per scenario are illustrated in Figure 8.

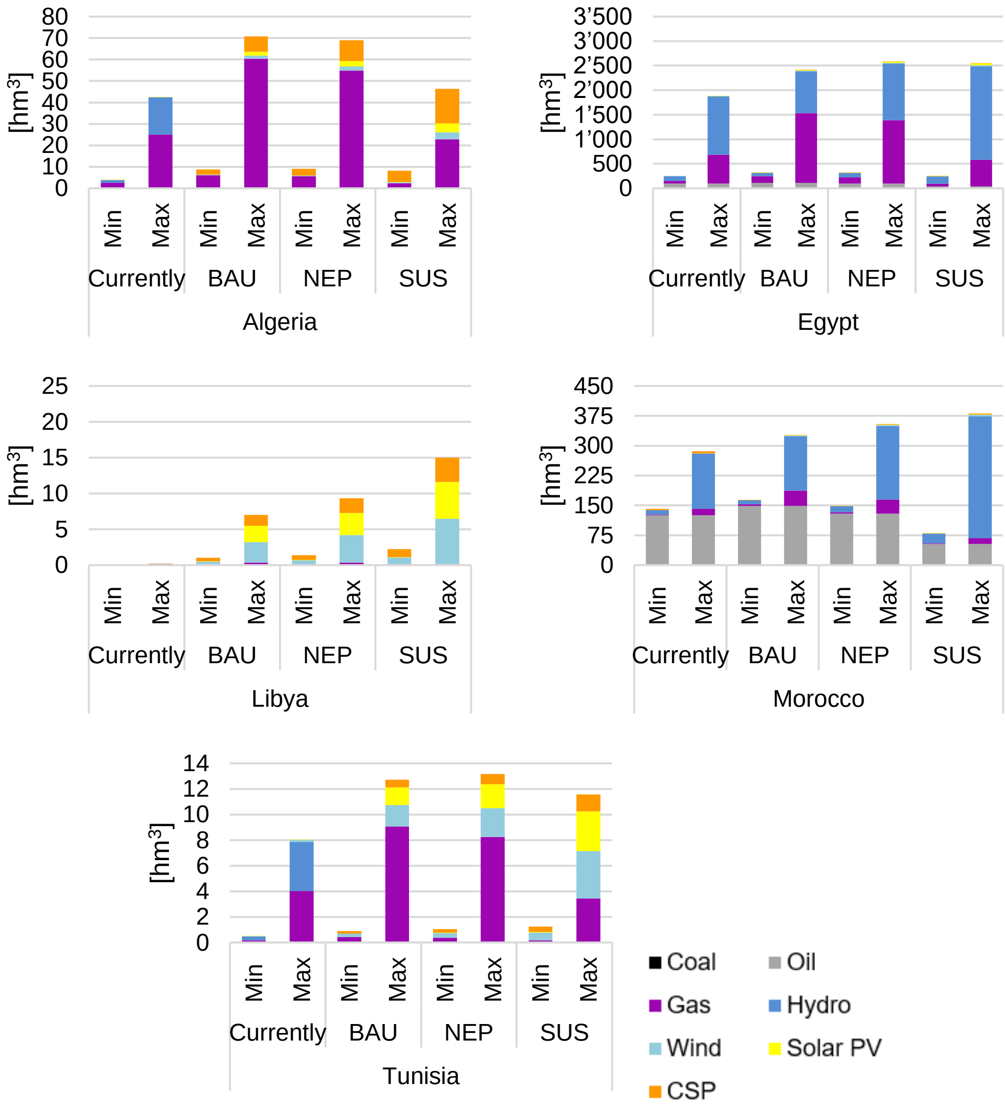

Figure 8 – Water usage per energy source at country level currently and in future scenarios. Shares per energy source on a country level are in Figure 16 in *Annex B - Technology per country*.

The installation of more RES capacity and at the same time a decrease of fossil technologies (SUS) can mean less overall water usage (Algeria, Tunisia, Egypt) or more water usage (Libya, Morocco), compared to an increase in fossil technologies and an intermediate installation of

RES if maximum water use factors are considered. At the same time, the highest minimum water use factor value in Egypt and Morocco is in NEP and BAU scenarios, respectively.

A strong increase in the installation of hydropower can result in an increase in water usage. M8 watershed in Morocco receives a share of 64% of the newly installed hydropower capacity which is the reason of an increase of water usage in the SUS scenario of up to 120%. On the other hand, Morocco shows a decrease in water usage in the SUS scenario only with minimum water use factors (-43%). This can be explained through the big range of water use factors in hydropower of maximum and minimum factors. Countries without hydropower but with an increase in fossil technologies (mainly natural gas), except for Libya, show a higher water usage with maximum water use factors than countries in the SUS scenario (Algeria, Tunisia). Egypt shows, although there is hydropower, the same pattern if NEP and SUS are compared.

The SUS scenario in Libya has a strong water use increase (up to +18'193% with minimum water use factors) compared to the current situation. The reason is that Libya uses almost no freshwater in currently installed dry cooled power plants. However, compared to the other countries, Libya still has the second lowest water usage in the SUS scenario, after Tunisia, and the lowest water usage regarding the other two scenarios with maximum water use factors. Results with minimum water use factors show always the second lowest water usage in Libya.

In Libya, there is furthermore water usage in watershed L2, according to the assumption of allocating future RES as written in *3.5.1 Electricity generation*. The highest water use would be in the SUS scenario because of an assumed increase in installed capacity of RES, namely wind, CSP and solar PV. For these RES, more water has to be withdrawn than for the dry cooled conventional power plants in Libya.

In Tunisia, the scenario with the highest water use with maximum factors is the NEP scenario. This is because of the increase in installed capacity of RES, but contrary to the SUS the share of electricity produced from gas is still high. The scenario with the highest water use with minimum factors is the SUS scenario, as RES plants use more water with these values.

According to Table 11, the water usage across all the scenarios and water use factors can vary in a range of -13% to +37% compared to the current usage. Water is used in the same watersheds where it is also currently used, as most of the fossil technologies and the ten biggest cities, and therefore new RES, are installed in the coastal region and the Nile basin. Sinai in Egypt has a strong increase of up to +10'875% (with minimum water usage factors) because 6% of new RES, except for hydropower, are allocated in this watershed.

It should be highlighted that the water use itself does not inform about water stress. Indeed, as explained in *3.4 Water stress calculation*, water stress is not only considering the water usage but also how much surface water is available per watershed.

More results about the water usage can be found in *Annex B - Technology per country* and in *Annex C - Water usage*. An Overview about the *total surface water* in each watershed separately is given in Table 16. An additional figure (Figure 17) shows the range, applying the minimum and maximum water use factors, in hm^3 for the different countries and scenarios. Figure 18 and Figure 19 emphasized the difference of the water consumption per country from the current situation to the considered future scenario with an Index. The consumption and withdrawal per technology, country, and scenario, is depicted in Figure 15.

Below, in Figure 9 and Figure 10, the results are reported in maps with all five North African countries, while a table with the specific number for the water stress calculation can be found in the *Supplementary information*. It should be highlighted that water stress occurs if the used water is above 40% of the available water (see *3.4 Water stress calculation*). However, this threshold considers water usage for different sectors and not only for power production as in this report. No watershed exceeds this threshold. Maps in Figure 9 and Figure 10 show different ranges in the water stress calculation for each future scenario. The scales of each map are different.

The results for water stress calculated with minimum water use factors by the power sector in 2040 is estimated to be below 10%, in fact below 5% in all watersheds except one. The BAU scenario has the strongest tendency of being the most prone to water stress, while the SUS scenario performs with lowest values. M10 watershed in Morocco has the highest value (5.43%) when the energy scenario BAU and RCP 8.5 are considered. Generally, the lowest water stress level is obtained with the SUS scenario (1.76% with RCP 4.5, 2.07% with RCP 8.5). Watersheds with the highest water stress level are in North West Morocco (M8, M9, M10, M11), North of Libya (L1) and Sinai (see Figure 4 and Figure 5 in *3.2 Watersheds per country* for exact references to the watersheds). The described area in Morocco is where the majority of the power plants are located. Other areas showing a high water stress level are located on the coast of Libya where nine out of ten biggest cities are (see

Table 16, *Annex C - Water usage*). As a result, the highest amount of RES capacity in the future is forecasted to be located there. In the case of Sinai, the reason is the same. Here are two out of the ten biggest cities. RES-technologies, apart hydropower, might be installed and, therefore, water is used.

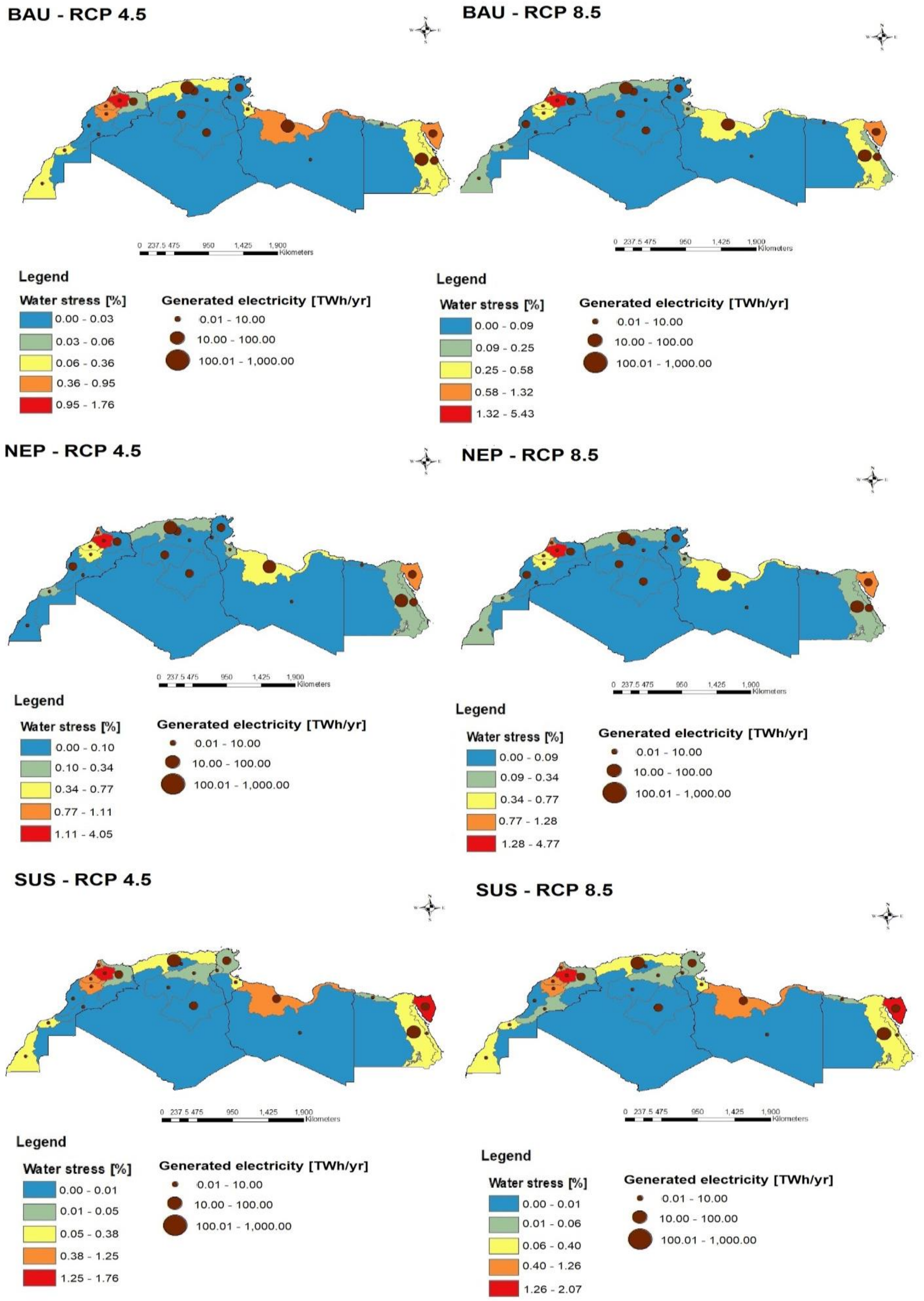

Figure 9 – Maps illustrating Water stress in the three future energy scenarios (i.e. BAU, NEP and SUS) coupled with the two climate change scenario (i.e. RCP 4.5 and RCP 8.5) for **minimum** water use factors in North Africa. Note: the scale for the water stress [%] is different for each map, while it stays the same for the generated electricity [TWh/year].

In general, when the water stress level is calculated with maximum water use factors (see Figure 10), the values are below 20% (in fact in the majority of the watersheds below 5%), which changes some findings with the minimum water use factors applied. There is a tendency observable of getting closer to water stress with the change from the BAU to the SUS scenario and with a change from RCP 4.5 to RCP 8.5. For instance, the future power sector scenario which shows the lowest water stress is BAU in the most critical watershed (Sinai with 7.79% in RCP 4.5, 8.68% in RCP 8.5), while it was SUS with minimum water use factors (M10 with 1.76% in RCP 4.5, 2.07% in RCP 8.5). Reasons of this difference of the scenarios can be found in the wide range of water use factors. In addition, SUS is the scenario with the highest water stress level values (Sinai with 16.84% in RCP 4.5, 18.75% in RCP 8.5) with maximum water use factors.

Additionally, the maps in Figure 10 show that the most critical watersheds are four in North West Morocco, namely M8, and M9, M10 and M11, and Sinai in Egypt. The Moroccan watersheds are reaching closer to the water stress threshold because of water consumption of hydropower. Furthermore, L1 in Libya is getting on higher pressure due to newly installed RES. Another relevant watershed is the Nile basin in Egypt. This watershed did not attract very much attention previously, when the minimum water use factors were considered. It shows relatively high values because eight out of the ten biggest cities, and therefore almost all future RES, are assumed to be located there.

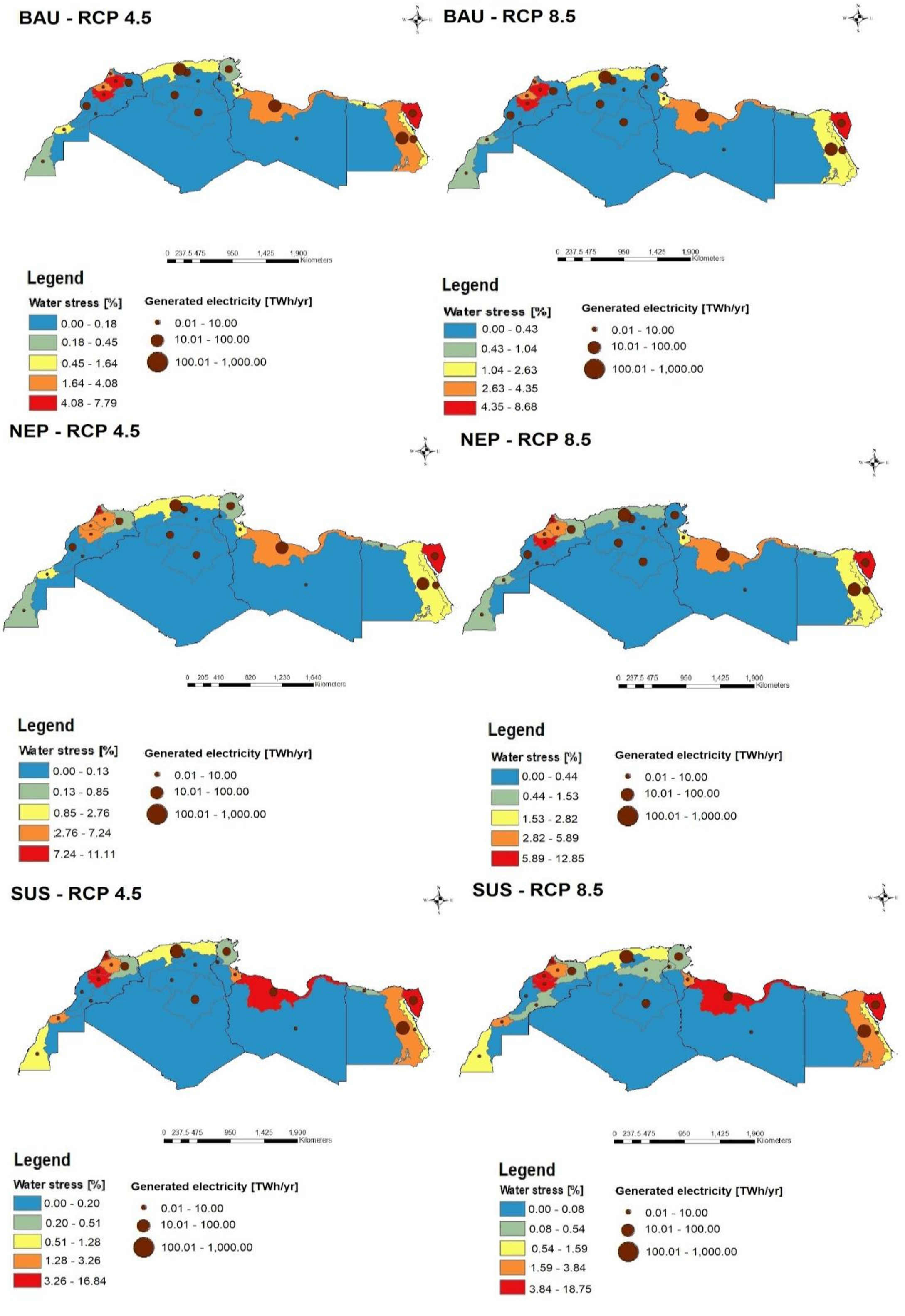

Figure 10 – Maps illustrating Water stress in the three future energy scenarios (i.e. BAU, NEP and SUS) coupled with the two climate change scenario (i.e. RCP 4.5 and RCP 8.5) for maximum water use factors in North Africa. Note: the scale for the water stress [%] is different for each map, while it stays the same for the generated electricity [TWh/year].

4.4 Sensitivity analysis

The sensitivity regarding future CSP plants with tower cooling instead of dry cooling system changes only one watershed (Sinai in Egypt) into a watershed in water stress. Sinai in scenario SUS and RCP 8.5 with maximum values is now in water stress because of the cooling system change (19% water stress under standard assumptions, 43% by considering a change in the type of CSP cooling system). This leads to the conclusion that the CSP cooling type has a marginal influence on the overall water stress level. Nonetheless, there is an increase of used water noticeable. A1, for example, has the highest number of newly installed CSP capacity in the SUS scenario (12’960 MW). The water stress level in this watershed rises from 1% to 5% with maximum water use factors and RCP 8.5 by changing the CSP cooling system as explained.

The sensitivity analysis with a distribution of the new RES capacity according to the share of *total surface water* in each watershed shows no water stress above the threshold of 40%. Watersheds, which have high values with maximum water use factors under standard assumptions, like M11 (13%), M8 (15%), or Sinai (19%) in SUS RCP 8.5, can lower their water stress level to 7%, 3%, and 2%, respectively. This emphasizes that a change of installed capacity can distribute water usage in a more equilibrated way.

Tables, which compare the standard assumption with a changed factor, are illustrated below. Figure 11 shows the legend for these two tables. Results of the sensitivity analysis can vary thereby in three classes: (i) no water stress in the standard setting and the sensitivity case, (ii) default case without water stress but new sensitivity case with water stress, and (iii) no calculation possible. The latter situation occurs in L2 because the standard assumption is that no *total surface water* exists at all in this watershed. This makes the water stress calculation impossible.

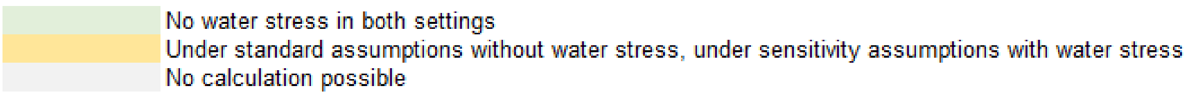

Figure 11 – Legend describing output of the sensitivity analyses.

The second sensitivity analysis addressing the allocation of future RES capacity is shown in Table 12. Hereby, each watershed gets the same share of RES capacities. This assumption is questionable as it is almost impossible to have in some areas hydropower. A consequence is water stress in several watersheds (E1, E2, E4, Sinai, M5, M6) and scenarios, but also lower water usage in some watersheds where electricity is produced under standard assumptions.

Table 12 – Sensitivity analysis with the assumption of allocating RES with the same share in each watershed instead of distribution according to the ten biggest cities per country.

Watershed	Sensitivity: Distribution of renewables with the same share in each water basin											
	BAU				NEP				SUS			
	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
A1												
A2												
A3												
A4												
A5												
A6												
Total Algeria												
E1												
E2												
E3												
E4												
Sinai												
Total Egypt												
L1												
L2												
Total Lybia												
M1												
M2												
M3												
M4												
M5												
M6												
M7												
M8												
M9												
M10												
M11												
Total Morocco												
T1												
T2												
T3												
T4												
Total Tunisia												

The last sensitivity analysis is focusing on the competition among different sectors for the water resource. An industrial share per country is applied on the *total surface water* which results in Table 13. Almost all countries (except Tunisia) show water stress with maximum water use factors in almost all scenarios (except Algeria in SUS). A possible reason to explain why Tunisia is different is the fact that it has a relatively high share of industrial water withdrawal from the total when compared to the other countries. This loosens the pressure on *total surface water* usable for power plants. The highest water stress level of Tunisia with the industrial share applied occurs in scenario NEP RCP 8.5 with maximum water use factors (2%).

It should also be highlighted that Morocco is only not in water stress with minimum water use factors in the SUS scenario, although this is the scenario with the most installed hydropower capacity (3'726 MW). The reason can be found in the wide range of minimum and maximum water use factors for hydropower.

Table 13 – Sensitivity analysis with the assumption of available water in the magnitude of the respective share of industrial withdrawal per country applied on the *total surface water*.

Country	Sensitivity: Industrial share applied											
	BAU				NEP				SUS			
	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
Algeria												
Egypt												
Libya												
Morocco												
Tunisia												

The *Supplementary information* includes, furthermore, data on the percentual change of the water usage of the scenarios in comparison to the current water usage and the water stress calculation in each basin and scenario for the sensitivity.

5 Discussion and Conclusion

This section addresses the results of the research questions. Key messages are given at the beginning of each subsection. Furthermore, limitations to the results are pointed out and discussed, as well as possible future work.

5.1 Evolution of the power sector for North Africa

The first question, *Which technologies are currently used to generate electricity and how can future power plants capacity be located across watersheds in North Africa?* can be answered with the following three main statements:

- Firstly, considering the developed scenarios for North Africa, the technologies deployed will still include fossil fuel power plants (mostly gas), with an increase in capacity in the BAU and NEP scenarios. A strong increase of RES power plants (solar, wind, and hydro) will also take place in the SUS scenario. The range of considered installed capacity grows from the current 71 GW to between 208 GW (SUS) and 225 GW (NEP) in 2040.
- Secondly, the future location of all new power plants across the 28 considered watershed, but especially of RES power plants is uncertain and, therefore, studied in two sensitivity analyzes..
- Thirdly, following the capacity evolution, the generated electricity is also expected to increase in 2040, according to the scenarios, in a range of +306% (SUS scenario) and +397% (BAU scenario) from current values for the entire region.

The obtained power sector evolution scenarios are depicted in Figure 12 below, where the obtained generated electricity in kWh/capita is presented for all scenarios. The current electricity generation values in this figure is based on data of the WRI (2019). Population data is retrieved from the World Population Review (WPR, 2019) which considers data from the United Nations for 2019 and 2040. The population in scenario SUS has, hence, to be less energy intensive than in the other two scenarios, where approximately the same high amount capacity has to be installed. Morocco is the most restrained country if they do not import electricity which they did in 2017, whereas 15.5% of the consumed electricity was imported (IEA, 2019).

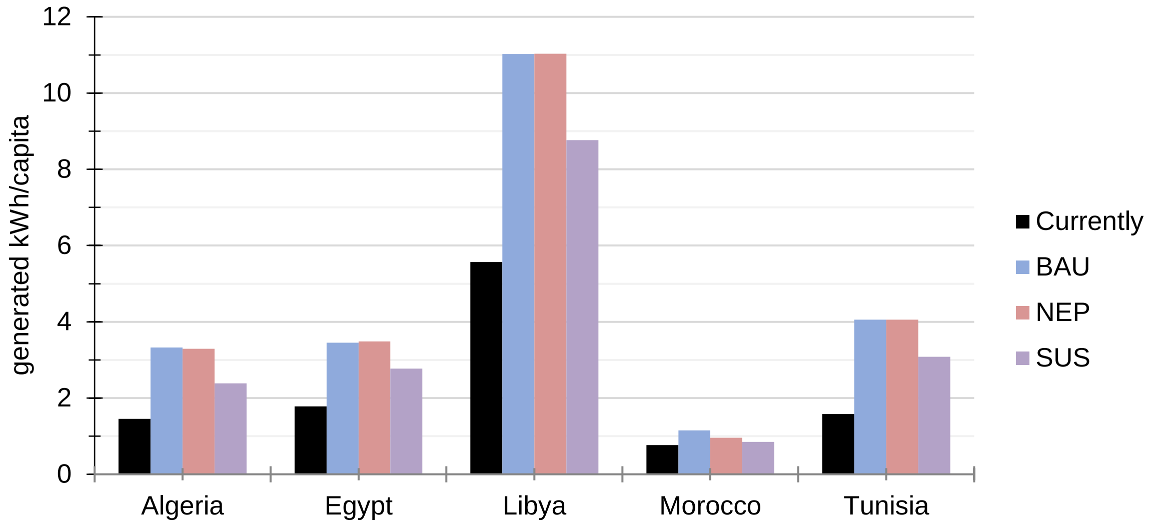

Figure 12 – Generated electricity in kWh per capita currently and for future scenarios on a country level.

It should be pointed that a limitation of the analysis were the considered watersheds which was defined by the authors. The watersheds definition as considered in this study itself were created on Pfafstetter level 4 (Lehner, 2014) which was adopted because the size of the created watersheds was sufficiently detailed to locate the power plants, but not excessively detailed which would complicate the analysis by further increasing the uncertainty of results regarding location of future power plants. However, the analysis could also have been done for other Pfafstetter level. Furthermore, a basic assumption is that the power plants withdraw and consume the water from the watershed they are operating. Not only that, but also some watersheds were, transboundary, but for this report were adjusted to the national borders of the countries as the *total surface water* is also given for each country separately (Table 15). Thus in this study we do not deal with transboundary water issues.

Regarding limitations on the location of the future fossil fuel power plants, these are considered to be located at the exact same locations where the existing plants are currently operating, and using the same cooling system. For new RES powerplants there is a higher uncertainty dealt with via the mentioned sensitivity analysis. As a standard setting, new RES capacity is considered to be built close to the currently ten biggest cities in each country. This assumption is based on the fact that thermal power plants are often located next to populated areas (Pappis et al., 2019), which is also assumed for RES power plants in this report.

5.2 Current and future water usage for power production

The response to the research question two *How does the water usage pattern for operation of power plants currently look like and how it will evolve?* is as follows:

- Current water use for the power sector in North Africa was estimated to vary between 390 hm^3 and 2’213 hm^3. The differences are due to the uncertainty associated to the efficiency and type of cooling systems (dealt with by considering minimum and maximum generic water use factors from the literature). Future water use can vary widely, also due to the different power sector evolution scenarios developed (additionally to the minimum/maximum water use factors). Thus, the 2040 water usage could either decrease from current values by 13% (SUS scenario, minimum water use factors) or in fact increase by 37% (NEP scenario, maximum water use factors). For the BAU scenario, the total future water usage can vary from 25-27% from current values, by 21-37% for NEP scenario and -13-36% in SUS scenario. This range in each scenario reflects the range of possible minimum or maximum water use factors, as mentioned. Thus, the increase in generated power does not translate in a corresponding increase of water use, since much of the new capacity is expected to be wind, solar, and dry-cooled gas power plants.

  - Water usage of solely RES power plants, can decrease by 23% less than current values (NEP scenario, minimum water use factors) or increase up to 74% more than current values (SUS scenario for minimum water use factors). The decrease occurs since some countries do not have any new hydropower plants, and since Morocco is expected to have a lower hydropower capacity in the NEP scenario than currently (2'255 MW currently compared to 2'549 MW in 2040). Thus, water use by hydropower power plants influences these outcomes substantially (although for some authors hydropower water use should not be considered).
  - Water usage of fossil power plants in 2040 can decrease to 22% less than current values (SUS, maximum water use factors) or increase up to 109% more than current values (BAU, maximum water use factors).

- Water was found to be used by the power sector mainly in the coastal watersheds, the Atlas Mountains, and the Nile basin (i.e. E3 watershed previously described).

It should be mentioned that the water usage in this report is defined as water withdrawn by the studied power plants, as well as the additional water consumed by hydropower plants. Siddiqi and Anadon (2011), for instance, focused more on the water consumption than withdrawal. However, this report considers the total demanded water in electricity generation and not only consumed water. The water use is in general dependent on the cooling system. This classification of cooling system types for the current power plants is based on an analysis of each power plant separately in Google Earth with the best knowledge of the authors by including definitions of cooling types of the USGS (2007).

5.3 Water stress

The third research question, *How will the water stress level evolve in the future due to climate change and expansion of the power sector?*, is addressed as follows:

- Water stress levels do not reach the threshold of 40% because of electricity production only. However, most critical watersheds regarding potential water stress are in the Atlas mountain region of Morocco, in Sinai, and the coastline of Libya. While with minimum water use factors, the BAU scenario is most prone to water stress, it changes with maximum water use factors and the SUS scenario becomes closer to potential water stress. Therefore, the SUS scenario is not necessarily more sustainable from a water use point of view.

- Climate change will exarcebate the importance of water use for the power sector and potential water stress, as less water discharge is expected in 2040 compared to current values. This is the case for all the 28 studied watersheds, except for the Nile basin (i.e. E3). As expected, results for the RCP 8.5 climate scenario are, therefore, more prone to water stress than results for RCP 4.5.

Regarding water stress, it is important to consider that this report does not consider a change in water use factors in the future. However, these water use factors could decrease in the future with improved cooling technologies, which could be investigated in a future work.

The threshold of 40% defined for water stress is defined based on research of Wada et al. (2011). By adjusting this threshold to another value, other results on water stress could be obtained. Furthermore, electricity generation may only be a very small sector withdrawing water of the *total surface water*. Groundwater is excluded from this report because it is not seen as a large renewable water source, as already in the last decade the groundwater withdrawal in semi-arid and arid regions is exploited with a too high rate (Edmunds, 2003; FAO, 2018).

Potential water stress found in some scenarios is, as pointed out in the results in *4.3 Water use and water stress in the future*, caused by the high water consumption of hydropower. If hydropower energy production can be achieved by low water consumption values (or even excluded from the analysis as done by some authors), the indicators on possible water stress would be substantially different. Morocco has currently and in the future a big share of the total installed capacity in hydropower. This leads to substantial water consumed and, hence, to a large water usage. Countries with no hydropower in the future (Algeria, Tunisia, Libya) tend to have lower water stress levels in the SUS scenario than in the other two scenarios. This is also true for Egypt, even though Egypt has hydropower, but it is not true for Libya. The share of hydropower in Egypt is relatively small to the total installed capacity. RES power plants require, in general, less water than fossil power plants, except for dry cooled conventional technologies. In Libya, only dry cooled conventional technologies and cooling systems with sea water are in operation currently. Thus, the change to RES in this country will potentially require, if the factors for water withdrawal will not change in the future, more water than the expansion of the installed fossil power plants.

Results for Egypt have to be seen with the different assumption of not taking the water discharge per watershed for calculating the share of the *total surface water* but the surface water area. The outcome for Sinai in Egypt should be treated cautiously because two out of the ten biggest cities (6% of their population) are located close to the border of watersheds E3 and Sinai, but inside the Sinai basin. A certain amount of RES are, therefore, assumed to be built in this rather water scarce watershed, except for hydropower.

5.4 Sensitivity analysis

Considering the last research question, *To which amount can the possible future water use for power generation scenarios be affected by certain assumptions?*, main conclusions are:

- CSP power plants were assumed to be in dry cooled by default and in the sensitivity analysis to be tower cooled. This assumption is interchangeable because no information is given for the future cooling types of CSP plants. However, the sensitivity analysis leads to the conclusion that CSP alone can have an effect, but it is not pivotal in overall water stress in North Africa.
- On the other hand, the allocation of new RES power plants across watershed can be decisive for the watershed's water stress calculation. A further step would be to investigate the impacts of assuming a location of new RES power plants according to the current and/or anticipated electricity grid location, which could be done in a future work.
- The competition among water uses, which is not just about surface water but about all water sources, between different sectors can cause tension among the stakeholders in the sectors.

Agriculture consumes nowadays in all the studied countries the largest share of water, while the industry (considered to include both the power sector and other industrial plants) consumes a lower value. This share could changes in the future, but the assumption for this report is the same value as in 2040, as the future share of water use per different economic sectors is very uncertain and out of scope of this study. Furthermore, industrial water withdrawal is not only water withdrawn for electricity generation. A more complete analysis of an agricultural, industry, and energy nexus would be of interest. As the definition of water use in this report considers water withdrawals for power generation and water consumption of hydropower, not only the share of withdrawn water but also of water consumption would be of interest. This data could be elaborated in more detail in future work. Water stress with the appliance of the industrial share on the *total surface water* occurs in particular in scenarios with the maximum factors applied.

Overall, this report may be useful for further research into water-energy nexus, water stress, and other topics related to water use or energy transition in North Africa. The results of this paper may provide valuable material for policy makers to decide the location and the type of electricity generation technology they want to promote in the future.

6 Acknowledgements

The authors would like to thank especially PhD Sofia Simões from FCT Universidade Nova de Lisboa for the advice and guidance throughout the project development, and professor Teresa Calvão for her useful insights on GIS. We would like to thank as well the Center for Environmental and Sustainability Research (CENSE) of the FCT NOVA de Lisboa and the colleagues for hosting us. Finally, the platform IAESTE should be mentioned, since thanks to them, this internship was possible.

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8 Annex

This Annex is subdivided accordingly to the topic:

- *Annex A - Watersheds and ten biggest cities per country*: details about the mapping related to the realisation of watersheds is presented.
- *Annex B - Technology per country*: The shares of installed capacity in the countries per technology and scenario are presented.
- *Annex C - Water usage*: More details on the results of water usage

In addition, further detailed results of the report are reported in the Supplementary information Excel file.

8.1 Annex A – Watersheds and ten biggest cities per country

This the Annex includes three tables. Table 14 gives thereby a more detailed insight in how the watersheds are merged.

Table 15 includes the calculated *total surface water* share of each watershed and its absolute value. The last table (

Table 16**Error! Reference source not found.**) entails the ten biggest cities per country, which was used to allocate the new RES.

Table 14 – Identity code of polygons of the watersheds (FID) merged in the layer of K. Andreadis et al. (2013). In Egypt, the watersheds in which the Nile flows, were considered as one.

Watersheds	FID	Watersheds	FID	Watersheds	FID
M4	147	**A6**	233	**L2**	246
	242		271	**E2**	216
	253	**T3**	225		221
A6	214		239		246
	231	**L2**	239		248
	268		232		258
	239		231		263
	232		268		270
	113		241		272
	223		267		259
	265		252	**E3**	156
	254		213		157
	242		244		172
	149		216	**Sinai**	0
	238		236		228
	222		245		249
	249		220		

Table 15 – Watersheds and their currently estimated *total surface water*. The first letter represents the country with the following coding: M = Morocco, A = Algeria, T = Tunisia, L= Libya, E = Egypt. Data calculated with SMHI (2019a).

Watershed	**Share surface freshwater per watershed [%]**	**Total surface water per watershed [hm^3/year]**	**Watershed**	**Share surface freshwater per watershed [%]**	**Total surface water per watershed [hm^3/year]**
M1	16.940	3’730	**T1**	83.850	2’870
M2	9.590	2’110	**T2**	14.280	488
M3	9.860	2’170	**T3**	1.270	43
M4	0.490	109	**T4**	0.600	21
M5	0.070	15	**L1**	100.000	200
M6	0.200	43	**L2**	0.000	0
M7	22.440	4’940	**E1***	0.002	2
M8	15.380	3’380	**E2***	0.055	47
M9	3.570	784	**E3***	99.910	84’400
M10	20.270	4’460	**E4***	0.002	2
M11	1.200	264	**Sinai***	0.034	29
A1	56.090	5’410			
A2	6.740	650			
A3	9.480	915			
A4	1.620	156			
A5	7.320	706			
A6	18.750	1’810			

*In Egypt the shares of *surface total water* was calculated according to the stream discharge area and not the discharge rate.

Table 16 – Ten biggest cities in each North African country. Data from WPR (2019).

Country	Watershed	City	Inhabitants	Country	Watershed	City	Inhabitants
Algeria	A1	Algiers	1’977’663	**Morocco**	M9	Casablanca	3’144’909
	A1	Boumerdas	786’499		M9	Rabat	1’655’753
	A1	Oran	645’984		M10	Fes	964’891
	A1	Tebessa	634’332		M9	Sale	903’485
	A1	Constantine	450’097		M7	Marrakesh	839’296
	A3	Biskra	307’987		M7	Agadir	698’310
	A1	Setif	288’461		M11	Tangier	688’356
	A1	Batna	280’798		M10	Meknes	545’705
	A1	Bab Ezzouar	275’630		M1	Oujda-Angad	405’253
	A1	Annaba	206’570		M1	Al Hoceima	395’644
Egypt	E3	Cairo	7’734’614	**Tunisia**	T1	Tunis	693’210
	E3	Alexandria	3’811’516		T1	Sfax	277’278
	E3	Giza	2’443’203		T1	Sousse	164’123
	Sinai	Port Said	538’378		T1	Kairouan	119’794
	Sinai	Suez	488’125		T1	Bizerte	115’268
	E3	Al Mahallah al Kubra	431’052		T4	Gabes	110’075
	E3	Luxor	422’407		T1	Ariana	97’687
	E3	Asyut	420’585		T2	Kasserine	81’987
	E3	Al Mansurah	420’195		T2	Gafsa	81’232
	E3	Tanda	404’901		T1	La Goulette	79’795
Libya	L1	Tripoli	1’150’989				
	L1	Benghazi	650’629				
	L1	Misratah	386’120				
	L1	Tarhuna	210’697				
	L1	Al Khums	201’943				
	L1	Az Zawiyah	200’000				
	L1	Zawiya	186’123				
	L1	Ajdabiya	134’358				
	L1	Al Ajaylat	130’546				
	L2	Sabha	130’000				

8.2 Annex B - Technology per country

Below, the shares of installed capacity per technology per scenario (currently and in the three future energy scenarios) in the five North African countries are presented. Natural gas is the main source of electricity power generation in this region, except for Morocco which has a higher contribution from coal. In the future energy scenarios, an increase in the share of installed capacity of RES is projected, in particular wind, solar PV, and CSP. Hydropower is forecasted to be relevant just in Egypt and Morocco.

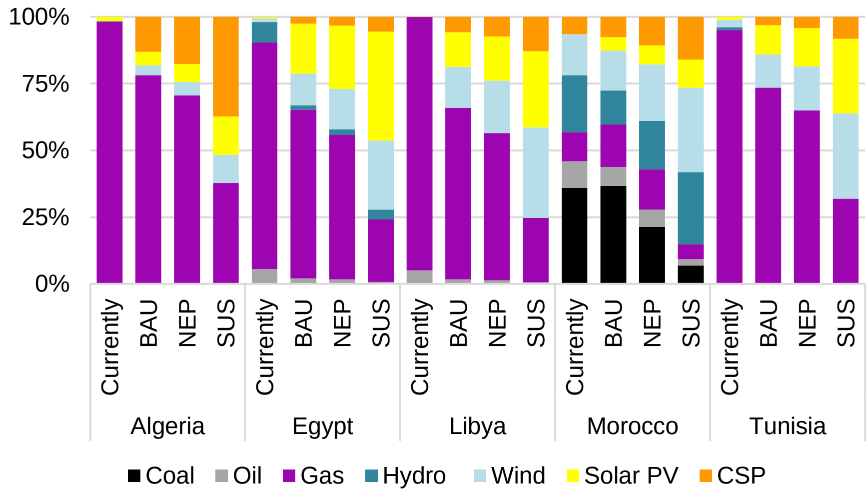

Figure 13 – Installed capacity in shares of primary energy sources on a country level currently and for the scenarios.

The chart below shows the shares of installed capacity of each scenario per technology and for all the five countries summed together. It should be underlined that in the future scenarios non-RES (i.e. gas, coal and oil) will still be the major energy carrier for electricity production (about 70% and 60% in BAU and NEP, respectively). On the contrary, this would be reduced a lot in the SUS scenario, since approximately 75% of the total installed capacity is coming from RES.

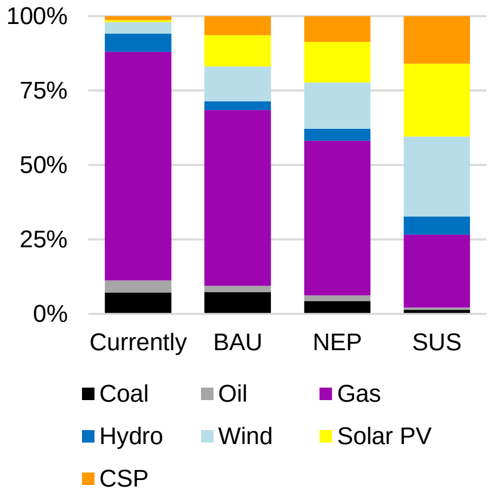

Figure 14 – Installed capacity in shares of primary energy sources in North Africa currently and for the scenarios.

8.3 Annex C - Water usage

The following five graphs illustrate the minimum and maximum water consumption (in light blue) and withdrawal (in dark blue) for the five analysed countries for each technology in the current situation. In the *Supplementary information*, the data of water withdrawal and water consumption are provided for each watershed and country. First of all, it should be highlighted that gas is often the main source of water withdrawal or consumption for electricity production.

The only exception is Morocco, in which oil and hydropower are the main contributors to water usage.

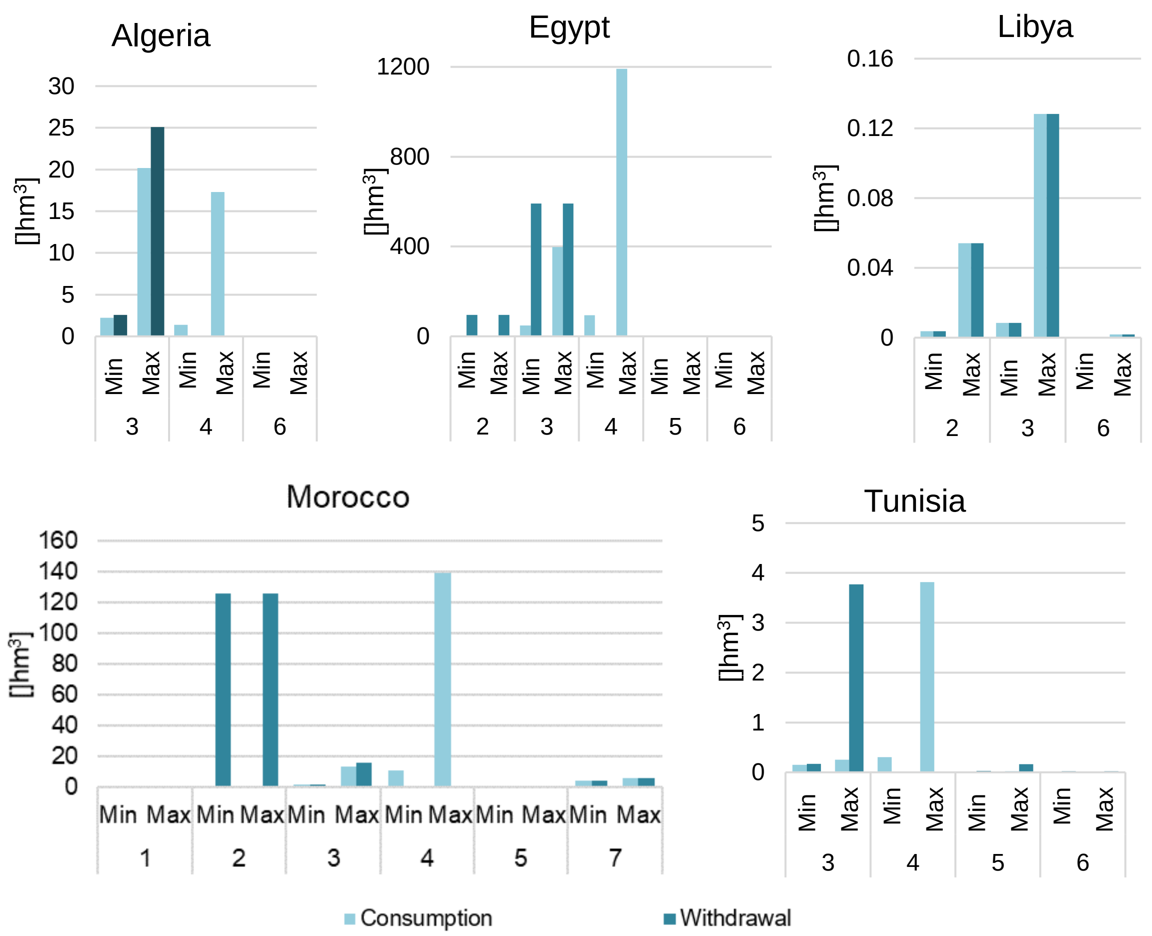

Figure 15 – Water withdrawal (i.e. With) and water consumption (i.e. Cons) currently of each technology in each country. The technology are namely: (1) coal, (2) oil, (3) gas, (4) hydro, (5) wind, (6) solar PV, and (7) CSP.

All of the following figures are linked to section 4.3.

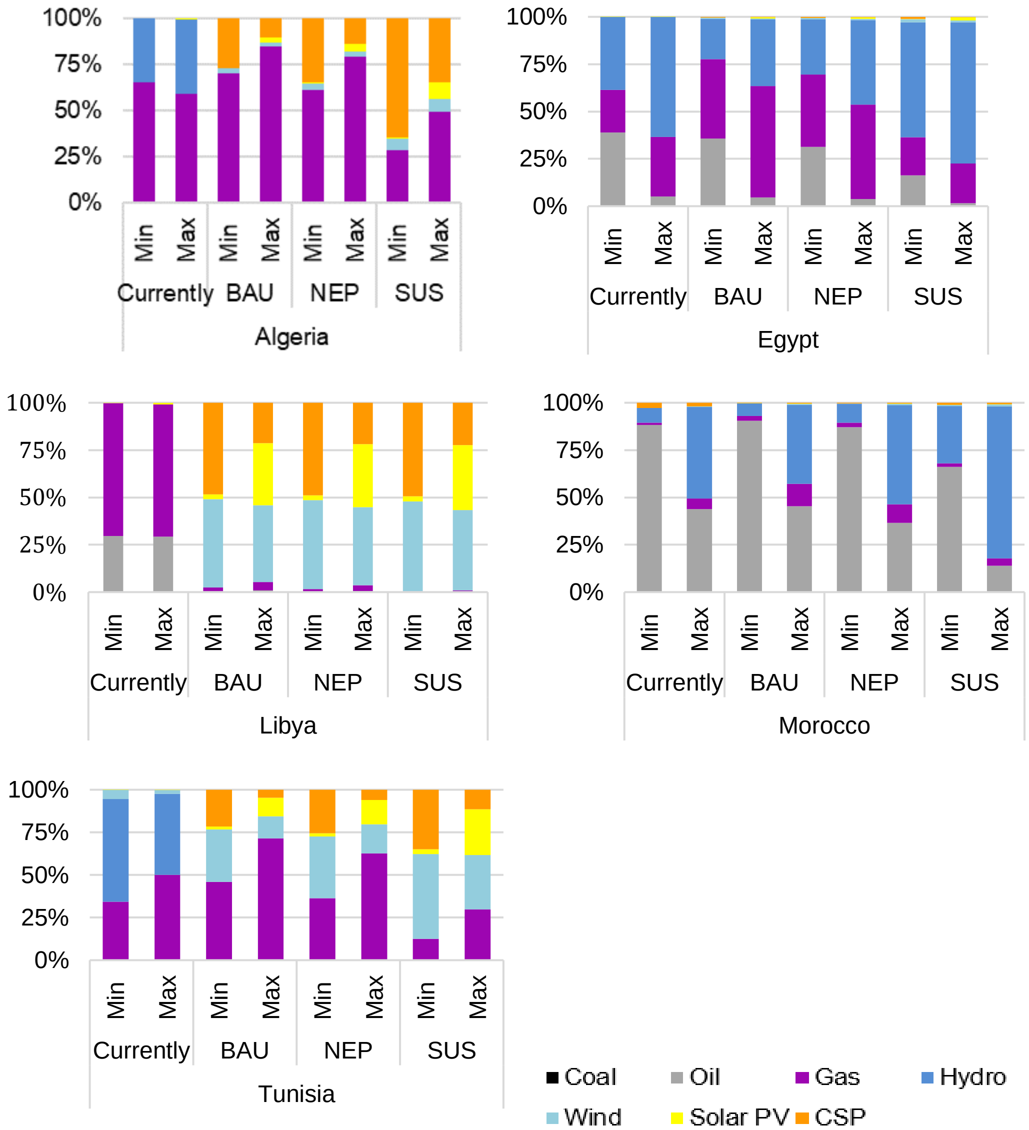

Figure 16 – Shares of water usage per country per technology currently and in future scenarios.

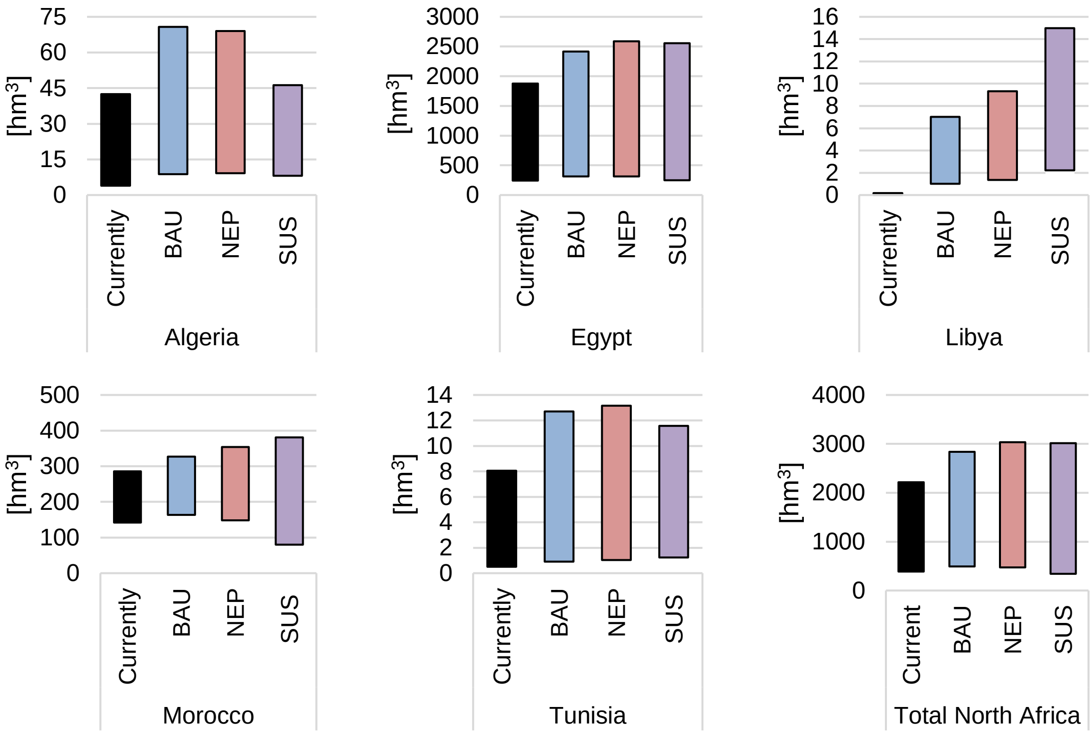

Figure 17 – Range of minimum and maximum water usage in hm^3 for the different countries and the entire region per scenarios.

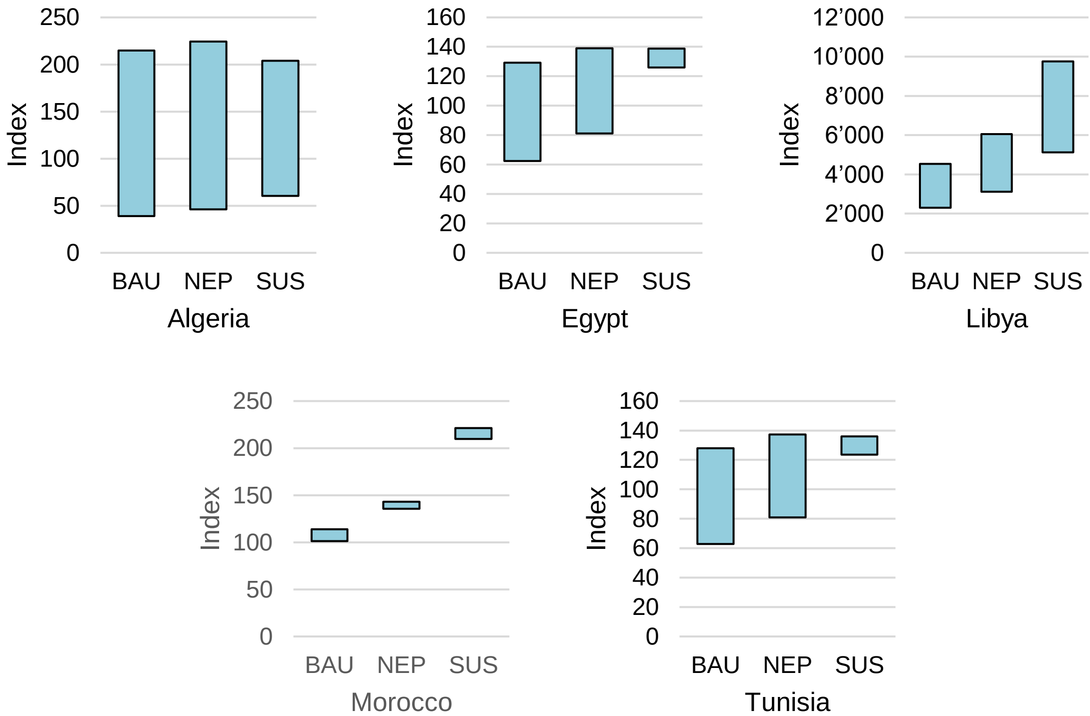

Figure 18 – Index describing the difference of the water consumption per country from the current situation to the considered future scenario.

The index was calculated as:

$$Index = 100 \times \frac{water\ consumption\ \ future\ scenario}{water\ consumption\ current\ situation}$$

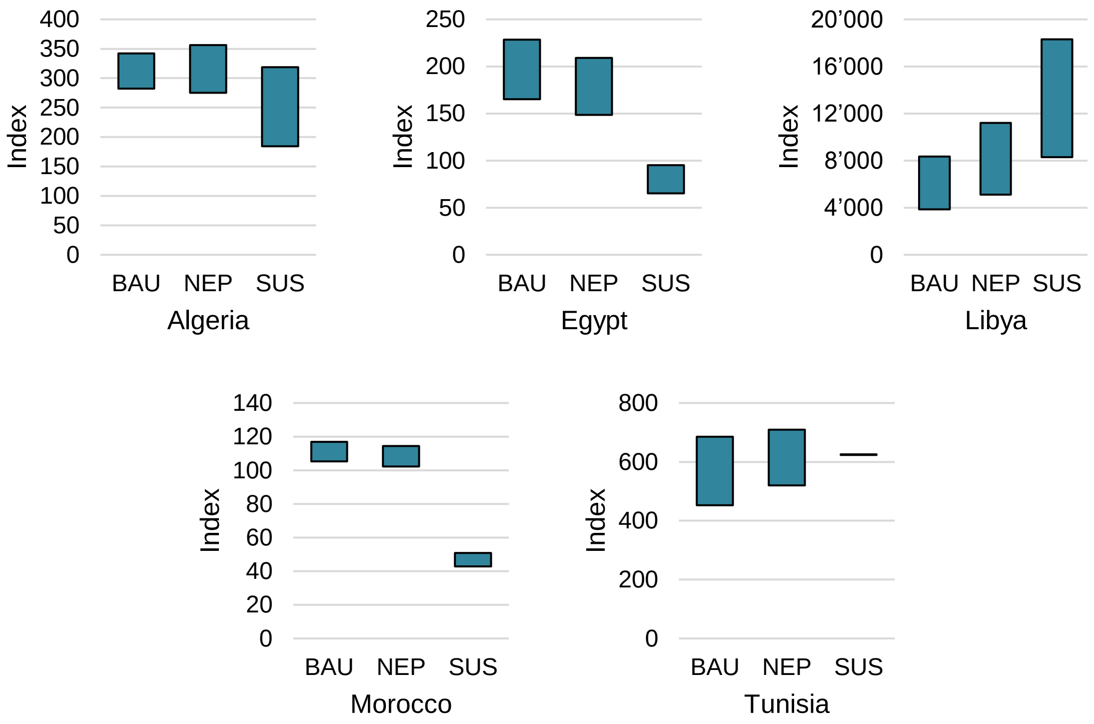

Figure 19 – Index describing the difference of the water withdrawal per country from the current situation to the considered future scenario.

The index was calculated as:

$$Index = 100 \times \frac{water\ withdrawal\ future\ scenario}{water\ withdrawal\ current\ situation}$$