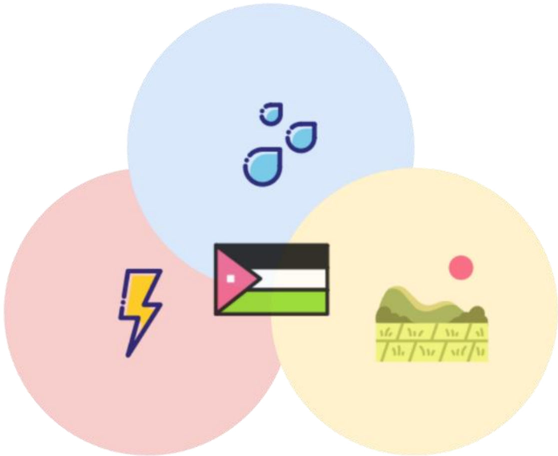
MASTERS THESIS

Mid-term Projections towards the Water, Energy and Agriculture Nexus in Jordan



by

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Deltares
Enabling Delta Life

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Abstract

Our world is experiencing unprecedented changes in the way of living. From a system analysis point of view, such changes need to be identified and the alternatives should be explored. Water, energy and agriculture are among the main sectors that play a pivotal role for the prosperity of people within a particular geographical context. Global drivers such as population growth, urbanization and climate change create critical pressures to the natural resources, such as water, energy and land, to a point that these resources cannot serve the demand anymore as they used to do. For this reason the water-energy-food (WEF) nexus approach has a growing significance.

In the case of Jordan, the water resources are overexploited while the water demand is increasing. The energy sector is heavily dependent on fossil imports, while Jordan is one of the most favourable countries of the world for the deployment of solar technologies. At the same time, agriculture constitutes around half of the total water withdrawals but contributes only 5% to the GDP. Moreover, the national planning for the energy and water sector requires the operation of technologies that need large quantities of energy and water for their operation. Additionally, the agriculture sector consumes energy, but does not exploit its potential for covering its own needs by agricultural biomass.

This thesis aims to address the potential interdependencies, trade-offs as well as synergies between the water, energy and agriculture until 2050 from a nexus point of view. Such point of view considers the prosperity of all sectors. The findings of this study include the identification of the most critical interconnections between the nexus sectors. Additionally, a further analysis is made using the Open Source Energy Modelling System (OSeMOSYS) to quantify these interlinkages until 2050. Finally, based on the mid-term projections, potential trade-offs and synergies are identified between the sectors of water-energy and agriculture-energy, respectively.

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Abbreviations

ATPP	Aqaba Thermal Power Plant
CCGT	Combined cycle gas turbine
CEPP	Combustion Engine Power Plant
CLEW	Climate, Land, Energy, Water
CSP	Concentrated Solar Power
CSP_A	Concentrated Solar Panels with 8 hours storage capabilities
DOS	Jordanian Department of Statistics
ELS	Environmental Livelihoods Security
ET	Evapotranspiration
GDP	Gross Domestic Product
GT	Gas turbine
GWh	Giga Watts hours
INDC	Intended Nationally Determined Contributions
MEMR	Ministry of Energy and Mineral sources of Jordan
MENA	Middle East and North Africa
MSW	Municipal Solid Waste
MWI	Ministry of Water and Irrigation in Jordan
NEPCO	National Electric Power Company
OSeMOSYS	Open Source Energy Modelling System
PV	Photovoltaics
PV-UTL	PV in utility-scale
RSDSP	Red Sea-Dead Sea Water Conveyance Project
TOE	Tons of Oil Equivalent
UNCHR	United Nations Higher Commissioner for Refugees
UNECE	United Nations Economic Commission for Europe
WEA	Water, Energy, Agriculture
WEF	Water, Energy, Food
WUE	Water Use efficiency
WWTP	Wastewater Treatment Plant

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1. Introduction

Water, energy, and food (WEF) are foundational resources of every country and they have complex interactions in the MENA region (Borgomeo et al., 2018). Seeking security on these resources can be considered as the backbone of economic and social prosperity for a country or a region. It has often seen that insecurity in one of these sectors can make a country dependent on other countries' interests by importing the respective commodities.

Several drivers, such as population growth and climate change, create critical pressure on WEF resources. To this end, the nexus approach has explicit linkages with the purpose of sustainable development. Addressing the WEF nexus in a country is an essential step for understanding the interconnections between the components of the nexus, and identifying potential synergies and trade-offs with regards to sustainable development (Nhamo et al., 2018; UNECE, 2015). The importance of the nexus approach has a growing recognition among international organizations and public institutions. However, in practice, the components of the nexus are often managed exclusively by sector-specific organizations. A common implication is that sectoral strategies and organizations have a structural "silo"[1] approach. Focusing on one sector may damage other sectors' value and therefore, negatively impact sustainable development (Nhamo et al., 2018).

The Hashemite Kingdom of Jordan is one of the most water-stressed countries in the world. Along with that, projections have shown that essential climate indicators such as temperature increase will worsen in the future as a result of climate change effects. Additionally, the energy sector is dependent on fossil fuel imports to sustain the increasing demand. Historically, energy imports contribute to more than 95% of the energy demand. Despite the increase in water and energy supply, the per capita consumption has decreased. Furthermore, the agricultural sector’s electricity demand is covered by the grid while the electricity potential from agricultural biomass remains untapped.

The national policy-makers have introduced ambitious strategies by 2030 to counter the adverse effects of climate change (MWI, 2016b; NEPCO, 2018, 2019). According to the Red Sea-Dead Sea Water Conveyance Project (RSDSP), desalination units is going to be an alternative source of water supply (ESIA, 2017). Despite the essential quantities of water that a desalination unit could supply, such technologies are much energy-intensive. Furthermore, the planning for energy sector aims to increase energy security by the utilization of domestic resources as well as renewables. Such kind of resources include uranium and oil shale. Despite the increase of energy security that these measures would bring, such technologies are much water-intensive.

1.1. Problem statement

Despite the ambitious targets set by the policymakers in Jordan by 2030, there are no predictions about how these changes will affect the water energy and food sectors by 2050.

In the Jordanian case, planning in one sector may also compromise the proper operation of another. Technologies that extract and utilize fuels such as uranium and oil shale, but also renewable technologies such as Concentrated Solar Panels (CSP), require a vast amount of water for cooling purposes (Macknick et al., 2012). In a water-scarce country like Jordan,

[1] “silo” refers to the management approach in which the sectors are isolated from each other and collaboration among them is lacking.

studies have examined the reduction of water availability in the long term (Smiatek, Kunstmann, & Heckl, 2014).

At the same time, the national plans for the expansion of the water require significant quantities of energy. Novosel (2014) estimated that the desalination plants with reverse osmosis, including the activities for capacity expansion, will require around 16,580 GWh until 2050. Based on the statistical portal of the MEMR[2], this amount is slightly higher than the total electricity demand for 2012, which was 16355 GWh. Another indication regarding the increased energy use in the water sector is that the water demand will increase for domestic and agricultural purposes, complying with the demographic and societal trends (Hoff, Bonzi, Joyce, & Tielbörger, 2011).

Regarding the agricultural sector, its electricity consumption was around 1160 GWh in 2019, but it produced only 3.5 GWh through biogas for the same year (MWI, 2015; NEPCO, 2018, 2019). Based on estimations from Al-Hamamre (2017), biomass potential including Municipal Solid Waste (MSW), crop residues and biogas could reach as much high as approximately 2315 GWh annually. On the other hand, biomass related combustion technologies are intensive water consumers (Macknick et al., 2012).

The above situation indicates a problem, which is the allocation of energy and water resources after the implementation of the national strategies by 2050. As described above, the Jordanian energy and water sectors are likely to compromise one another without an approach that integrates the decision-making processes of both sectors. The knowledge gap also exists in the quantities of resources that will be required to cover the demand by 2050. This situation is coupled with impacts from external drivers such as population growth, urbanization, climate change and economic development that put extra pressure on demand and supply.

1.2. Research objectives

The two objectives of this research are (i) to identify the critical interlinkages between the nexus sectors in Jordan, considering the national planning to the respective sectors; and (ii) to identify trade-offs and synergies by quantifying the above interlinkages and projecting their performance by 2050.

1.3. Research questions

The objectives of the thesis are achieved by answering three research questions:

1. What are the most critical nexus interlinkages for the case of Jordan?

In order to answer this question, the nexus framework was applied to the Jordanian case using information from peer-reviewed papers relevant to the nexus bibliography. By answering this question, the first research objective is achieved.

2. Concerning the identified interlinkages, how much energy, water and agriculture will be needed in Jordan by 2050?

In order to answer this question, a quantitative model was built using a bottom up, cost-optimization energy modelling tool. This model captures the expansion of the energy sector

[2] http://eis.memr.gov.jo/index.php/2016-04-03-07-04-42/2016-04-03-07-10-16/consumption-by-sector

as well as energy-water and energy-agriculture interlinkages. The interlinkages between water and agriculture sector are assessed using information from the relevant literature.

3. What are the trade-offs and synergies concerning the WEA nexus in Jordan?

The information gained from both of previous answers leads to the identification of trade-offs and synergies concerning the WEA nexus in Jordan.

1.4. Thesis outline

Chapter 2 elaborates on the methodology followed in order to answer the research questions. Chapter 3 describes the nexus approach reviewing the relevant bibliography from two perspectives: The conceptualization of the nexus and the modelling efforts towards the nexus. Having this as the basis, in Chapter 4, the WEA nexus framework is applied to Jordan in national scale. Through this chapter, the most critical interlinkages were identified. Chapter 5 delivers information regarding the development of the quantitative model. More specifically, it describes the inputs and the assumptions made in order to develop the mid-term model. Chapter 6 presents and discusses the results of this study. Finally, Chapter 7 summarizes the answers given for each research question and identifies future research directions.

2. Methodology

In this thesis, the WEA nexus is applied to the country of Jordan in order to identify the relevant interlinkages between the sectors under investigation. The study aims to answer real-life problems concerning a given situation. Thus, the data were obtained from the official documentation, peer-reviewed publications and professional reports. It can be characterised as practice-oriented research. However, a theoretical concept was applied to a real-life problem. Three types of practice-oriented research concerned. Firstly, the qualitative part of the work represents the problem analysis and secondly diagnosis. Thirdly, the outcome of the quantitative model is a design-oriented since it helps towards finding possible solutions.

2.1. Research framework

The research framework in Figure 1 was framed through the information provided by Verschuren & Doorewaard (2010). The purpose of the research framework is to demonstrate a guide with the steps needed to answer the research objectives. More specifically, the research framework has made up with the following components: (a) The preliminary analysis demonstrated both the WEA nexus concepts as well as knowledge on the current policies and situation in Jordan. The next two components deliver further information on the nexus concept, in brief: why and how it has used. (b) The conceptual model was framed through the application of the WEA nexus to Jordan and the development of the quantitative model. These two parts combine relevant energy and water policies until 2030. Mid-term projections were developed under three different scenarios. (c) The mid-term projections were developed using a quantitative cost optimization energy modelling tool. The purpose of its use is to quantify the relevant interlinkages that were identified. The developed model did not include projections regarding the water sector. For this reason, projections from the national authorities were determined and used for analyzing the results. (d) Recommendations were made when the indications were solid enough to predict that specific actions in one sector may compromise the other.

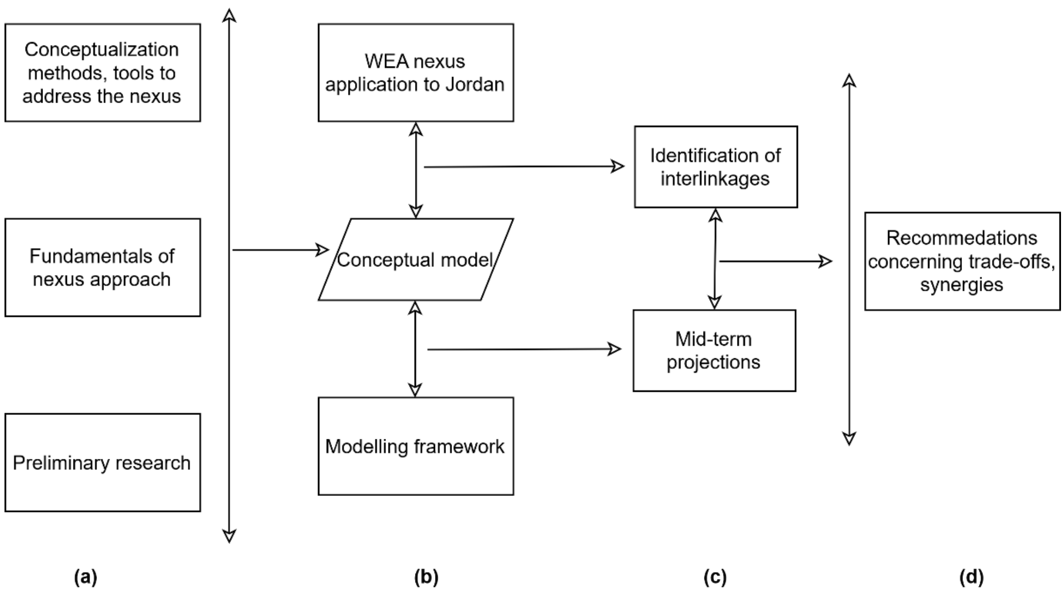


Figure 1- The research framework

2.2. Defining concepts

WEA nexus

The WEA nexus means that the water, energy and agriculture sectors are inextricably linked with each other. In other words, the operation of one sector affects the function of the two other sectors. When it comes for policy planning and formulation, multiple implications arise when the planning in one sector compromise the other two. Concerning that the decision-making often operates in sectoral isolation, this is very likely to happen (Leck et al., 2015). This study has analyzed the agricultural sector instead of the food sector due to data availability.

WEA nexus modelling

The WEA nexus modelling is one method to address the interdependencies between the components of the nexus. Energy modelling as a scientific and professional field of expertise has a considerable contribution to the nexus framework since its capabilities allow to optimize the reference energy system (RES), including water and food indicators (Brouwer et al., 2018).

Drivers

The combination of external factors heavily drives the implications of nexus sectors. (Hoff, 2011). Drivers vary from case to case. This study examined the role of external drivers, such as population growth, urbanization, climate change and economic development on the WEA sectors of Jordan.

Scenarios

As UNECE (2015) defines, the scenario is "an expected or possible situation characterized by certain conditions". Three scenarios were developed for this study.

Components of the nexus

The components of the nexus are the sectors contained in the respective nexus approach (UNECE, 2015).

Trade-offs

When the planning activities seek the prosperity of one sector but compromise others (UNECE, 2015).

Synergies

When two or more sectors participate in the same decision-making process. The outcome of this process will be the identification of actions that benefit more than one sectors (UNECE, 2015).

2.3. Research strategy

This study is based on desk research. The data gathered, analyzed and processed were obtained from the relevant documentation in grey and academic literature. This study does not use any kind of surveys and interviews for collecting data.

Moreover, this study has set research boundaries in order to verify that the scope of this research will be met within the timeframe. The author of this study, complying with this direction, has identified, analyzed, and modelled the most critical interlinkages between the WEA sectors concerning also the data availability. However, it does not mean the level of quality of this study will decrease.

2.4. Data collection

As presented in Table 1, data were collected from multiple sources and using multiple methods.

Research question	Data required	Source	Accessing method
What are the most critical nexus interlinkages for the case of Jordan?	Qualitative data that examine whether the performance of an activity in one sector compromises the activity in another sector, at a significant level.	• Peer-reviewed publications • Statistical databases, e.g., DOS, MWI, MEMR, FAOSTAT, World Bank	Desk research, content analysis
Concerning the identified interlinkages, how much energy, water and agriculture will be needed in Jordan by 2050?	Quantitative data for the supply and demand	• Peer-reviewed publications • Publicly available techno-economic data from energy-water relevant sources • Official statistical databases, e.g., MWI, MEMR, NEPCO	Linear optimization, data processing, data visualization
What are the trade-offs and synergies concerning the WEA nexus in Jordan?	Quantitative and qualitative insights derived from the conceptual model	Own analysis	Content analysis

Table 1- Research materials and methods followed to obtain relevant data

2.5. Data analysis

The software that was used to build the model is the Open Source Energy Modelling System (OSeMOSYS). It was introduced by Howells (2011), intending to increase public participation in energy decision-making primarily in the countries of the Global South. Moreover, OSeMOSYS was evaluated as one of the top-performing open-source energy modelling tools, and its insights are comparable to commercial solvers (Brouwer et al., 2018; Groissböck, 2019; Howells et al., 2011). Despite its extensive use in energy planning, i.e. Taliotis (2016), peer-reviewed papers presented the incorporation of water, climate and land-related indicators into OSeMOSYS (Sridharan et al., 2020). OSeMOSYS is written in different programming languages such as GAMS, Python and GNU Mathprog. Its code is publicly available through its GitHub repository[3] and provided under the Apache License 2.0. In this study, the GNU Mathprog version "OSeMOSYS_2017_11_08" was used.

OSeMOSYS's structure is presented in Fig. 2. The cost-optimization function takes place in the objective (1). More specifically, under this function, the model chooses the least cost energy technology to meet the demand considering simultaneously several indicators and various

[3] https://github.com/OSeMOSYS/OSeMOSYS_GNU_MathProg

constraints. The modelled technologies both use and generate energy. The relevant costs (2) that were captured in this study are the capital/investment costs, variable costs and fixed costs for every energy technology. The costs were captured yearly. The storage functionalities were not used in this model; thus, the Group (3) of equations did not deploy. Group (4) of equations captures capacity-related indicators that ensure that there is enough capacity for the system in order to meet the necessary production levels. The Group (5) of equations ensures that the production of fuels is enough to meet the demand for each year and timeslice. The Group (6) of equations gives the possibility to constrain some variables in brief: to limit the upper or lower value of a variable. The Group (7) of equations allows emission accounting. It is attributed for each technology, and it is measured using units of emissions per units of energy. This set of equations was also used for water accounting in this study.

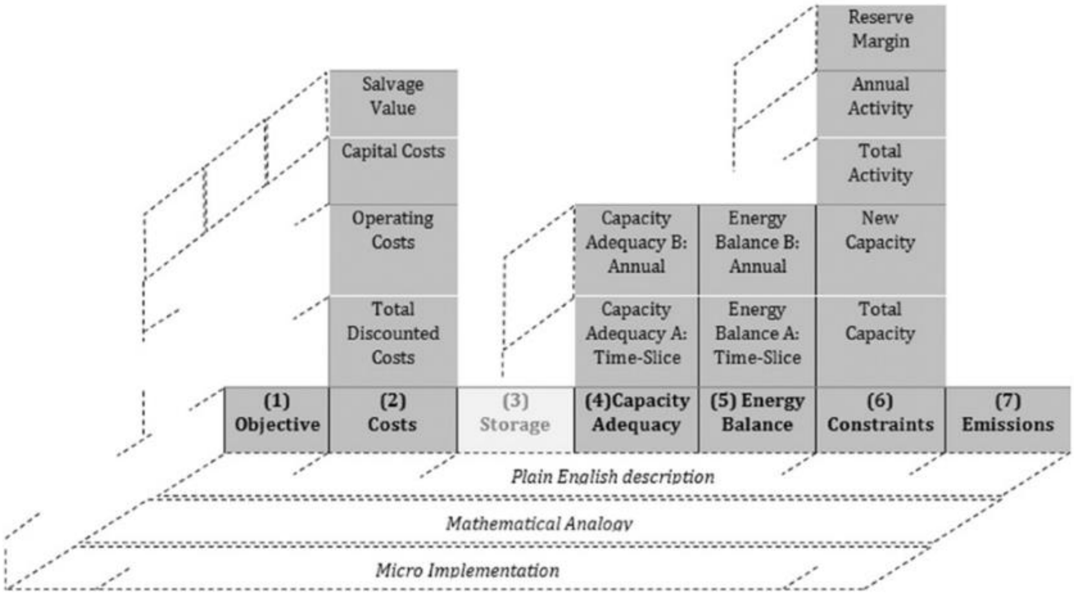


Figure 2- The structure of OSeMOSYS, Source:(Howells et al., 2011)

Three scenarios were developed for this study in order to compare different future alternatives. All of them incorporate the planning activities until 2030. The business as usual scenario does not incorporate the targets for the share of renewable resources in 2030, and the OSeMOSYS chooses the least cost energy technology to support the demand from 2030 and onwards. The RENEW-BASE scenario incorporates the renewable targets for 2030, and OSeMOSYS chooses a share of at least 30% renewables in 2030 and 40% renewables in 2040 until 2050. The third scenario minimizes the water consumption for the energy sector while modelling the agricultural biomass at its maximum potential.

2.6. Ethical considerations

This research conducted without any commercial or financial relationships that could construe as a potential conflict of interest. Additionally, the data collection was achieved using peer-reviewed publications, publicly available information provided by the national authorities of Jordan or verified journals. To this end, this research complies with the ethical principles and data management requirements that are set by the ethics committee of the Faculty of Behavioural, Management, and Social Sciences of the University of Twente.

3. The Water-Energy-Food Nexus

During the last 50 years, several peer-reviewed publications were pointed out the interlinkages between water, energy and food systems using a diverse mix of tools and conceptualization methods (Hannon, 1979; Hawkins & Jewell, 1962; King, 1983; Lorah & Wright, 1981; Swaminathan, 1991; Zucchetto & Jansson, 1979). During the previous decade, these interconnections emerged into a greater field of focus considering analyses that cover a broader scientific and professional context (Cooley, Christian-smith, Gleick, Allen, & Cohen, 2008; International Water Management Institute, 2007; Kahrl & Roland-Holst, 2008; The World Bank, 2008; World Economic Forum, 2009). In light of the developments in the 2010s, the concept of WEF nexus was firstly introduced and framed comprehensively by Hoff (2011) at the Bonn Conference and World Economic Forum (2011). The scientific attention to the nexus concept expanded with empirical studies that span from water, energy, agriculture to environmental related sciences as it is examined by Veysey (2018).

The WEF nexus recognizes the complex interdependencies between the water, energy and food sectors and promotes an integrated analysis instead of a "silo" process. This chapter will review and identify the nexus frameworks, the tools as well as the nexus governance, which are used for integrated assessments[4] with reference to the nexus approach. To do so, the meaning of the above terms is defined for this study. The aim of this chapter is to provide further insights from the existing literature that focuses on the nexus approach in order to apply the nexus framework appropriately in the Jordan case. For this purpose, peer-review scientific articles and documents by professional organizations were reviewed.

3.1. Drivers of the nexus

The rapid increase of the global population during the last 50 years led to a significant increase in water demand. The population in urban areas will consume more water than previous decades and will need to ensure access to electricity while the structure of the economy will cause increases in carbon emissions. This situation puts great pressure on the environment in a way that climate change effects can cause unprecedented changes. Water, energy and food resources will be stressed through various changes in demographics, economics and climate-related factors (World Economic Forum, 2009). Based on the global population trends and the increased trends in urbanization, it is estimated that the global energy demand will rise by 80%, the water demand by 55% and the food demand by 60% until. (Altamirano et al., 2018; OECD, 2012). The growing electricity demand in urban areas coupled with rural electrification, especially in countries of the global South causes critical implications for the expansion of the electricity system. (Handayani, Krozer, & Filatova, 2017).

Urbanization constitutes an integral part of the uniform profiles of the human populations, which is augmented via the rise of consumerism. This urban lifestyle is underlined by the increase of consumption and waste production. As a result, the main demand and waste products derive from the cities compared to rural areas, which is reasonable considering the higher population proportions and subsequently the higher per-capita resource consumption (Hoff, 2011). The higher consumption necessitates larger quantities of resources, such as

[4] As defined by Cinelli et al., (2014) "Integrated assessment are all the approaches that try to handle the information from individual indicators in a comprehensive manner, by considering interrelations and interdependencies among them, accounting for the different importance that they might have, and adopting different degrees of aggregation."

Water–Energy–Food (WEF), with the latter becoming increasingly insufficient (Covarrubias, 2019).

The urbanization is associated with various challenges regarding poverty and unemployment. The rapid concentration of populations in the cities has resulted in challenging issues that need to be taken with caution, such as poverty and unemployment that were mentioned above, as well as the growth of slums and peri-urban areas; a rise of gated cities and the lack of public spaces; the bottleneck of primary urban infrastructure; considerable inequalities between urban and rural areas; and the significant negative effect of urbanization on the climate. The challenges underlining the rapid urbanization indicate that corporate actions at national, regional and global levels are a matter of necessity, in order to ensure the urban lifestyle will be accompanied by economic growth and prosperity, setting in parallel the goal for sustainability (ESCWA, 2015).

To put things into perspective, the development of urbanization in combination with the agricultural decline in the MENA region can be directly reflected by the considerable water demand and subsequently, the impacts on the energy sector (Hameed et al., 2019).

3.2. Nexus conceptualization methods

Different assessment frameworks exist for the analysis of the nexus. In some studies, the framework is based on the analysis of the WEF nexus, while in others the chosen framework includes Climate, Land, Energy and Water (CLEW) sectors (Chang et al., 2016; Welsch et al., 2014).

Hoff (2011) presented the first conceptualization of the WEF nexus approach at the Bonn Conference in 2011. In that conceptualization, the water sector is the epicentre of the nexus approach, while external drivers of population growth, urbanization, economic development, and climate change accelerate the pressure on water, energy, and food sectors. As a result, the security of each sector is compromised through its dependency on imports. Additionally, the security of a sector can be compromised by when the operation of one could affect the operation of another negatively.

Biggs (2015) investigate the correlation of the WEF nexus with the livelihoods towards sustainable development goals. They describe the approach of sustainable livelihoods by making a review of relevant definitions from academia and professional organizations. Additionally, they argue that the integration of livelihoods with the nexus framework could lead to opportunities for sustainable development. They point out the limitations of existing nexus frameworks on including livelihoods in their approach. To this end, they introduce the environmental livelihoods security (ELS) framework, which conceptualizes the interlinkages between water, energy, food and livelihoods (Fig. 2). This approach aims to enrich possible alternatives and achieve sustainable development for the relevant system. In order to define the system, an assessment needs to be carried out for the identification of the WEF nexus interactions. The authors argue that the ELS framework could support policy formulation by safeguarding the livelihoods taking examples from various case studies.

Rasul & Sharma (2016) link the adaptation to climate change effects with the water energy food nexus concept. This comes as a response to the need for creating sustainable solutions by integrating economic, social and environmental indicators towards sustainable development. To support the framework, the authors include a matrix with key findings concerning the co-benefits and complementarities between the water energy food nexus approach and the climate change adaptation approach. The proposed framework illustrates the necessity to conceive how the context of vulnerability to both climate and non-climate change affects the development of poverty and how people adjust their adaptation strategies, before devising a nexus-based strategy. It supports the improvement of cross-sectoral and cross-border cooperation in order to tackle the nexus-based adaptation challenge properly.

Bazilian (2011) introduced the Climate, Land, Energy, Water (CLEW) framework according to which the components of the nexus are Climate, Land use, Energy and Water. This framework was applied in the case of Mauritius (Fischer et al., 2013; Welsch et al., 2014). According to the authors, such integrated approach does not only enable the identification of interlinkages but also contributes 1) to the decision making processes, 2) to policy analyses concerning cost-effectiveness, 3) to avoid the trade-offs between the selected sectors by contradictory technological advancements, 4) to the development of relevant scenarios in order to investigate alternative developmental pathways.

3.3. Nexus modelling tools

Modelling tools were used in the nexus approach to quantify the interlinkages between the nexus sectors and project their future condition. There are tools with different characteristics and different uses, although they contribute to the same topic.

Energy modelling tools play a central role in nexus modelling (Brouwer et al., 2018). They can provide critical insights into policy planning for the energy sector; however, its structure has the potentials to include indicators from water and food sector, respectively. Additionally, the optimization used in energy modelling tools allows the model to choose the optimal solution concerning economic, environmental, technical and natural limitations. When water and food-related indicators are considered, the outcome may be beneficial for more than one sector (Brouwer et al., 2018).

Welsch (2014) developed a nexus model using the CLEW framework that was introduced by Bazilian (2011). More specifically, the study was conducted at a national level for Mauritius and investigates different scenarios for local ethanol production until 2030. In order to present the added value of the CLEW framework, four modelling tools were combined corresponding to each component of the nexus. Temperature and rainfall indicators were captured using General Circulation Models as parts of the climate component. The irrigation needs and fertilizer input estimated under various climate scenarios using the Agro-Ecological Zones production tool. Moreover, the Water Evaluation and Planning System (WEAP) used in order to develop the surface water system which has included hydrological, climate and land use parameters. The last tool applied for this study was the Long-range Energy Alternatives Pathways (LEAP) which modelled the energy supply and demand. The results from different scenarios shown that when considering all of the CLEW sectors, hydro-electricity was decreased considerably due to the reduction of rainfall, the electricity demand for the water sector has increased while the dependence on fossil fuel imports has increased. As a result, there is a significant increase in CO_2 emissions.

A peer-reviewed publication that integrates CLEW but with a different mix of software tools was presented by Sridharan (2020) with a focus in Uganda's hydropower sector. More specifically, WEAP was used to model the surface water resources of Uganda and integrate climate-relevant and land use parameters. The modelling tool to capture the expansion of the energy sector was OSeMOSYS. The main task for soft-linking the two models was the temporal resolution. WEAP has a monthly temporal resolution while OSeMOSYS can capture daily splits within a month[5]. The soft-linking was achieved by integrating the monthly capacity factors of WEAP into the four-day splits of OSeMOSYS. Through this procedure, it was examined that the energy model was strongly dependent on the different capacity factors used for hydropower under different scenarios.

Another peer-reviewed publication that focuses on developing water and energy projections towards hydropower generation presented by van der Zwaan (2018). The geographical focus was on Ethiopia, and the relevant tools that applied were TIAM-ECN[6] and RIBASIM[7]. More specifically, the two models performed projections for hydropower generation until 2050 without being soft-linked. The results showed that the theoretical potential of hydropower performed in TIAM-ECN was much higher than the potential performed in RIBASIM). This was because the energy model was developed from the technical-economic perspective while the water allocation model developed, including indicators such as water availability and climate.

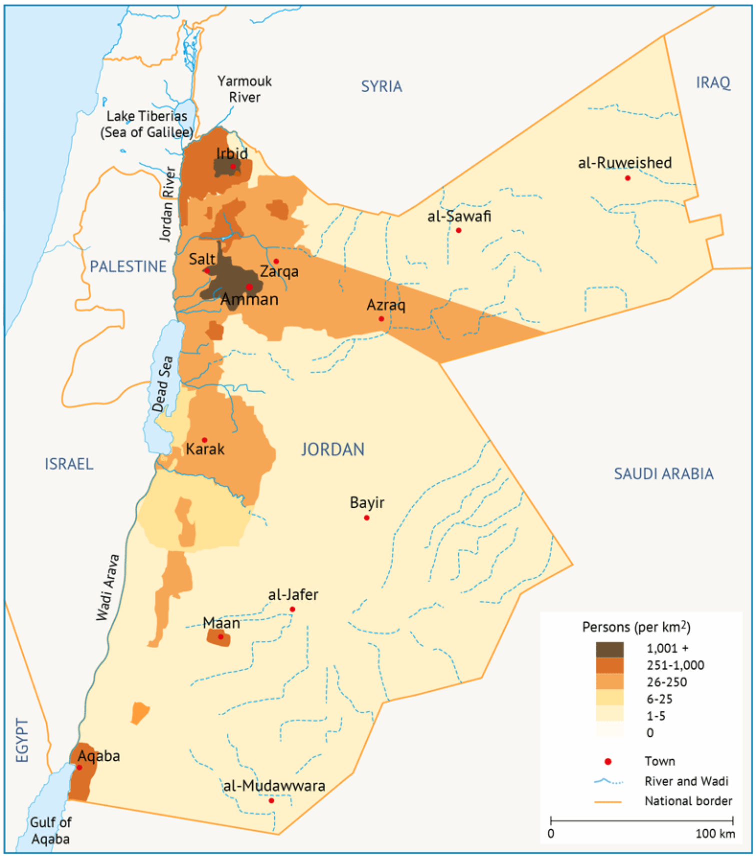
[5] Four different splits have presented: Morning, Day, Night, Peak.

[6] TIAM-ECN is a bottom-up linear optimization tool that is operated by ECN. TIAM (the TIMES Integrated Assesment) is based on TIMES (The Integrated Markal-EFOM System) which has developed in the context of IEA-ETSAP (International Energy Agency's Energy Technology Systems Analysis Program). (van der Zwaan et al., 2018)

[7] The River Basin Simulation tool developed by Deltares (van der Zwaan et al., 2018)

4. Water, Energy and Agriculture Nexus in Jordan

Jordan is a member state of the Arab League. Israel and Palestine border it to the west, Syria to the north, Iraq to the north-east and Saudi Arabia to the south-east . The total surface land covers an area of 89,342 km^2. The Jordanian territory is divided by 12 provinces. The total population for 2019 was 10.102.000 inhabitants[8]. Amman is the capital and most populated city with approximately the 2/5 of the total population. The population density is approximately 114.000 people per sq.m which is increased by 10.000 people during the last 5 years (WDI, n.d.).



Map 1 – Jordan population density, Source: Fanack, 2015

The average population growth rate for 2019 was 4.9%. The percentage of the population in urban areas has increased in the last 20 years by 12%, reaching 91.2% in 2019 (WDI, n.d.). The increase in the urban population has affected the availability of land for agriculture. As the urban areas are continuously increasing, adapting to the urbanization trends, the agricultural land is decreasing. The agricultural land area is approximately 12% of the total while arable and crops area covers 2.6% and 0.97% respectively[9]. The unemployment in Jordan has increased rapidly during the last decade, reaching the levels of unemployment during the early '90s for both sexes which were equal to approximately 19%[10]. The national Gross Domestic Product (GDP) has increased in monetary values during the last ten decades, with an average growth of 2.6%. Although, due to the corona pandemic and its consequences Jordan's economy is estimated to shrink by 5% for 2020 which is lower than the average of 6.6% for the countries in the Middle East[10].

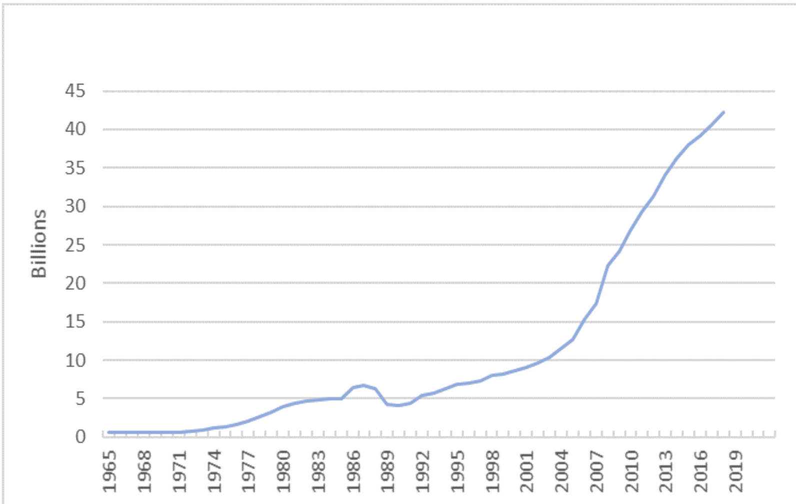


Figure 3 – GDP growth in Billions USD for Jordan, Source: WDI

[8] http://data.un.org/en/iso/jo.html
[9] http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en
[10] https://www.imf.org/external/datamapper/NGDP_RPCH@WEO/MENA/JOR/MEQ

4.1. WEA sectors in Jordan

The components of the nexus for this study are Water, Energy and Agriculture. While the relevant documentation within the nexus bibliography focuses on food rather in agriculture, this study concerning the lack of data for the food supply chains did not include the food sector in this analysis. Instead, the agricultural sector was included as a component of the nexus concerning the data availability from both grey and academic literature but also the national documentation.

4.1.1. Water sector

The water sector of Jordan is characterized by scarcity. The water demand has historically increased in order to cover the municipal, agricultural and industrial needs. As Fig. 4 shows, the industrial demand has slightly decreased over the decade while the withdrawals for agricultural sector experienced an increase of 9%. The municipal water withdrawals, driven by population growth and urbanization, have the most notable increase, at a rate of 33%.

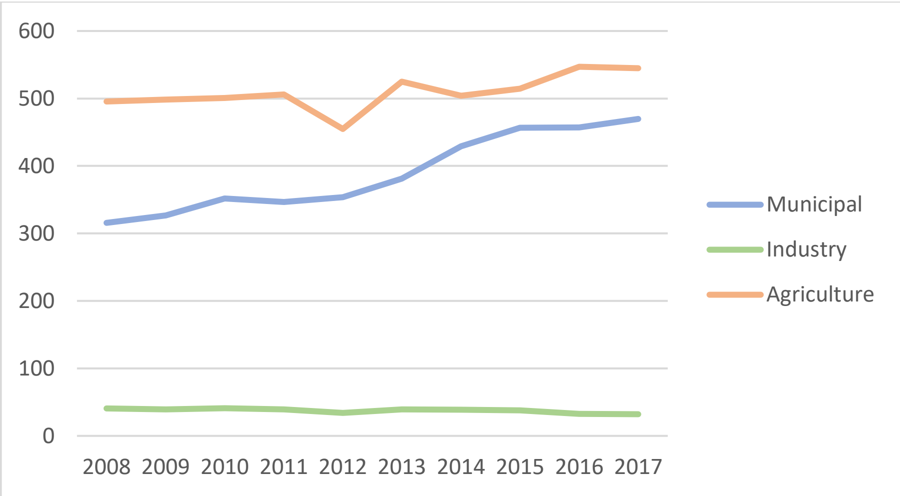


Figure 4 - Historical water withdrawals by economic sector in Jordan, Source:(MWI, 2017)

Within the same period, there is a notable increase in withdrawals from all the water resources (Fig. 5). Wastewater withdrawals had a more considerable increase which is about 31% while the surface and groundwater resources had a rise of 13% and 19% respectively.

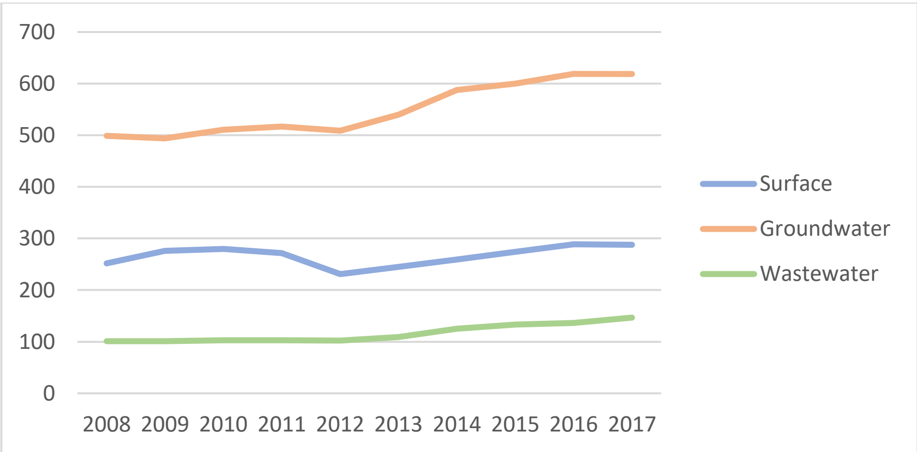


Figure 5 - Historical water withdrawals by source, Source:(MWI, 2017)

Groundwater is mobilized to approximately 58% of the total withdrawals in order to cover the demands for the municipal, agricultural and industrial sector in 2017 (Table 2). Agriculture is the most water-intensive sector having water demands in the range of 52% of the total water withdrawals in 2017. More than half of groundwater is mobilized to cover the domestic sector demands in 2017.

Uses/Resources MCM	Surface Water	Groundwater	Treated Wastewater	Total
Domestic	131.3	338.4	0	469.7
Agriculture	154.4	253.2	144.2	551.8
Industry	2.4	27.2	2.5	32.1
Total	**288.1**	**618.8**	**146.7**	**1053.6**

Table 2 - Water use by water resources in 2017, Source:(MWI, 2017)

Even though municipal water demand has increased, the water availability per capita has decreased (Fig. 6). This could indicate that the water sector has limitations on covering the per capita demand of previous years under such growth of urbanization and population. Consequently, the implication of these demographic characteristics led the national authorities to expand the operation of wells in order to avoid water shortages (MWI, 2018).

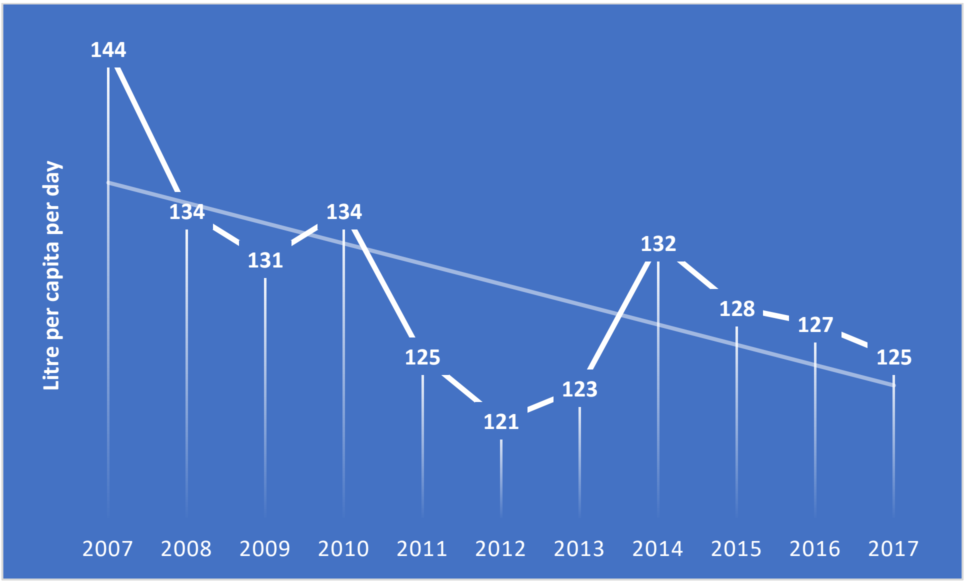


Figure 6- Water supply per capita per day, Source:(MWI, 2017)

A notable fact in the Jordanian water sector is the high percentage of non-revenue water. More than half of the municipal water is lost due to theft and leakages on the network as well as respectable amounts are lost due to illegal groundwater pumping for agricultural purposes (MWI, 2017, 2018; Whitman, 2019). This enforced the national authorities to introduce measures in order to mitigate the significant water losses (MWI, 2016a).

4.1.1.1. Surface water

Jordan is composed of 15 surface water basins in which the river basins of Jordan and Yarmouk have particular transboundary relevance. Other surface water resources include the wadis which have a seasonal flow only during the rainy season of the year (Al-Bakri et al., 2013; Hoff et al., 2011; Rajsekhar & Gorelick, 2017; UN-ESCWA & BGR, 2009; Whitman, 2019; World Bank, 2017).

Major dams	Design capacity million m^3	Start of operation	Use*
Wehdeh /unity	110	2006	1,2,3
King Talal	75	1987	1,6
Karameh/Karama	55	1997	1,5,7
Mujeb	29.8	2003	1,2,3
Wadi Arab	16.8	1986	1,2,3,6
Tanour	16.8	2001	1,3
Kafrain	8.5	1997	1,4
Wala	8.2	2003	1,2,3,4
Kufranjeh	7.8	n/a	1,2
Zeqlab/Ziglab	4	1967	1,2,3
Karak	2	2016	1,4
wadi Shueib	1.4	1969	1,4
* 1= Irrigation, 2=Municipal, 3=Industrial, 4=Recharge, 5=Recreation, 6=Electricity, 7=Desalination			

Table 3- Major dams in Jordan and their use, Source:(Hadadin, 2015; MWI, 2017)

Annual rainfall for 2017 was slightly above 8 billion m^3 although 93.5% of the renewable water was lost due to evaporation. The rest of it flowed into the rivers and other catchments as well as exploited by water harvesting infrastructure in the country. 12 large dams (Table 3, Map 2) located mostly in the Jordan valley, 61 small ones, as well as several earth ponds across the country, operate with a combined capacity of approximately 446 million m^3 (Ababsa, et al., 2013; Hadadin, 2015; MWI, 2017, 2018).

Map 2 – Location of major dams in Jordan, Source: (Al-ghussain, 2017; Fanack, 2015)

In addition to dams, wastewater treatment plants (WWTP) are operating within the country. Their operation has an increasing trend from 2011 while the national authorities plan to expand the capacity of wastewater treatment in the near future.

4.1.1.2. Groundwater

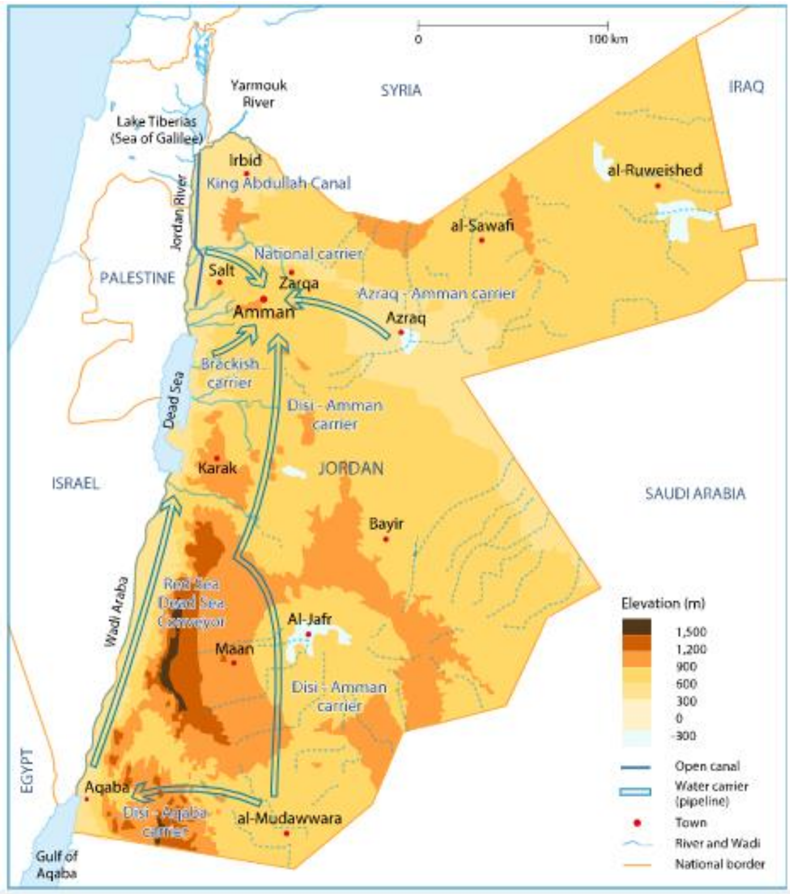
Jordan contains 12 groundwater basins. Jordan is heavily dependent on groundwater resources to meet the increasing water demand. Groundwater was historically the most important source for water supply. It contributes to more than half to all uses while 79% delivered to the municipal water supply in 2014 (Al-Ansari et la., 2014; MWI, 2017, 2018; Whitman, 2019).

The intensified groundwater pumping has declined the groundwater levels during the last 20 years. The national authorities have installed wells in different areas across the country in order to monitor the groundwater table depth and obtain a clearer picture regarding the groundwater aquifers. More specifically, for most of the installed monitoring wells, is noticed a decline in the water table depth. The most notable declines are noticed in wells installed in Irbid governorate (65 m), Mafraq (55 m) and Amman (44m) while in some other wells present a reduction of the water table between 22m and 35m (MWI, 2018).

Groundwater Basin	Safe Yield (MCM)	Abstraction (MCM)	Deficit (MCM)
Disi	125	141.58	-16.58
Amman-Zarqa	87.5	164.98	-77.48
Yarmouk	40	54.53	-14.53
Jordan Side Valley	15	45.64	-30.64
Azraq	24	69.66	-45.66
Jafer	27	35.53	-8.53
Jordan Valley	21	27.04	-6.04
Dead Sea	57	83.85	-26.85
Araba South	5.5	10.9	-5.4
Hammad	8	1.59	6.41
Sirhan	5	0	5
Araba North	3.5	6.56	-3.06

Table 4- Groundwater pumping abstractions and deficit for 2017 by groundwater basin, Source:(MWI, 2017)

The most populated places in Jordan such as Amman, Yarmouk, Irbid, Azraq and the Jordan valley have the largest water deficit in relation to the southern areas and desert areas of Jordan (Table 4). The only south area that has a relatively high deficit is the Disi aquifer. Since 2013, the Disi aquifer supplies the capital Amman with water which is pumped from groundwater and transferred through a pipeline (Map 3) (Tockner et al., 2016; UN-ESCWA & BGR, 2009).



Map 3 - Water transfer in Jordan, Source: Fanack, 2015

This is an indicator which verifies the increased water demand due to the urbanization and rapid population growth. Fig. 7 shows that the groundwater abstraction was historically exceeding the safe yields while at the same time was the backbone of the water supply covering more than 55% of the total water withdrawals.

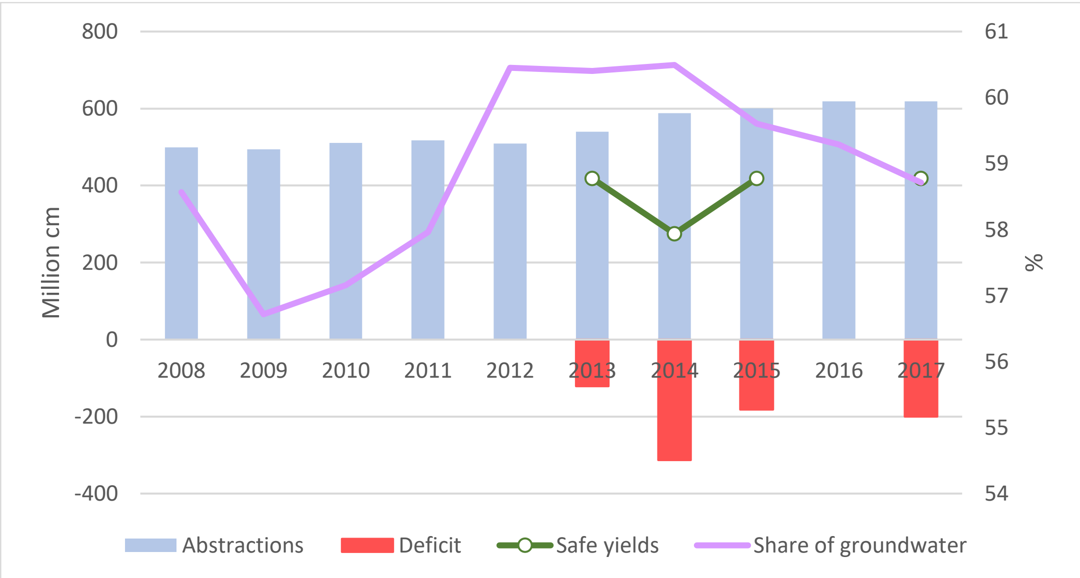
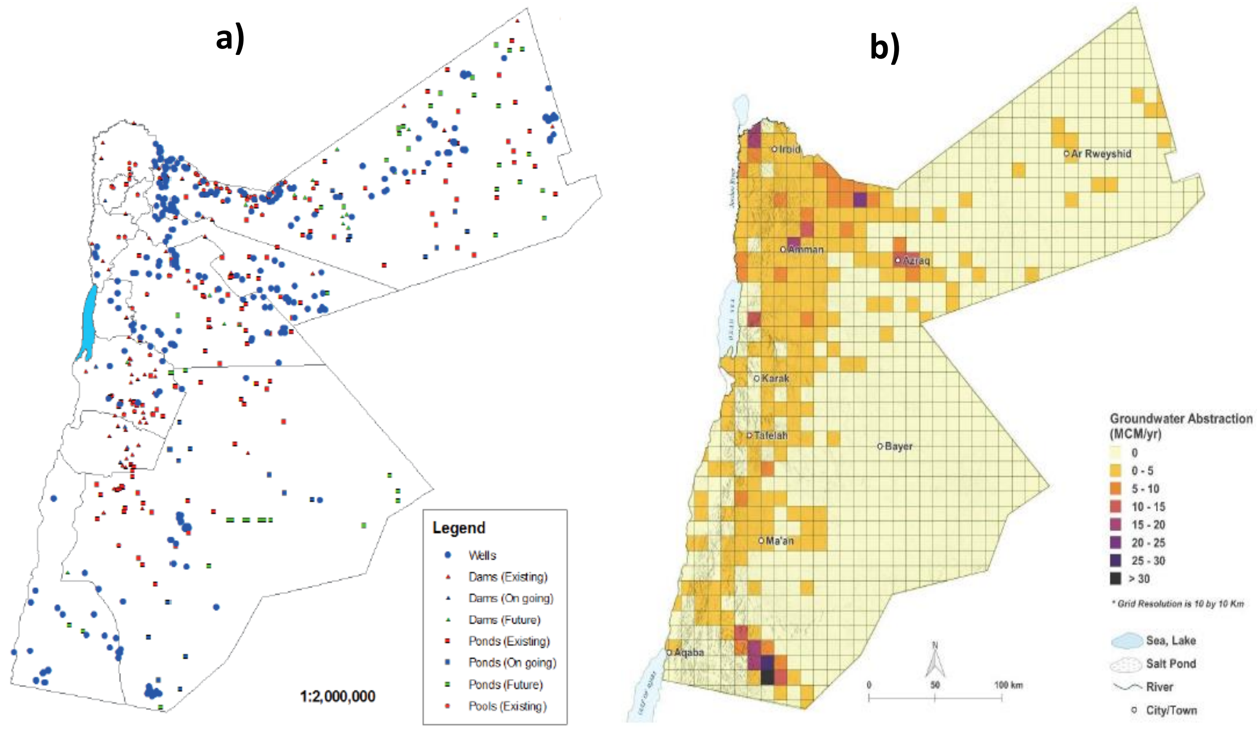


Figure 7 - Overview of historical groundwater withdrawals, Source:(MWI, 2013, 2015, 2017)

The groundwater activity is achieved through the operation of 3211 wells that spread across the country (MWI, 2017). As shown in Map 4, the wells are concentrated mostly to the northern and central areas, while a notable number is located in the south area of the Disi

Aquifer. The groundwater density is in line with the location of wells since the groundwater abstraction is higher in northern and central areas that surround the most populated areas as well as the South Jordan where the Disi-Amman conveyance project takes place.



Map 4 - a) Spatial distribution of wells in Jordan by 2013, Source: (Salman et al., 2016) - b) Spatial distribution of groundwater abstraction by 2017, Source: (MWI, 2018)

4.1.2. Energy sector

Jordan is dependent on energy imports to meet its energy demands. Even though Jordan produces natural gas and crude oil, (Al-Omary et al., 2018; IUCN ROWA, 2019; Mansour et al., 2017) the energy imports are used to cover around 97% of the total energy demand. Natural gas and crude oil are imported at levels beyond 96% from the neighbouring Gulf countries, Egypt and Iraq. Due to operational challenges on Iraq's oil production, the unrest of Arab spring in Egypt, as well as the financial impacts of the fossil imports to the national GDP, Jordan's energy security passes through the penetration of renewables. This situation can be expected to become more challenging in the coming years. On the one hand, energy and electricity consumption will increase rapidly. For example, existing projections forecast a doubling of the electricity demand in the next 15 years. On the other hand, due to societal and political challenges and increasing uncertainties, the supply of fossil fuel energy[11] from the neighbouring countries will most likely become less stable and less reliable (Al-Omary et al., 2018).

As depicted in Fig. 8, Jordan's imports for 2018 consisted mostly of natural gas (38.5%) and oil products (55.8%) such as crude oil (25.7%), diesel (12.6%) and gasoline(11%). Consequently, importing energy sources has contributed to the national GDP at 19% in 2011 (Komendantova et al., 2017). According to the Ministry of Energy and Mineral Sources (MEMR, 2018b), the final energy consumption was equal to 6,866,800 TOE. Considering the non-oil products,

[11] A definition for this term can be found here: https://www.sciencedirect.com/topics/engineering/fossil-fuel-energy

electricity had the largest share of approx. 22% with consumption of 1,507,700 TOE. Although electricity generation is dominantly dependent on fossil fuels at a percentage of 89.3% for 2018 (NEPCO, 2018). Renewables such as solar and biomass contributed 285,500 TOE having a share of approx. 4% of the total energy consumption.

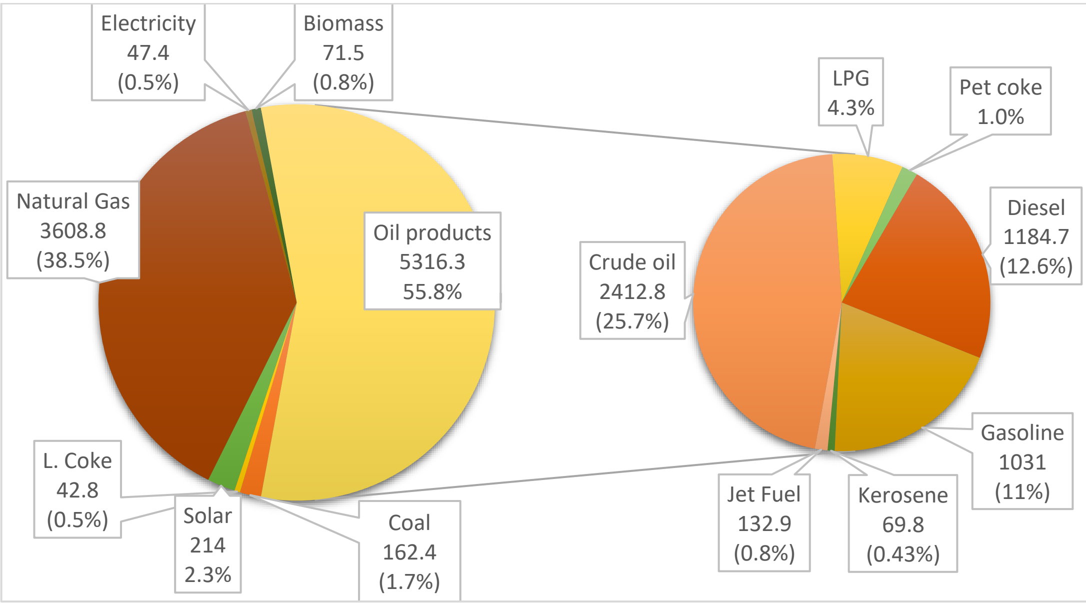


Figure 8 – Imports (in thousands TOE) for 2018 in Jordan, Source:(MEMR, 2018b)

Oil products contribute with 4,862,200 TOE having a share of approximately 71% of the total energy consumption (Fig. 9). Diesel is the most used oil product with contributions of 1,971,800 TOE and a share 29% of the total energy consumption. Gasoline is the second most used oil fuel with contribution 1,604,300 TOE and a share 23% of the total. LPG usage is equal to 483,900 TOE with a share of 7% of the total energy consumption. The rest of oil products consumed energy of 808,200 TOE having a share of 12% of the total energy consumption.

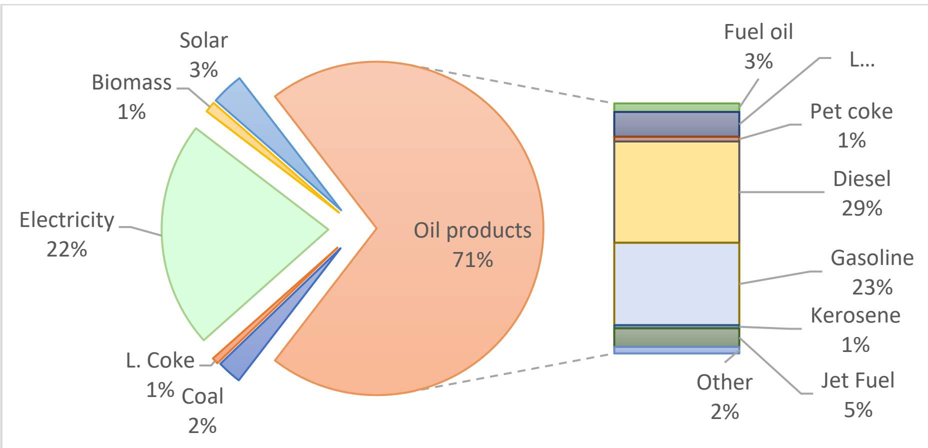


Figure 9 - Final energy consumption for 2018 in Jordan, Source:(MEMR, 2018)

According to the studies of national authorities, the transports sector is the most energy-intensive sector of Jordan, accounting for approximately 50% of the total energy consumption (Fig. 10). This is also reflected in the GDP, since the transportation sector accounted for 14.5%

of the total national GDP in 2015[12] (Komendantova et al., 2017). The transportation sector consumes oil products entirely. Diesel and gasoline are the most used oil fuels.

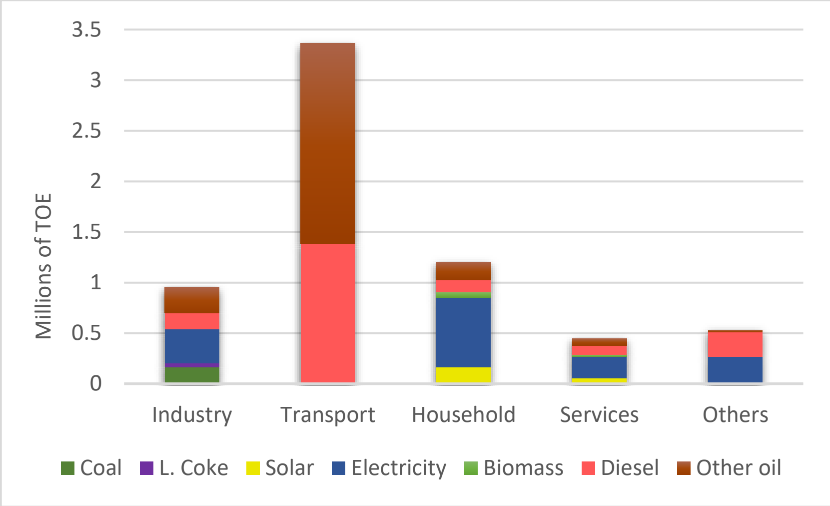


Figure 10 - Energy consumption by fuel and sector. Based on (MEMR, 2018a)*, others sector is referred to commercial, agricultural sectors along with street lights. Source:* (MEMR, 2018b)

Based on the World Development Indicators (WDI), the CO_2 emissions from the transport sector in 2014 were 29.2% of the total emissions from the fuel combustion activities. The industrial sector consumes 333,400 TOE from electricity and 414,000 TOE from oil products. In the households sector the largest share of renewables is through the consumption of solar energy, with approximately 160,800 TOE. The rest is split between electricity, oil products and biomass.

Additionally, a notable contribution of solar takes place in the services sector. Although the energy demand is met primarily through electricity (215,600 TOE) and oil products (161,100 TOE). Electricity and diesel contribute significantly to the sector's needs with 267,500 TOE and 242,800 TOE, respectively.

4.1.2.1. Electricity system

The electricity generation sector has a crucial role in mitigating CO_2 emissions since along with the heat sector contributed with 40% of CO_2 emissions in 2018[13]. In this context, Jordan policymakers aims to promote renewable sources. For this reason, the Jordanian authorities has estimated the size of investment in renewables to fulfil that percentage to 15 billion USD (Al-omary et al., 2018).

The Jordanian electricity system consists of three main sectors: generation, transmission and distribution. The generation capacity for the year 2018 reached 5,236 MW, compared to 4,300 MW in 2017 with a growth rate of 21.8%. The generation capacity of renewable energy projects carried out on the transmission and distribution grids reached about 980 MW by 2018, representing about 19% of the total generation capacity (Fig. 11) (NEPCO, 2018).

The current capacity of the grid is limited, presenting a significant bottleneck for increasing electricity generation to cover the growing demand. In 2015 the government needed to cancel

[12] https://oxfordbusinessgroup.com/overview/stabilising-force-increased-foreign-investment-coupled-domestic-expansion-has-transformed-sector
[13] https://www.iea.org/countries/jordan

proposals to build five wind power plants with a total capacity of 400 MW, as the grid was unable to afford additional loads (Davies et al., 2016; Komendantova et al., 2017).

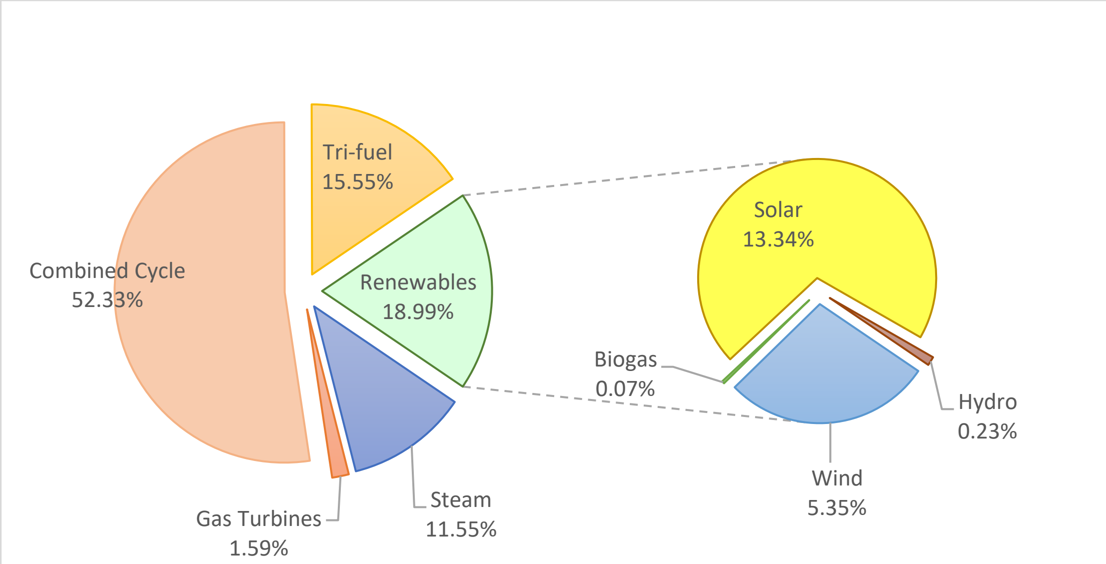


Figure 11 - Share of the installed energy technologies in the power sector in Jordan for 2018, Source:(NEPCO, 2018)

The electricity consumption has increased by around 4,600 GWh during the period 2010-2018 (Fig. 12). As mentioned in previous chapters, this increase can be attributed to external drivers, i.e., population growth and urbanization.

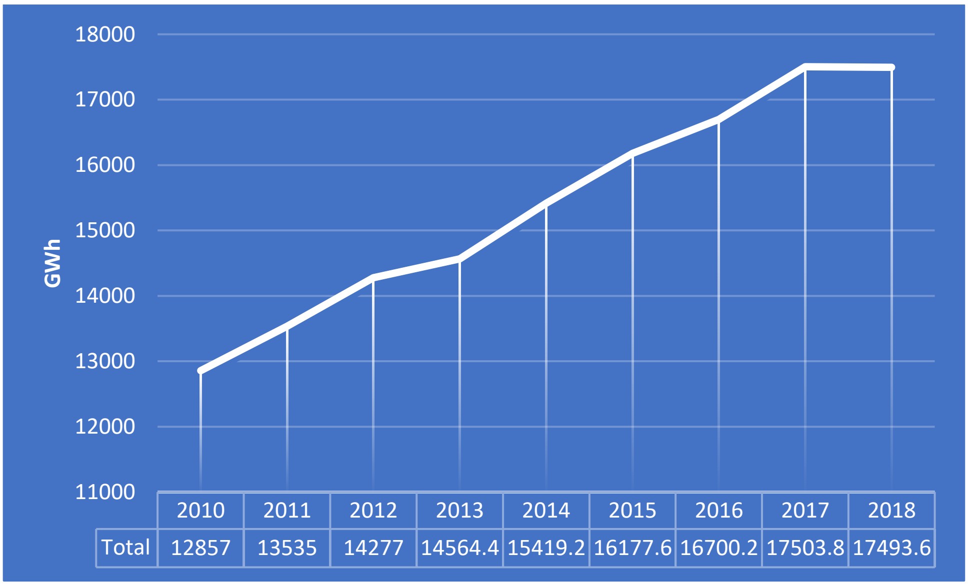


Figure 12 - Total electricity consumption in Jordan by year, Source:(NEPCO, 2018)

Fig. 13 shows the electricity consumption by sector. The electricity demand for domestic use experiences the highest increase in comparison to the other sectors. Electricity consumption for agriculture and water pumping purposes also notes a considerable increase, especially after 2013.

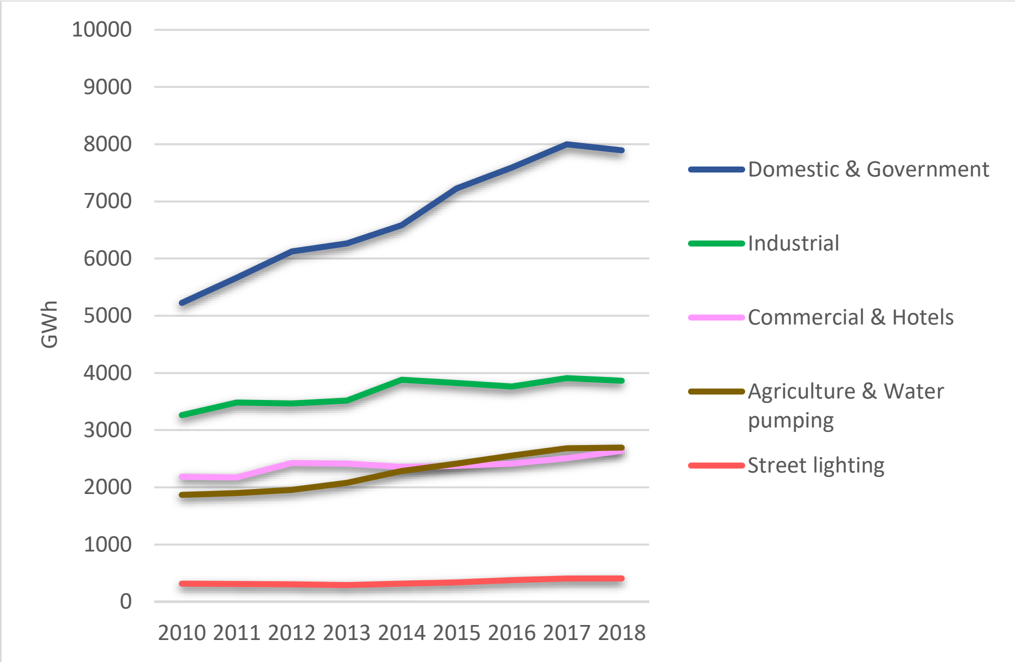


Figure 13- Electricity consumption by sector (2010-2018), Source:(NEPCO, 2018)

4.1.3. Agricultural sector

Even though the agricultural sector contributes to approximately 5% of the national GDP, its water withdrawals are more than half of the total water withdrawals. Further, Jordan is heavily dependent on food imports. More specifically, Jordan is highly dependent on food imports such as cereals, sugar and rice, but it produces all of its needs in vegetables. For 2014, vegetable exports generated an income of 750 USD for 2014 while contributing 8% of the total exports (Mansour et al., 2017).

Jordan's arid area covers approximately 80% of the country with low levels of rainfall. Rainfed agriculture has limited options for cultivation since a very little portion of land receives enough rainfall to support the rainfed crops (Fig. 14). Moreover, considering the expansion of urban areas, the growth of population and climate change effects, a critical decrease of cultivated areas is projected by 2050 (Al-Bakri et al., 2013; Mansour et al., 2017).

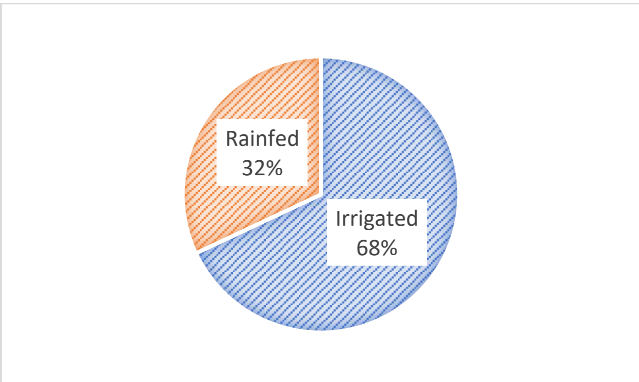


Figure 14 - Method of irrigation for crop production, Source: WRI Aqueduct data[14]

[14] https://www.wri.org/aqueduct#aqueduct-tools

4.1.3.1. Biomass potential

Given that Jordan is primarily dependent on energy imports, which was mentioned in previous chapters, biomass could support a vision towards energy security. Al-Hamamre (2017), investigated the biomass potential in Jordan. According to this research, energy can be obtained from the production of biogas, MSW, crop residues and animal wastes. The biomass potential for electricity production could be more than 2315 GWh annually. The current biomass contribution to the electricity mix is coming only from biogas and it is 3.4 GWh for 2018 and 3.5 GWh for 2019 respectively (NEPCO, 2018, 2019). Considering this information, it has assumed that there is significant untapped potential for electricity production from this resource.

4.2. Drivers of the WEA nexus in Jordan

Jordan is considered as one of the most water-scarce countries in the world, and the situation is increasingly strained by population growth, climate change and by the region's geopolitics (Hoff et al., 2019). Rational use and supply of natural resources that contributes to feeding urban population are becoming increasingly complex in a time of rapid change in demographics and climate change. Projections on the total unmet demands vary between the bibliography although indicate that population and economic policies play a central role in ensuring future water, energy and food security in the country (Hoff et al., 2011).

4.2.1. Population growth

The population in Jordan has more than doubled since the 1970s (Fig. 15). According to the projections carried out by the United Nations, the population will still increase under all selected scenarios until 2075 except the low fertility scenario. After 2075 it is noticed a decrease in 4 of the 9 scenarios while under one scenario is noticed a stabilization and in four scenarios an increase of the total population. The context of each scenario has summarized in Table 5.

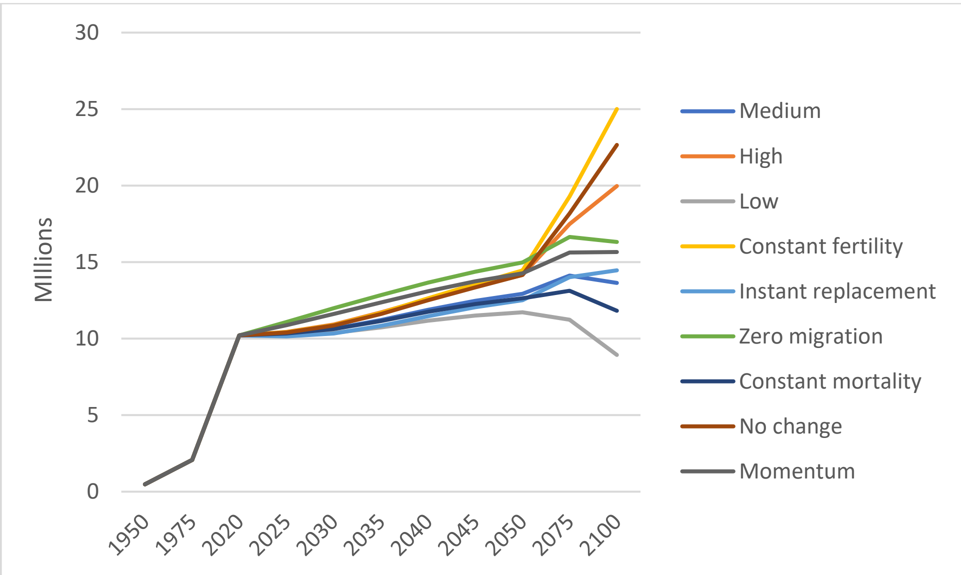


Figure 15 – Population growth and projections for Jordan, Source: UN population division, (2019)

Population growth is strongly dependent to the expansion of urban and agricultural development in the region (Odeh, Mohammad, Hussein, Ismail, & Almomani, 2019).

Projection variants	Assumptions Fertility	 Mortality	 International migration
Low fertility	Low	Normal	Normal
Medium (fertility)	Medium (based on median probabilistic fertility)	Normal (based on median probabilistic fertility)	Normal
High fertility	High	Normal	Normal
Constant-fertility	Constant as of 2015-2020	Normal	Normal
Instant-replacement-fertility	Instant-replacement as of 2020-2025	Normal	Normal
Momentum	Instant-replacement as of 2020-2025	Constant as of 2015-2020	Zero as of 2020-2025
Constant-mortality	Medium	Constant as of 2015-2020	Normal
No change	Constant as of 2015-2020	Constant as of 2015-2020	Normal
Zero-migration	Medium	Normal	Zero as of 2020-2025

Table 5 – Scenario description for population projections, Source: UN population division, (2019)

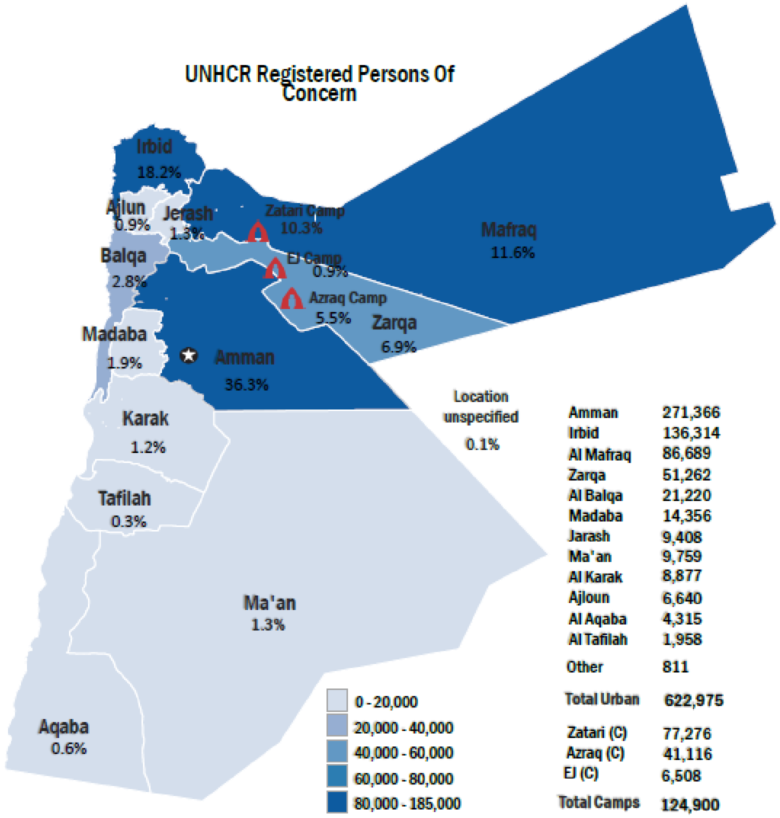
Jordan has experienced a rapid increase in the refugees' population mostly due to the Syrian civil war. Since 2011, half of the country's pre-war population were killed or fled their homes. Families are struggling to survive within Syria or make a new life in neighbouring countries. Others are risking their lives to Europe, hoping to find acceptance and opportunities (Ministry of Planning and International Cooperation of Jordan, 2016).

Based on UNHCR, Jordan had a population of 747,875 registered refugees for 2020[15] (UNHCR, 2020a). The large majority of the refugees are Syrians (87.9%) while the rest of the refugee population are Iraqis (9%), Yemenis (2%), Sudanis (0.8%) and from other nationalities (0.3%) (UNHCR, 2020a). Approximately half of the registered refugees are children between 0-17 age (UNHCR, 2020a). Concerning both the registered and unregistered Syrians, Jordan has provided refuge to approximately 1.266 million Syrians (Ministry of Planning and International Cooperation of Jordan, 2016).

The vast majority of the refugees live in urban areas, while the rest of them live in camps (Map 5). More specifically, 622.975 (83.3%) refugees reside in urban areas with the governorates of Amman, Irbid, Mafraq and Zarqa concentrating the largest population. On the other hand, 124,900 (16.7%) refugees live in the camps of Zatari, Azraq and Ej (UNHCR, 2020b).

The increased population of refugees in the country, coupled with population growth, increased the demand for energy, water, food, infrastructure, and public services, which has further strained Jordan's finances, natural resources, and community relations. Demand for water and energy are acute concerns for current and future water and energy resources (Combaz, 2019; Ministry of Planning and International Cooperation of Jordan, 2016).

[15] Until June, 2020



Map 5- Population intensity of refugees in Jordan, Source: (UNHCR, 2020b)

4.2.1.1. Population growth impact on the energy sector

Population growth, coupled with the influx of refugees has increased the demand for energy and electricity, while the consumption of residential energy has risen significantly. Furthermore, services for water (pumping, treating, trucking, and wastewater collection) are interlinked with energy demand (Combaz, 2019).

Rapid population growth over the period 1960-2017 increased the total primary energy consumption on the national level, as shown in Fig. 16. More specifically the population was more than tripled between during the period 1980-2013 following an increase of 258%. During the same time period, the total primary energy consumption was more than quadrupled following an increase of 338%.

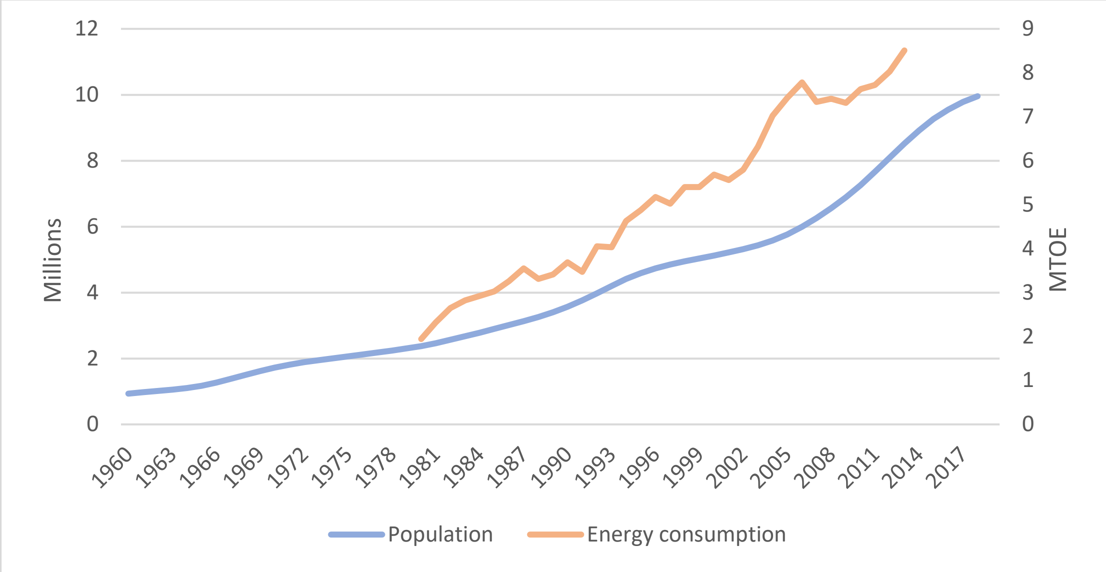


Figure 16 - Historical growth of population and energy consumption, Source: Knoema[16], WDI

4.2.1.2. Population growth impact on the water sector

The population growth increased the municipal and agricultural water demand throughout the years. As shown in Fig. 17, the total water withdrawals almost doubled (95% increase) within the period 1980-2017. Domestic water in the northern governorates has increased by 40% in the last few years as a result of the refugee crisis (MWI, 2017).

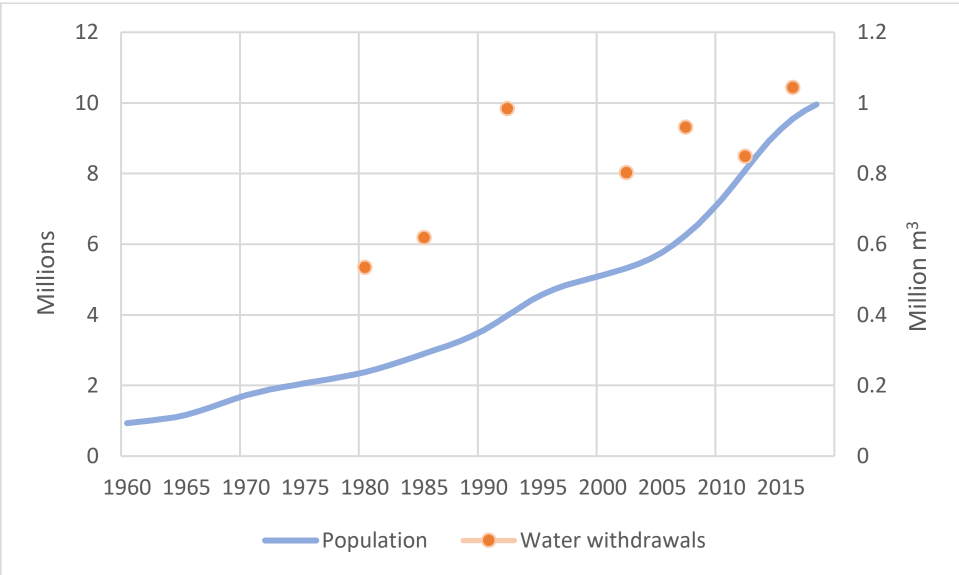
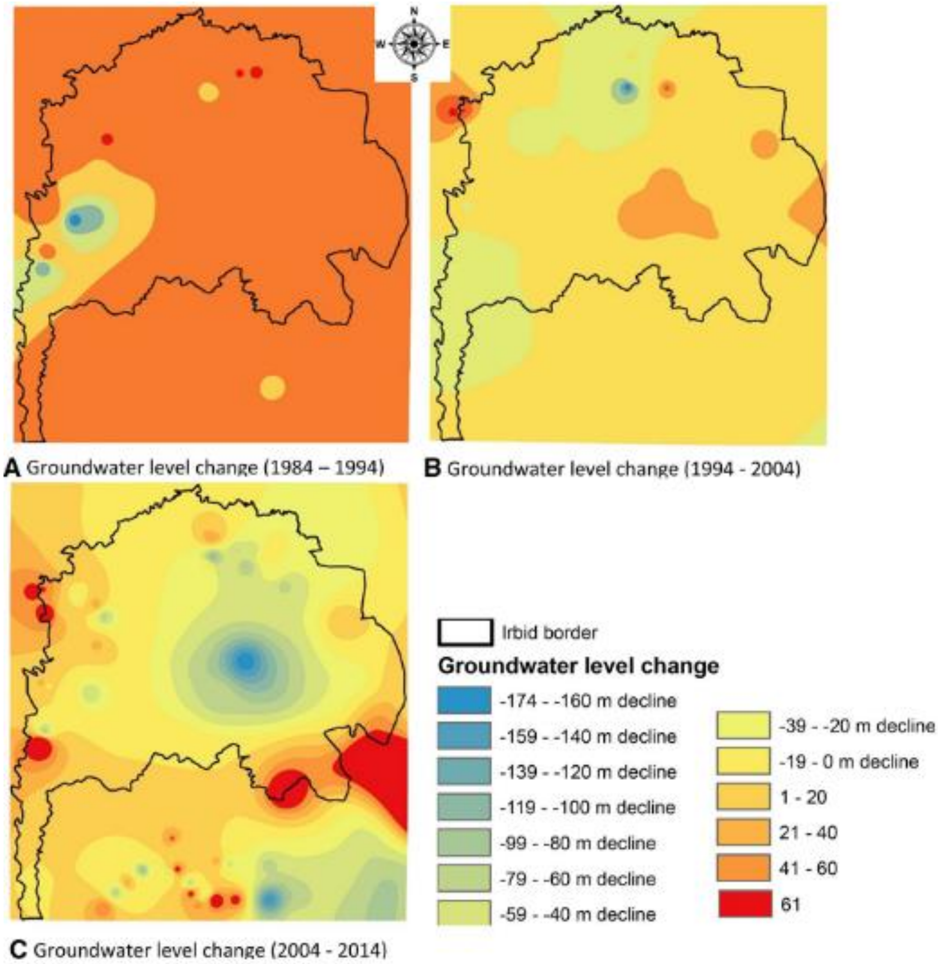


Figure 17- Population growth and water withdrawals, Source: Aquastat[17], WDI

While the population in Jordan is expected to continue to increase the unmet water demands is expected to increase too. The water supply had dropped from 144 million m^3 in 2007 to 125 million m^3 in 2017. Jordan's water resources are limited to support the population needs in a sustainable perspective. Estimations depict that the annual growth in demand for water in Jordan will be around 25 million m^3/yr (Hadadin, Qaqish, Akawwi, & Bdour, 2010). Moreover,

[16] https://knoema.com/atlas/Jordan/topics/Energy/Total-Energy/Primary-energy-consumption
[17] http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

as it is noticed by Odeh (2019), the groundwater resources are currently overexploited (Map 6) and overpumped (Fig 18) above their safe yield.



Map 6- Historical decline of groundwater levels in Irbid governorate, Source:(Odeh et al., 2019)

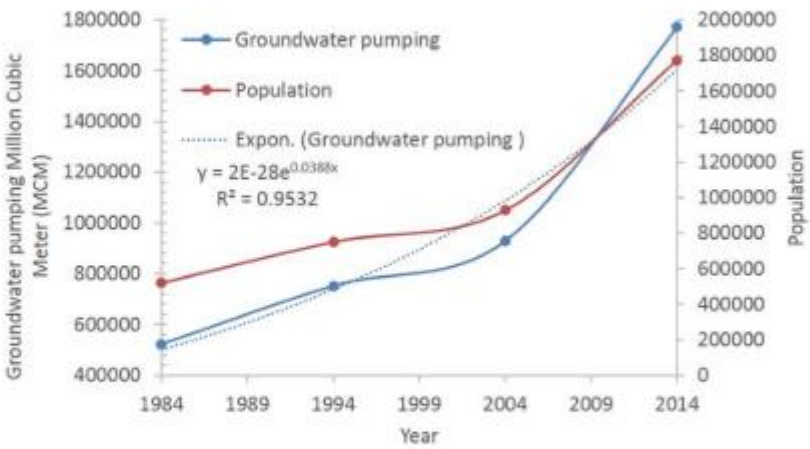


Figure 18 - Relation between population growth and groundwater pumping, Source:(Odeh et al., 2019)

4.2.1.3. Population growth impact on the food sector

The increasing population creates the challenge of meeting food demands. As presented in Fig. 19 and Fig. 20, respectively, the production of vegetables and field crops were analogically increased (Jordanian Department of Statistics, n.d). The increase in the production of vegetables was 119% concerning values from 1995 and 2016 respectively. At the same time, the production of field crops was more than tripled (212%) concerning the same time period.

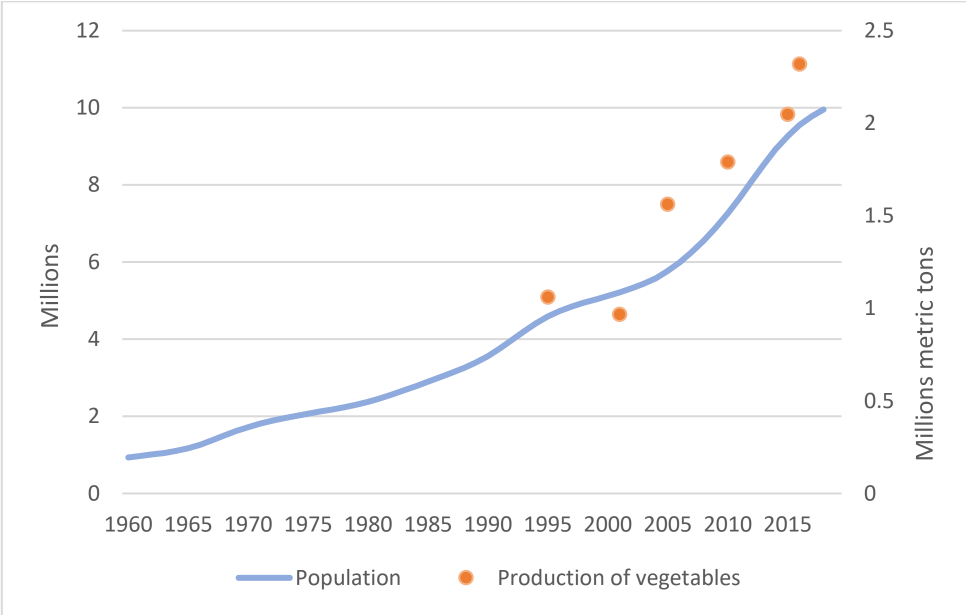


Figure 19 - Growth of population and production of vegetables, Source: WDI, Department of Statistics

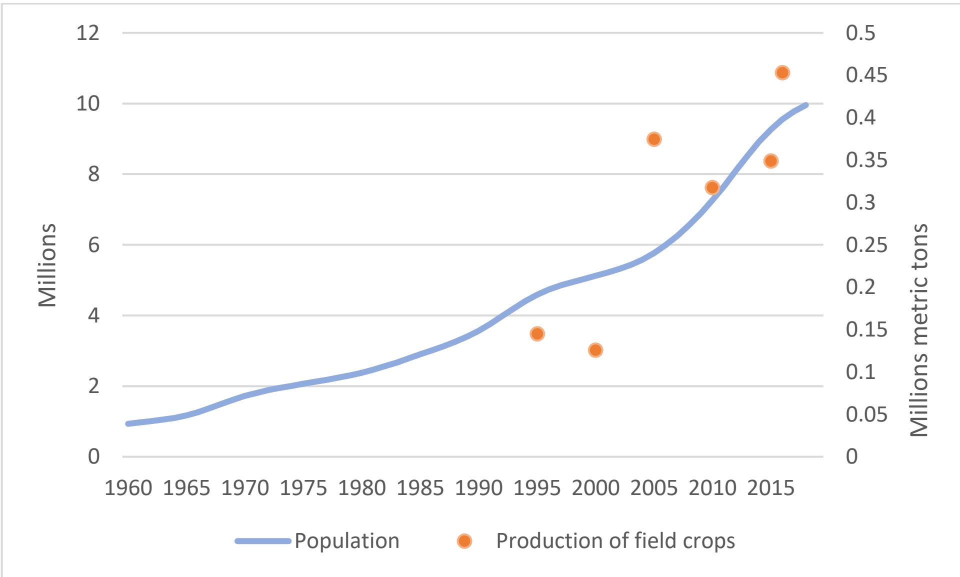


Figure 20 - Growth population and production of field crops, Source: WDI, Department of Statistics

4.2.2. Urbanization

The urban population of Jordan has significantly increased between 1970 and 2020 (Fig. 21). The agricultural expansion trend observed in rural areas is not noticed in urban areas. Due to the further fragmentation of land ownership and the fact that the choice of some owners is to no longer cultivate their portions of land, agricultural areas of the past are not cultivated anymore. (Talozi, Al Sakaji, & Altz-Stamm, 2015).

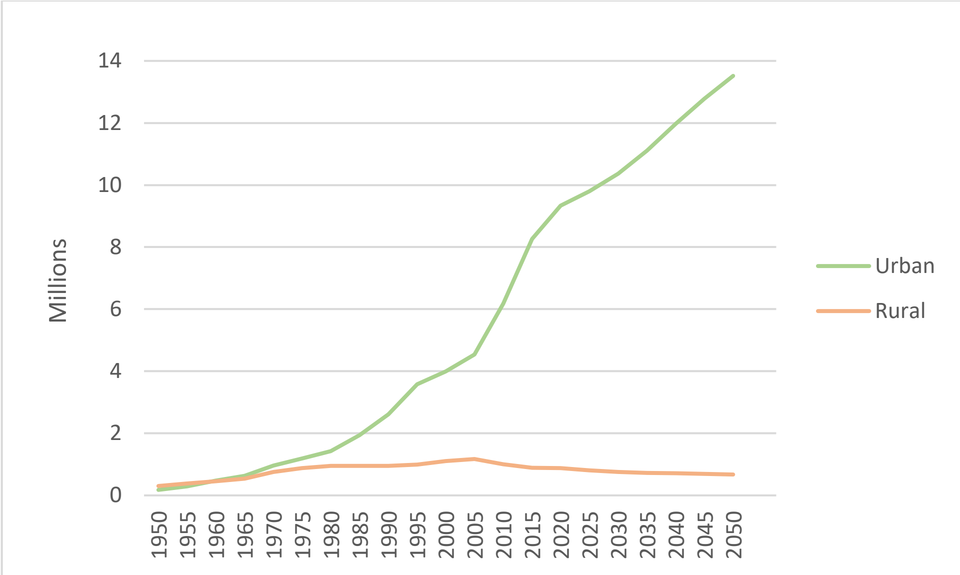


Figure 21 – Urbanization in Jordan, Source: UN Population prospects, 2019

As depicted in Table 6, the urban population of Amman accounts for the 40% of the country's total population, while together with Irbid and Zarqa account for approximately 70.6%.

#	Urban Population	% of the country's total
Amman	4,307,300	40.8
Irbid	1,807,300	17.1
Zarqa	1,454,100	13.7
Balqa	446,300	4.23
Mafraq	423,600	4.01
Karak	207,000	1.96
Jarash	201,700	1.91
Aqaba	177,100	1.68
Malaba	163,700	1.55
Ajlun	163,400	1.55
Ma'an	94,700	0.90
Tafiela	83,000	0.79
Total	9,529,200	90.18

Table 6 – Urban population density per province for 2019, Source: Department of Statistics

4.2.2.1. Urbanization impacts on the water sector

The agricultural sector is noticed to consume the largest amounts of water in comparison with the municipal and industrial sector. Although the municipal demand are projected to increase their share the nexr years. (Fig. 22) (Siddiqi, Kajenthira, & Anadón, 2013).

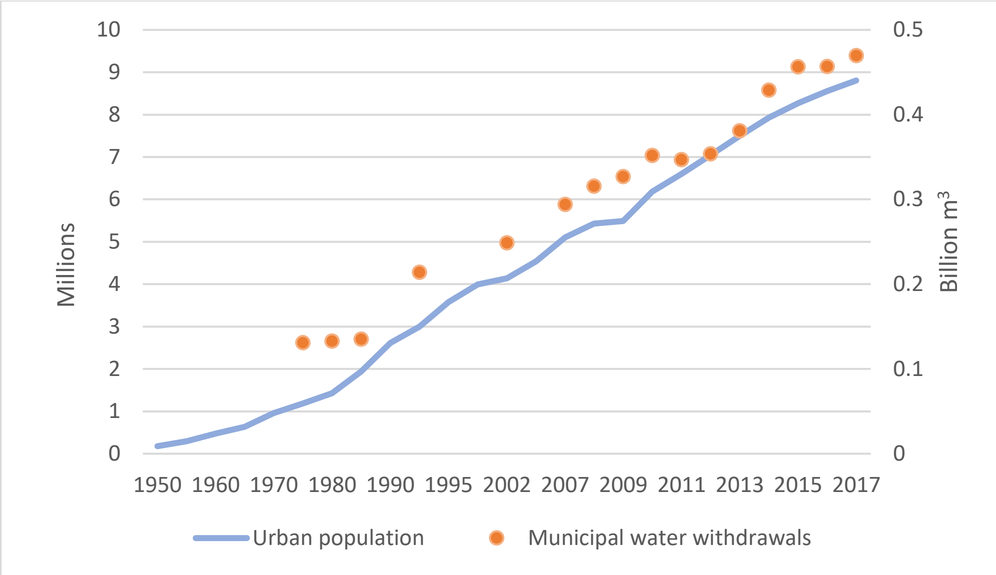


Figure 22 – Growth of urbanization and municipal water withdrawals, Source: United Nations Urbanization, MWI, Aquastat

The expansion of urban areas in Jordan had negative impacts on the groundwater levels and its salinity (Odeh et al., 2019). Population growth, urbanization and economic development have increased the demand for water resources, which affected both the quantity and the quality of water resources. As a result, these factors are associated with the over-exploitation of water resources and their contamination (Hadadin et al., 2010).

4.2.2.2. Urbanization impacts on the energy sector

The most populated areas have greater energy demand in order to meet the needs of an expanding population, infrastructure, transportation and other sources of demand (Avtar, Tripathi, Aggarwal, & Kumar, 2019). This is also the case for Jordan since its energy consumption is driven by the growth of urban population as it is depicted in fig 23. More specifically, the urban areas had an average increase of 4.8% of energy consumption on the national level while the urbanization rate followed an average increase of 5.1% for the time period 1980-2013.

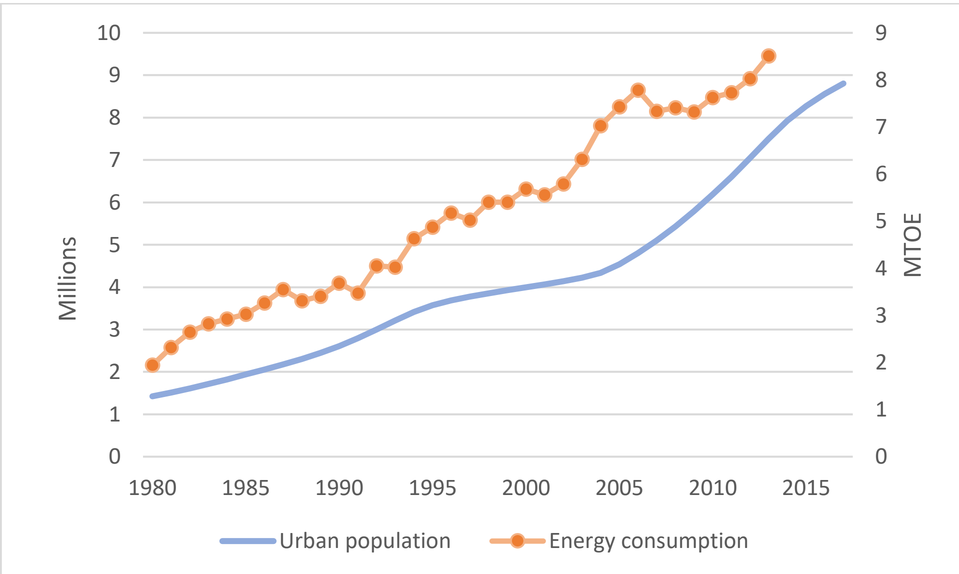


Figure 23 - Historical growth of urban population and energy consumption, United Nations, Knoema

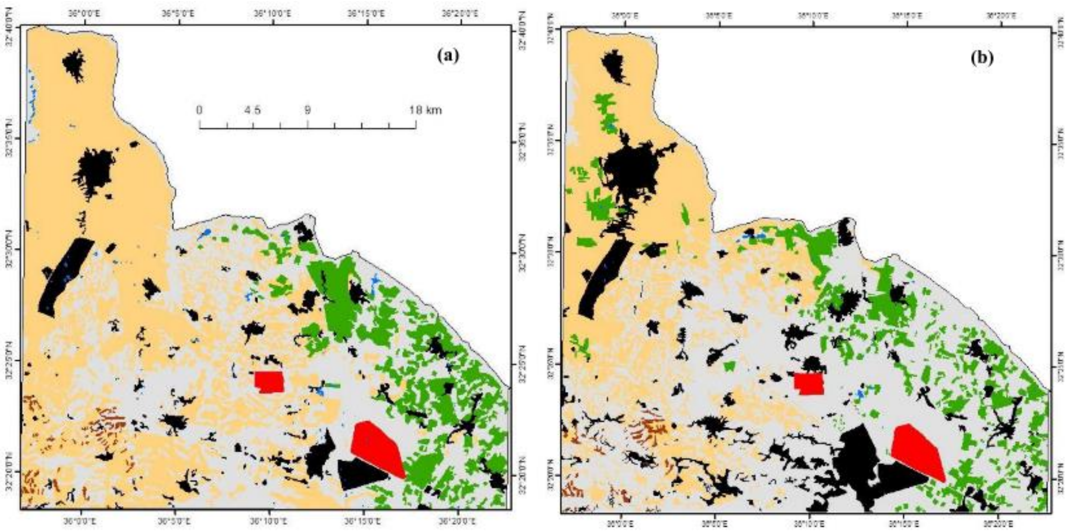
4.2.2.3. Urbanization impacts on the food and land use sectors

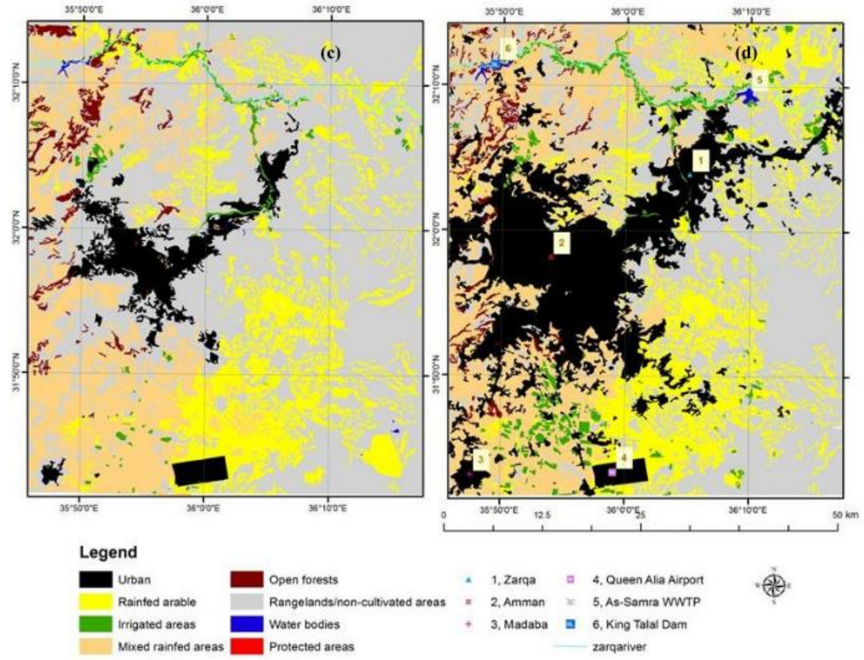
The increase in urban areas reduces the availability of arable land. Jordan experiences critical losses of agricultural portions of cultivated land due to urbanization (Hoff et al., 2019). A study performed by (Al-Bakri et al., 2013) examined the urbanization consequences on land-use considering the most populous areas in the country, Amman, Irbid and Zarqa. It is noticed that while the urban population was increasing the irrigated lands were decreasing at a rate of 126 ha per year from 1992 to 2010 (Table 7). This was caused by the decline in water quality as a resultd of over-exploitation of groundwater and the salinization of soil.

Land use/cover	Irbed			Amman-Zarqa		
	1992	2002	2010	1983	1994	2010
Urban	7.2	9.8	12.4	6.1	12.3	22.0
Mixed rainfed areas	42.4	39.8	29.4	35.4	39.4	36.9
Irrigated areas	9.4	8.4	7.6	1.1	3.3	2.4
Forests	0.6	0.6	0.6	2.0	1.8	1.8
Rangelands/ non-cultivated	40.0	41.2	49.9	55.3	43.0	36.7
Water bodies	0.4	0.2	0.1	0.1	0.2	0.2

Table 7- Land use change in urbanized cities, Source: (Al-Bakri et al., 2013)

As depicted by Map 7, the urban areas have replaced the areas with rainfed agriculture within time. The absence of land use law in Jordan had a critical role in this change. This decline in rainfed areas is also reflected in frequent drought and rainfall irregularity in the past two decades. Under climate change circumstances, the expected decrease in rainfall would also result in the decrease of rainfed areas (Al-Bakri et al., 2013).





Map 7- Land use/cover maps of Irbed in 1992 (a) and in 2010 (b) and for Amman-Zarqa in 1983 (c) and 2010 (d), Source: (Al-Bakri et al., 2013)

4.2.3. Climate

A historical decrease of 8% in precipitation levels is noticed through observations in Amman airport station, during the period 1960-2010, Fig. 24 (Abdulla & Malkawi, 2020). Furthermore, Abdulla (2020) presented historical data during 1970-2010 from Amman airport station that depicts the increase of mean, minimum and maximum annual temperature (Fig. 25).

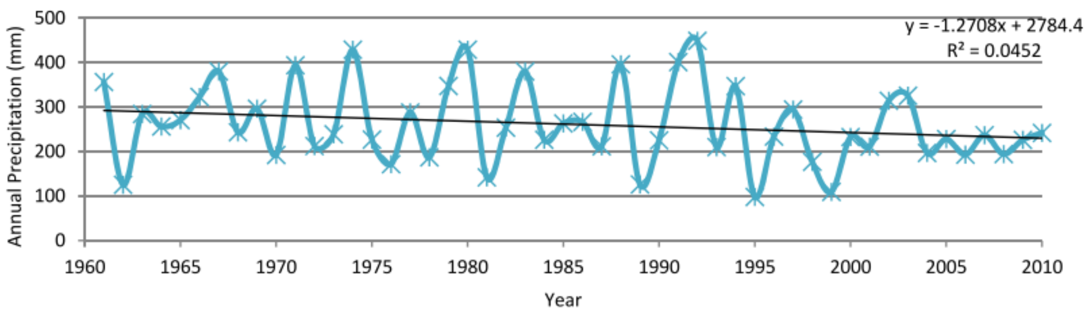


Figure 24- Historical precipitation, Source: (F. A. Abdulla & Malkawi, 2020)

Regarding the temperature variations, historical data collection during 1970-2010 from Amman airport station, shows the increase of the mean, minimum and maximum annual temperature. More specifically, an increasing trend is noticed for the mean annual minimum temperature of more than 3 degrees. At the same time, the mean annual temperature has an increase of 1,5-2,0 degrees while the mean maximum temperature has a slight increase. Historical data gathering and analyses from 8 meteorological stations in Jordan present variations of the annual mean, maximum and minimum temperature of ± 0,55 degrees. (F. Abdulla, 2020)

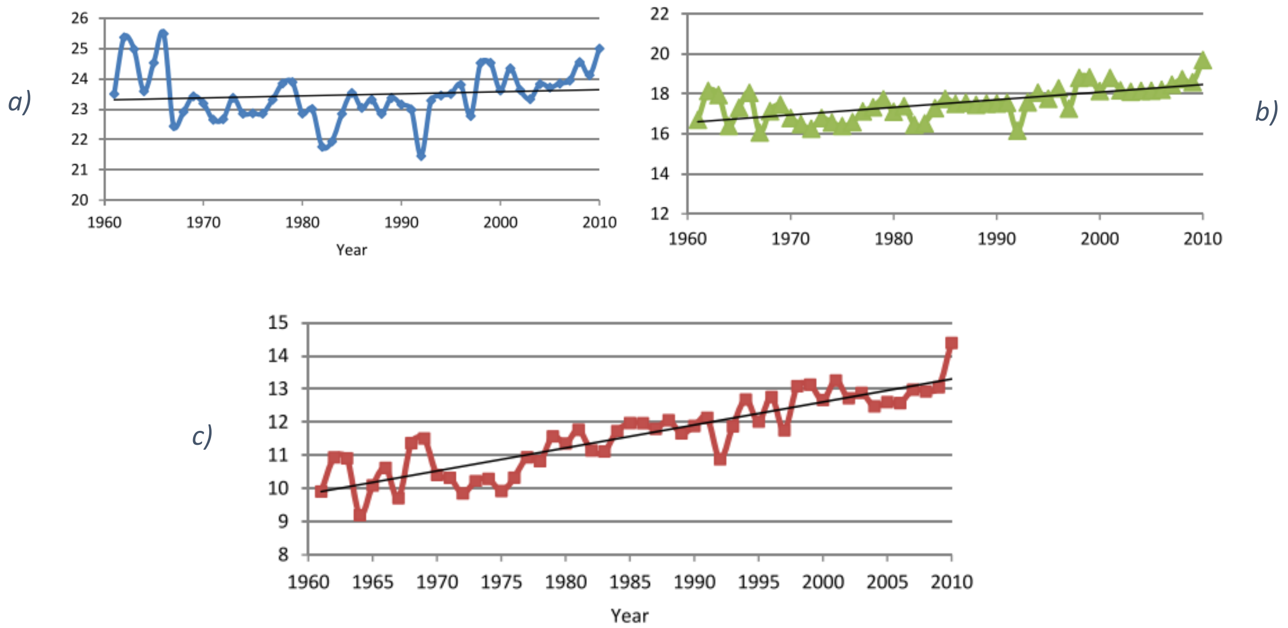


Figure 25 - Historical temperatures in Amman. a) Mean annual maximum temperature. b) Mean annual temperature. c) Mean annual minimum temperature. Source: (Abdulla, 2020)

Another indicator that needs to be taken into account in order to understand the climate conditions of the country better is the evapotranspiration. Evapotranspiration (ET) is the process in which the water evaporates from the soil and transpired from the crops. The increase in temperature can lead to greater water losses through ET. More importantly, increased ET and soil infiltration will cause a decrease in soil moisture thus more water demand for irrigation will be needed (World Bank, 2017). Jordan seems to have an oriented spatial distribution of potential ET (Al-Qinna, 2018).

Increased temperature in combination with insufficient precipitation and high ET levels as well as the unequal distribution of water supply and demand can be the causes for droughts. As explained above, the ET levels are much higher than the annual precipitation levels while the temperature has increasing trends at certain locations. Abu Hajar (2019) analyzed the annual precipitation for certain locations in Jordan between 1980 and2016 in order to identify the events of major droughts. It was concluded that extreme events of droughts experienced during 1998–1999 year. Furthermore other years signified the occurrence of droughts such 2007–2009, and 2013–2014. Such droughts have diverse effects on the socioeconomic, agricultural, and environmental conditions (Al-Qinna, Hammouri, Obeidat, & Ahmad, 2011). The agricultural sector, which represents a source of income for more than a quarter of the population, continues to grapple with challenges of scarcity and droughts. Therefore, monitoring of drought phenomena is one of the most important factors that could preserve rainfed agriculture.

4.2.3.1. Climate change projections

Climate change reinforces the ominous future of water resources by limiting water availability and constricting groundwater aquifers with outreached recharge rates to date. The combined impact of climate change and population growth (including migration) is expected to deteriorate the already limited land and water resources and confront the challenges of sustainable development in Jordan (Ministry of Foreign Affairs, 2018).

Future projections at various spatial scales within Jordan territory, estimate an increase of the temperature. Based in Table 8, the increase is spanning from +0.9 °C to 5 °C by the end of the century.

Projections	Level of uncertainty[18]	Projected change	Period	Source	Scale
Temperature	Low	+1°C to +4°C	By 2099	(MoEnv, 2013)	National
		+2.5°C to +5°C	By 2099	(F. Abdulla, 2020)	National
		+0.9°C to +3.7°C	By 2099	(F. Abdulla & Al-Shurafat, 2020)	Yarmouk River basin
		+4.5°C	By 2100	(Rajsekhar & Gorelick, 2017)	National
		+2°C to +4°C	By 2100	(Ministry of Foreign Affairs, 2018)	National

Table 8- Temperature projections

Concerning the same period, the precipitation is projected to decrease as well, with the rates spanning from -2.6% to -60% for the Yarmouk river basin and -10% to -37% on the national level (Table 9). As it is argued by the Jordanian authorities (MoEnv, 2013), there is a low uncertainty for temperature projections, while a high uncertainty is noted for projections on precipitation and other extreme events.

The projected increase of temperature and decrease of precipitation have a negative impact on the streamflow and ET (Table 10). As it is projected by Hammouri (2017) and Rajsekhar & Gorelic (2017), the streamflow will decline at 22% on the national level by 2080 while the decline will be between 51% to 75% for the Jordan river basin and 67.3% for the Yarmouk river basin by the end of the century. Additionally, the potential ET is projected to increase at 10.6% in Yarmouk river basin and around 150mm on the national level by 2100.

[18] Based on (MoEnv, 2013)

Projections	Level of uncertainty[19]	Projected change	Period	Source	Scale
Precipitation	High	-10% to -37%	By 2099	(F. Abdulla, 2020)	National
		-2.6% to -60%	By 2099	(F. Abdulla & Al-Shurafat, 2020)	Yarmouk River basin
		-30%	By 2099	(Rajsekhar & Gorelick, 2017)	National
		-15% to -60%	By 2099	(MoEnv, 2013)	Multiple
		-15% to -20%	By 2100	(Ministry of Foreign Affairs, 2018)	National

Table 9- Porjections on precipitation

Projections	Level of uncertainty[19]	Projected change	Period	Source	Scale
Streamflow	/	-51% to -75%	By 2100	(Rajsekhar & Gorelick, 2017)	Jordan River basin
		-22%	By 2080	(Hammouri et al., 2017)	National
		-67.3%	By 2099	(F. Abdulla & Al-Shurafat, 2020)	Yarmouk River basin
ET	/	+10.6%	By 2099	(F. Abdulla & Al-Shurafat, 2020)	Yarmouk River basin
		+150mm	By 2100	(Ministry of Foreign Affairs, 2018)	National
		+150mm	By 2100	(MoEnv, 2014)	National
		+70 to +100mm	By 2050	(MoEnv, 2014)	National

Table 10 – Future projections on streamflow and evapotranspiration

[19] Based on (MoEnv, 2013)

4.2.3.2. Climate change impacts on the water sector

It is projected through climate change scenarios that incorporate decreases in rainfall and increases in temperature, that water resources will furtherly strained(Hoff et al., 2011). Therefore, the major future challenge for the water sector in would be the development of relevant infrastructure to support the increasing water demand. An example, is The Disi groundwater wells which will provide 100 Mm^3/year of water to the capital Amman. Other examples come the the deployment of more WWTP and the exploitation of surface water resources through the operation of more several types of dams. Also, improvements in irrigation efficiency will lead to fewer losses and would save 88 million m^3 for water supply in the year 2022. By summarizing the estimations of demand and supply, the annual water budget is presented for years 2022, 2030 and 2050 (Table 11) (Al-Bakri et al., 2013).

	Without climate change				With climate change		
	2010	**2022**	**2030**	**2050**	**2020**	**2030**	**2050**
Supply without Red-Dead conveyor	1,144	1,360	1,460	1,540	1,292	1,314	1,232
Supply with Red-Dead conveyor	1,144	1,940	2,040	2,120	1,872	1,894	1,812
Water Demand	1,564	1,617	1,675	1,788	1,666	1,802	2,001
Water balance without Red-Dead conveyor	−420	−257	−215	−248	−374	−488	−769
Water balance with Red-Dead conveyor	—	323	365	332	206	92	−189

Table 11 - Annual water supply and deficit (Mm^3) in Jordan with and without climate change, Source:(Al-Bakri et al., 2013)

A study by Hoff (2011) projected the future water demand for the Jordan river basin under different socio-economic and climate change scenarios. More specifically, four different socio-economic demand scenarios assuming no impacts of climate change and one climate change scenario with increased irrigation demand were selected. Based on the results (Fig. 26), similar contributions are noticed to the unmet water demand between the selected scenarios. Additionally, the results indicate the significant contribution of population growth and economic development to the future unmet water demands which seems to have increasing trends by 2050.

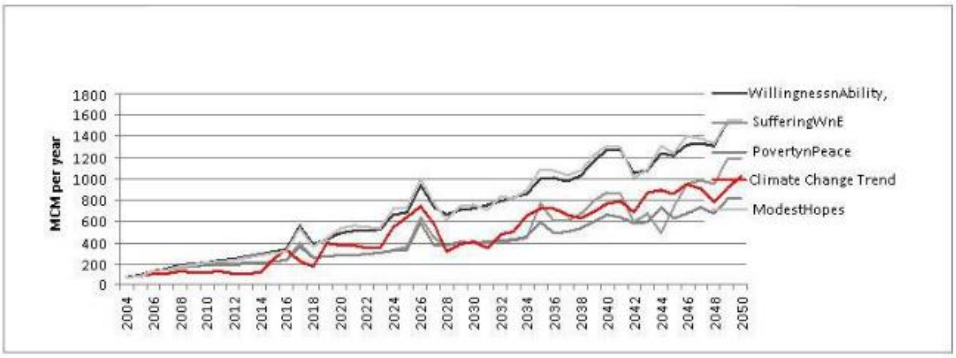


Figure 26 - Unmet water demand under socio-economic and climate change scenarios for the Jordan River Basin, Source:(Hoff et al., 2011)

4.2.3.3. Climate change impacts on the energy sector

Climate change effects will affect the supply and demand of the energy sector of Jordan. The past few years several blackouts[20] occurred in many areas of Jordan during very hot and very cold days. Some of these events extended for many hours causing economic implications, and in some cases dangerous conditions in the daily life of the population. Based on the National Electrical Power Company (NEPCO) these blackouts occurred due to the extremely sudden load increases on the demand and were exceeding the generation capacity (Almuhtady et al., 2019).

4.2.3.4. Climate change impacts on the food sector

A study performed by Al-Bakri (2013) showed that the increase of temperature by 2°C would increase the irrigation needs for certain crops by 23%, while the combined impacts of increased air temperature and land-use change would reduce the total production of most irrigated crops significantly. Key findings from this study were the variability in ET and productivity among the cultivated crops (Table 12). Such variability would depict possible shifts in cropping patterns to adjust with the problem of water shortage in the country. Considering the ratio between productivity and ET, which is defined as the water use efficiency (WUE), farmers is possible to abandon the cultivation of crops like wheat and olives, for which the WUE is very low. Without efficient irrigation systems, the average decrease in WUE would reach 9 and 17% by the years 2030 and 2050.

Crop	Location	Present				Year 2050			
		ETc (mm)	Area (ha)	Production ($\times10^3$ ton)	WUE (kg/ha/mm)	ETc (mm)	Area (ha)	Production ($\times10^3$ ton)	WUE (kg/ha/mm)
Alfalfa	Khirbet As-Samra	1673	609	34.2	33.6	1754	444	24.9	32.0
Alfalfa	Aqaba	1935	479	25.5	27.5	2092	349	18.6	25.5
Apple	Maan	505	1,293	18.3	28.0	561	944	12.1	22.8
Banana	Shooneh Janoobiyeh	1536	826	13.7	10.8	1640	603	10.0	10.1
Citrus	Shooneh Janoobiyeh	731	388	5.3	18.7	781	283	3.8	17.2
Citrus	Deir Alla	834	661	6.7	12.2	929	483	4.9	10.9
Egg Plant	Deir Alla	267	532	17.2	121.1	305	389	11.3	95.2
Olive	Mafraq	562	7,039	11.2	2.8	607	5,138	7.3	2.3
Potato	Deir Alla	205	888	21.4	117.6	253	648	14.1	86.0
Potato	Rum	512	282	8.8	60.9	547	206	5.8	51.5
Squash	Deir Alla	185	580	10.6	98.8	228	424	7.0	72.4
Tomato	Ghour Safi	218	2,441	101.5	190.7	253	1,782	66.7	147.9
Tomato	Deir Alla	254	870	46.9	212.2	299	635	30.8	162.2
Tomato	Mafraq	499	1,850	96.2	104.2	533	1,350	63.2	87.8
Wheat	Irbed	736	5,027	6.2	1.7	832	3,519	3.5	1.2

Table 12- Current and projected change in crop production for major irrigated crops in Jordan, Source: (Al-Bakri et al., 2013)

4.2.4. Economic development

Jordan's has one of the weakest economies in the Middle East with limited natural resources while its energy demand is covered from imports. With a national GDP slightly above 40 billion USD for 2018 and a GDP per capita slightly above 4 thousand USD for the same year, the economy is strained with ongoing regional uncertainty and the impact of adjustment which have suppressed domestic and external demand (World Bank, 2018).

[20] http://www.nepco.com.jo/en/news_page_en.aspx?news_code=1&news_year=2012&news_ser_no=67

Based on the (Ministry of Planning and International Cooperation of Jordan, 2016) the influx of refugees during the period 2011-2016 had a critical impact on the national economy. During this period the national debt increased by 82.8% while foreign direct investment decreased by a rate of 42.6%. Moreover, despite the decrease in global oil prices, the trade deficit continued to increase.

The GDP distribution across the economic sectors for 2018 is shown in Fig. 27. The most dominant economic activities are those within the industrial and services sector. Based on the definition provided by the United Nations[21], the agricultural sector is complemented by economic activities relevant to agriculture, hunting, forestry and fishing. The industrial sector includes the economic activities relevant for mining, manufacturing, construction, wholesale and retail trade as well as restaurants and hotels.

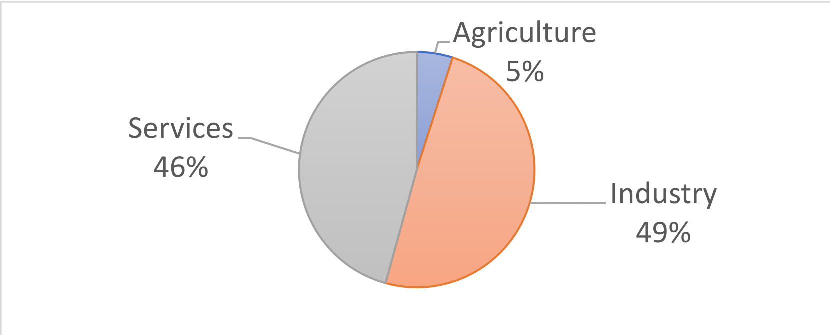


Figure 27- GDP distribution by economic sector for 2018 in Jordan, Source: United Nations data

4.2.4.1. Tourism

Tourism is a key driver of the national economy. Based on the central bank of Jordan[22], tourism's contribution to the national GDP for 2017 was equal to 14% for 2017. The summer period of the year is the most favourable in terms of income. It is worth noting that tourism is a key pillar of the economy with income rising by 14.7% in 2017 and 13.1% in 2018 respectively. However, due to Covid-19 crisis, the contribution tourism to GDP is estimated to be in lower levels for 2020. Based on the information from the Department of Statistics, 2018, tourism is strongly interrelated with economic activities of hotels and restaurants. The number of tourists within the period 1998-2009 was the main driver for variations on the GDP produced by hotels and restaurants (Fig. 28). Additionally the tourism is directly associated with the electricity demand from the commercial & hotels sector, presented by the national authorities (NEPCO, 2018).

[21] https://unstats.un.org/unsd/publication/seriesm/seriesm_4rev3_1e.pdf
[22] https://www.france24.com/ ar/20180118-ارتفاع-الدخل-السياحي-في-الاردن-عام-2017-ليبلغ-46-مليار-دولار

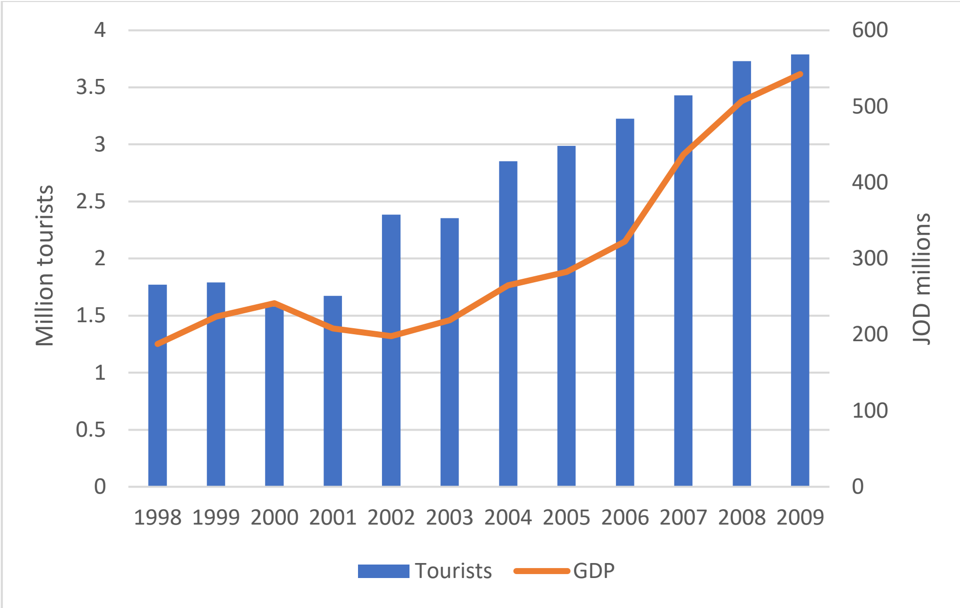


Figure 28- Number of tourists and the GDP produced by hotels and restaurants, Source: Department of Statistics[23], WDI

4.3. Nexus interlinkages

Considering the above sections, a WEA nexus framework is presented in order to answer the research questions and reach the research objectives of the thesis (Fig. 29). The components of this nexus framework are the water, energy and agriculture sectors. Except for the interactions that each sector has with another, implications can also be caused by the external drivers of climate change, population growth and urbanization as well as economic development. The population growth and urbanization create similar pressure to the sectors by the increase of the demand. Whenever the symbol (+) is used signifies the increase of the mentioned phenomenon, the drivers can be determined since they put pressure outside of the operation of the relevant sectors.

[23] https://www.ceicdata.com/en/jordan/gdp-gross-output-by-industry-current-price/gdp-gross-output-hotels-and-restaurants

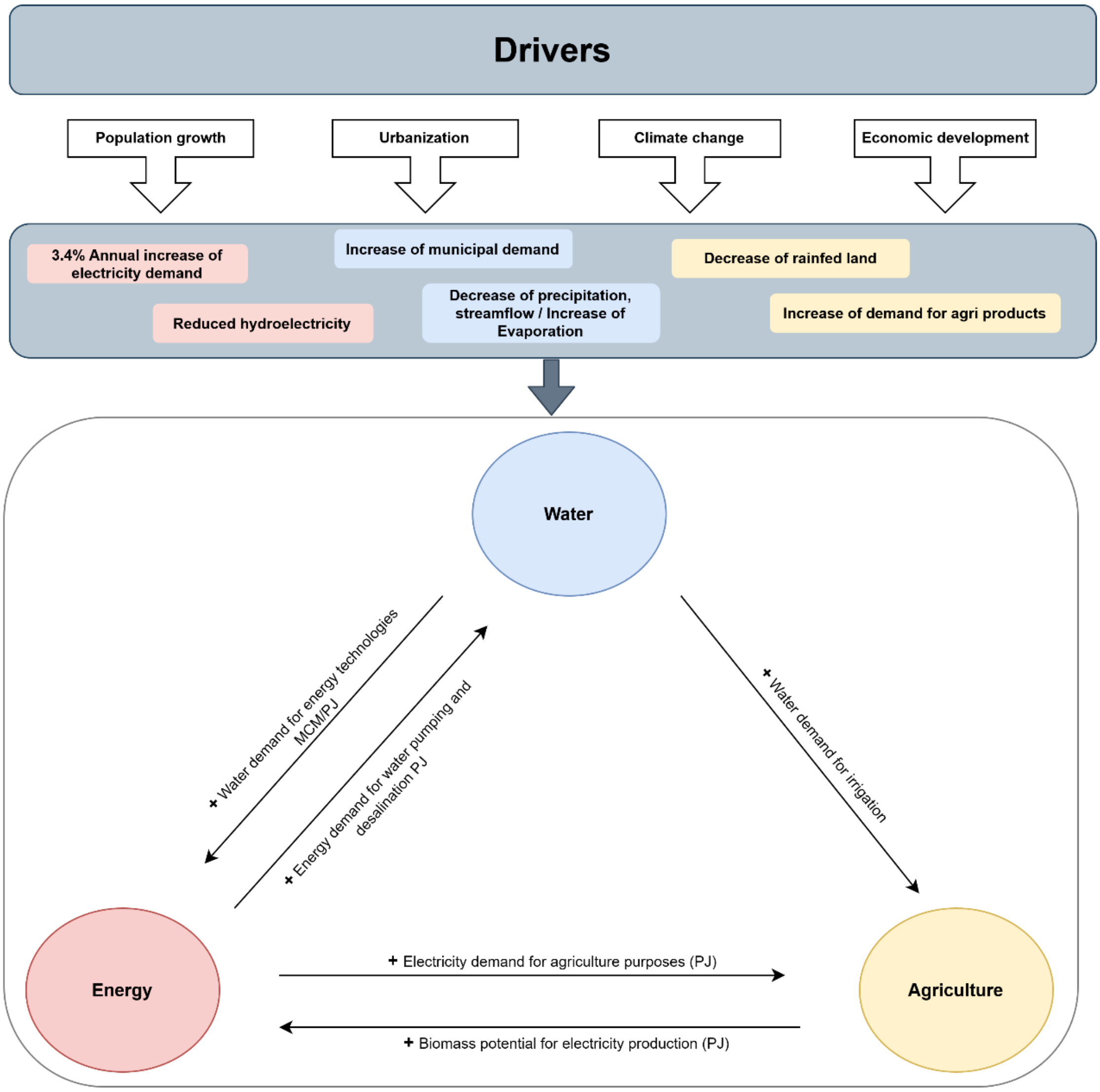


Figure 29- WEA nexus framework for Jordan

4.3.1. Water use for energy production

Electricity generation is met primarily by the operation of gas and steam turbines. Renewables account for approximately 20% of the installed electricity capacity. Solar energy and wind account for 13,3% and 5,35% respectively, while hydro and biomass have lower contributions. Based on (Siddiqi et al., 2013), the cooling technologies that have used for these power plants are based mostly to air and non-fresh water usage and conclude that there is little dependence on freshwater for electricity generation in Jordan.

Based on simple research to verify this claim, the cooling methods for each fossil power plant in Jordan are presented in Table 13. As can be seen, dry-cooling with no water use is the most applied method for the gas turbines. The IPP3 powerplant operates with a diesel engine and can use natural gas, diesel and oil fuels for its combustion. The cooling method for this powerplant is the closed-loop, with lower water withdrawals than once-through cooling systems but higher water consumption of the withdrawn water[13]. Additionally, the Aqaba thermal powerplant is a steam turbine that uses natural gas and heavy oil fuel for its combustion. Considering that is closely located to the Gulf of Aqaba, this power plant uses seawater for its cooling demand.

For the extraction and refining activities, water usage is not at significant levels. Based on the data provided by the Jordanian refining company in 2011, the water consumption for the refining activities were approximately 5% of the industrial sector's withdrawals (Siddiqi et al., 2013).

Despite the past and current indications about insignificant water usage in the energy sector, the water demand in the future has projected to increase. Based on the national plans for the exploitation of oil shale and nuclear, the water demand is expected increase from 15 million m^3 in 2015 to 150 million^3 by 2030, while other estimations project the water demand in the energy sector at 70 million m^3 by 2025 (Komendantova et al., 2017; Mansour et al., 2017; WRG, 2012).

Fossil power plant	**Cooling method / resource use**
Al Qatrana CCGT Power Plant Jordan	Dry cooling[24]
Amman East (AES Jordan) CCGT Power Plant Jordan	Dry cooling[24]
Aqaba Thermal Power Plant Jordan	Seawater[25,26]
IPP3 CEPP Power Plant Jordan	Closed-loop[27,28]
Rehab CCGT Power Plant Jordan	Dry cooling[29]
Risha GT Power Plant Jordan	Dry cooling[30]
Samra CCGT Power Plant Jordan	Dry cooling[31]
Al-Zarqa CCGT Power Plant	Dry cooling[24]

Table 13 - Cooling methods for current fossil power plants in Jordan

4.3.2 Water for hydropower generation

Hydropower generation has contributed with 22.7 GWh for consumption and 12 MW installed capacity in 2018. Based on Jaber (2012) and NEPCO (2018) King Talal Dam is the most critical unit for hydropower while the Aqaba thermal power plant can use the seawater which is used for the cooling process to produce hydro-electricity[32].

Based on (Jaber, 2012), there are several opportunities for the expansion of hydropower generation in Jordan by the operation of small to medium scale hydropower units. More specifically, the estimated power generation could reach 175,710 MWh per year. However, studies find that hydropower plants consume a large amount of water (Mekonnen & Hoekstra, 2012).

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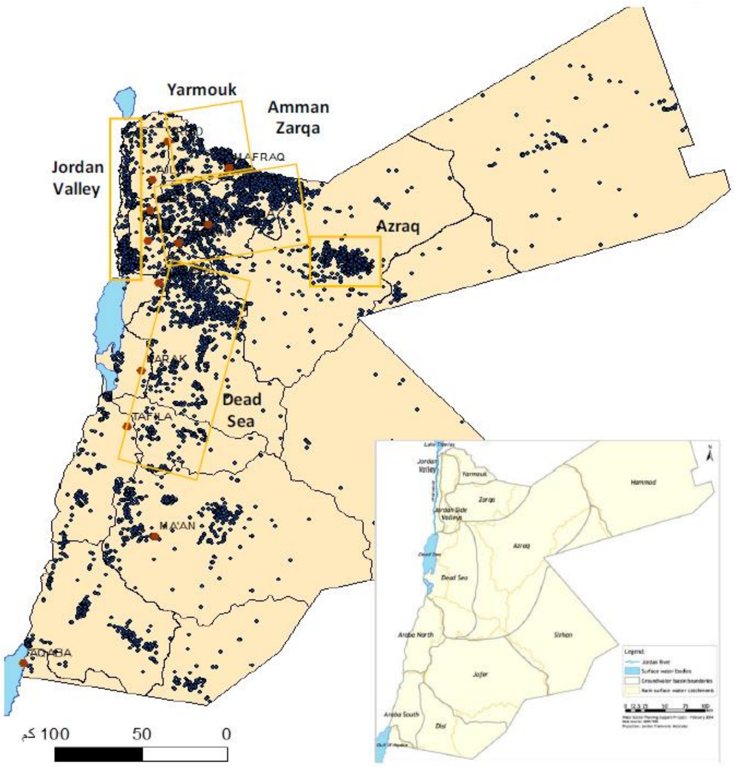
24 From the available data every CCGT power plant uses dry cooling
25 https://www.cegco.com.jo/Aqaba-Thermal-Power-Station
26 https://www.jica.go.jp/english/our_work/evaluation/oda_loan/post/2003/pdf/2-35_full.pdf
27 https://www.wartsila.com/docs/default-source/power-plants-documents/downloads/white-papers/general/wartsila-bwp-combustion-engine-power-plants.pdf
28 https://www.wartsila.com/energy/learn-more/technical-comparisons/combustion-engine-vs-gas-turbine-water-consumption
29 https://www.cegco.com.jo/View_Article.aspx?type=2&ID=784
30 https://www.cegco.com.jo/View_Article.aspx?type=2&ID=783
31 https://www.process-cooling.com/articles/87187-dry-cooling-system-orders-for-indonesia-jordan-and-mexico
32 https://energypedia.info/wiki/Jordan_Energy_Situation

4.3.3. Energy use for water pumping

Based on (NEPCO, 2018), the total electricity consumption for 2017 was 17,503 GWh while the electricity consumption for water pumping was approximately 1,577 GWh or 9% of the total (MWI, 2017). Considering the energy consumption by sector, it is assumed that groundwater pumping is operating not only using electricity but diesel fuel as well (Hammad & Ebaid, 2015).

The energy consumption that has noticed for the groundwater pumping has strongly connected with the operation of wells. Based on (MWI, 2017), 2210 wells were operating in 2017 for agricultural uses, while 1062 wells were operating for other uses. Considering the operating wells in other countries of the MENA region, Jordan has a relatively low number of wells. This can be attributed to the salinity of groundwater as well as the cost of abstracting groundwater. The majority of wells in Jordan are operating in depths of 150 and 450 m (Molle, 2017). Despite the operation of the registered wells that are mentioned above, a respectable number of unregistered illegal wells operates in the country. According to (Molle, 2017) estimation, the number of illegal wells could be around 30% of the total registered wells.

As presented in Map 8, it can be noticed that the density of the wells is higher in the central and northern part of the country. Considering that these areas have the most intense demographic changes that mentioned previously, as well as the most intense agricultural production of vegetables, potatoes and tropical fruits, the location of the wells follows these socio-economic characteristics. As a result, the energy demand for groundwater pumping could be much higher in these areas than in the south Jordan. Provincial distribution of wells is provided by the authorities[33].



Map 8 - Spatial distribution of wells in Jordan, Source:(Molle, 2017)

33 http://www.dos.gov.jo/dos_home_e/main/agriculture/census/tables1/tab4_1.pdf

4.3.4. Energy use for wastewater treatment

The number of WWTP was increased drastically during 2007-2017, adding another nine plants after 2010 on the national level (Fig. 30). At the same time, more wastewater is treated and mobilized to cover the water demands of the country. Concerning the electricity demand for the operation of a wastewater treatment facility will analogically be increased as the production of treated wastewater. Although through the treatment process, there is a possibility for the WWTP to produce electricity and cover their own energy needs[34] without using electricity from the national grid. An example of this process could be considered the As-Samra WWTP, which covers 80% of its electricity needs through hydropower and biogas (Belda González, 2018).

Based on Siddiqi (2013), the energy intensity for wastewater treatment in Jordan is assumed to be around 0.2 to 0.5 kWh/m^3. Based on this assumption, the energy consumption for the production of 163.68 million m^3 would be around 57 GWh for 2017. Consequently, with regard to the energy consumption for groundwater pumping (1577 GWh) the energy consumption for wastewater treatment seems relatively low.

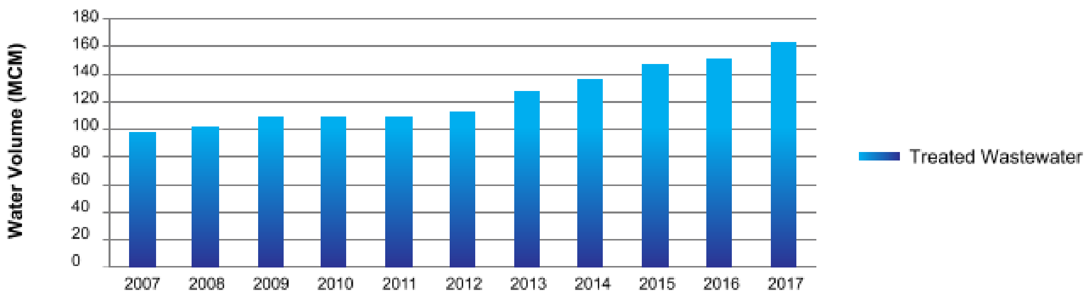


Figure 30 - Growth of treated wastewater, Source:(MWI, 2017)

4.3.5. Energy use for desalination

Based on official data, there are 21 desalination units in Jordan that treat saline or brackish water (MWI, 2018). However, it has noticed that the desalination units account for more than 50, which could be attributed to the fact that several decentralised units are in operation (Qtaishat et al., 2017). Additionally, a desalination plant was launched in 2017, which is located in the Gulf of Aqaba in South Jordan[35] , which is not part of the RSDS project. The unit has a capacity of 15,000 m^3 per day, and integrates a conventional system of microfiltration, ultrafiltration, and reverse osmosis. According to the national authorities, the plant provides a similar amount of water (5 million m^3/year) to the conveyance project transporting water from the Disi Aquifer to Amman (Walschot, Luis, & Liégeois, 2020).

[34] https://www.suez.com/en/our-offering/success-stories/our-references/as-samra-wastewater-and-biosolids-treatment-and-reuse

[35] https://www.jordantimes.com/news/local/%E2%80%98jordan-has-invested-jd40m-desalination-projects-over-past-3-years%E2%80%99

Novosel (2014) has estimated the energy needs for the desalination plants under the RSDSP. According to these estimations, energy needs for desalination will be 16.58 TWh at lowest in 2050, while at highest it will reach 36.36 TWh.

4.3.6. Water use for agricultural production

Based on Fig. 31, the water stress, which results from intensified irrigation of crops, is classified to be at high to too high levels at the 62.9% of the total irrigated crops. At the same time, there is an increased interannual variability for 80.9% of the irrigated crops.

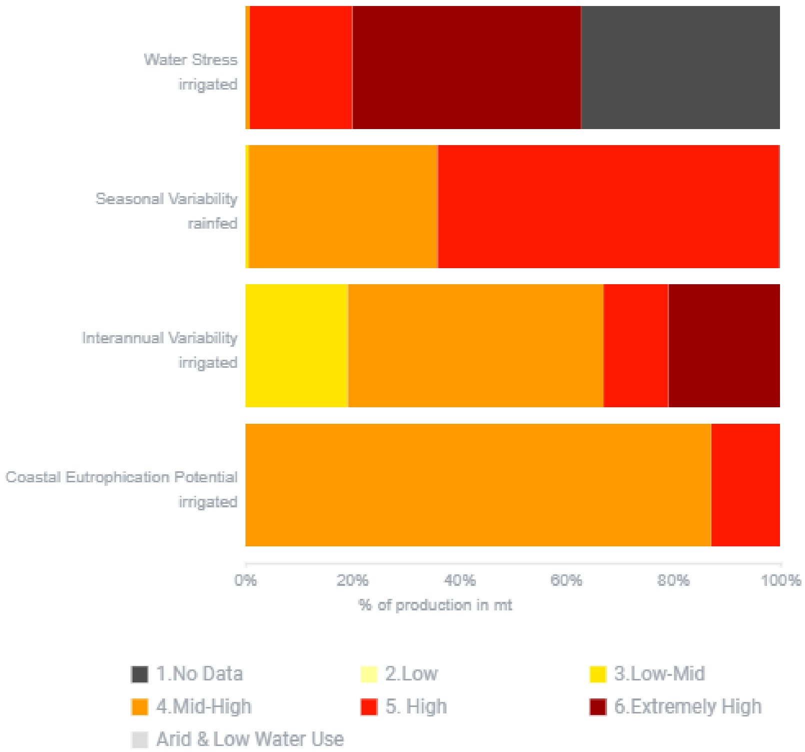


Figure 31 - Association of water risk and irrigation method for crop production, Source: WRI Aqueduct[36]

Considering the groundwater table decline and its relation with the irrigated agriculture can be noticed that around 30% of the irrigated crops pose high risks to the decrease of groundwater levels as presented by Fig. 32.

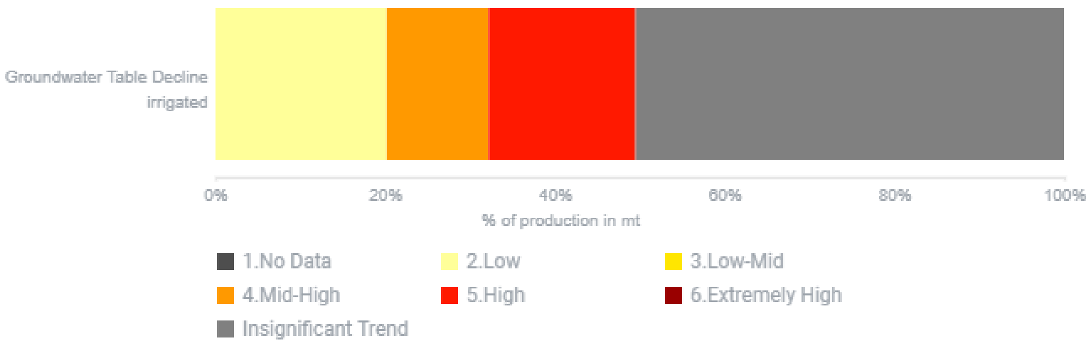


Figure 32 - Water table decline risk and irrigated agriculture, Source: WRI Aqueduct

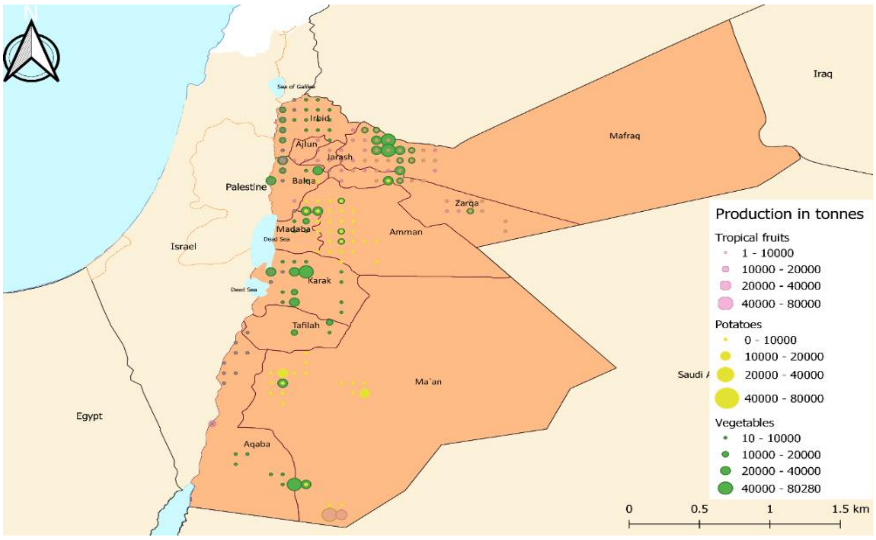
[36]https://www.wri.org/applications/aqueduct/food/#/?basemap=hydro&country=JOR&crop=all&food=none&indicator=none&irrigation=irrigated&lat=30.29&lng=34.02&opacity=1&period=year&period_value=baseline&scope=country&type=absolute&year=baseline&zoom=7

Based on Wood-Sichra (2016)[37,38], the production of vegetables, potatoes and tropical fruits are the most irrigated crops concerning the yields and the tonnes produced (Table 14).

	Total harvested area (ha)	**Total physical area (ha)**	**Production (metric t)**	**Yields (kg/ha)**	**Water footprint m^3/ton [39]**
Vegetables	30035.6	30034.3	1312618.5	7744579.2	43
Potatoes	3243.8	3243.8	135499.5	3468721.9	63
Tropical fruits	7306.2	7306.7	197317	1715166.5	N/A
Rest vegetables	593.9	593.8	2782.2	318634.3	N/A
Wheat	1140.6	1140.6	4080.9	241825.7	207
Chickpea	263.9	263.9	815.8	150557	224
Bananas	1856	1856	45297.5	123582.5	97
Barley	468.7	468.7	871.5	97471.7	79
Lentils	48.1	48.1	38.7	65469.2	489
Other pulses	371	371	355.9	64947.1	N/A
Tobacco	2554	2554	2306.1	7941.9	205

Table 14- Irrigated crop production in Jordan, Source: Wood-Sichra et al., 2016

Concerning Map 9, it can be noticed that the most cultivated crops are produced on the North-West side of the country, which is closely dependent on the Jordan Valley as well as in the Yarmouk river basin.

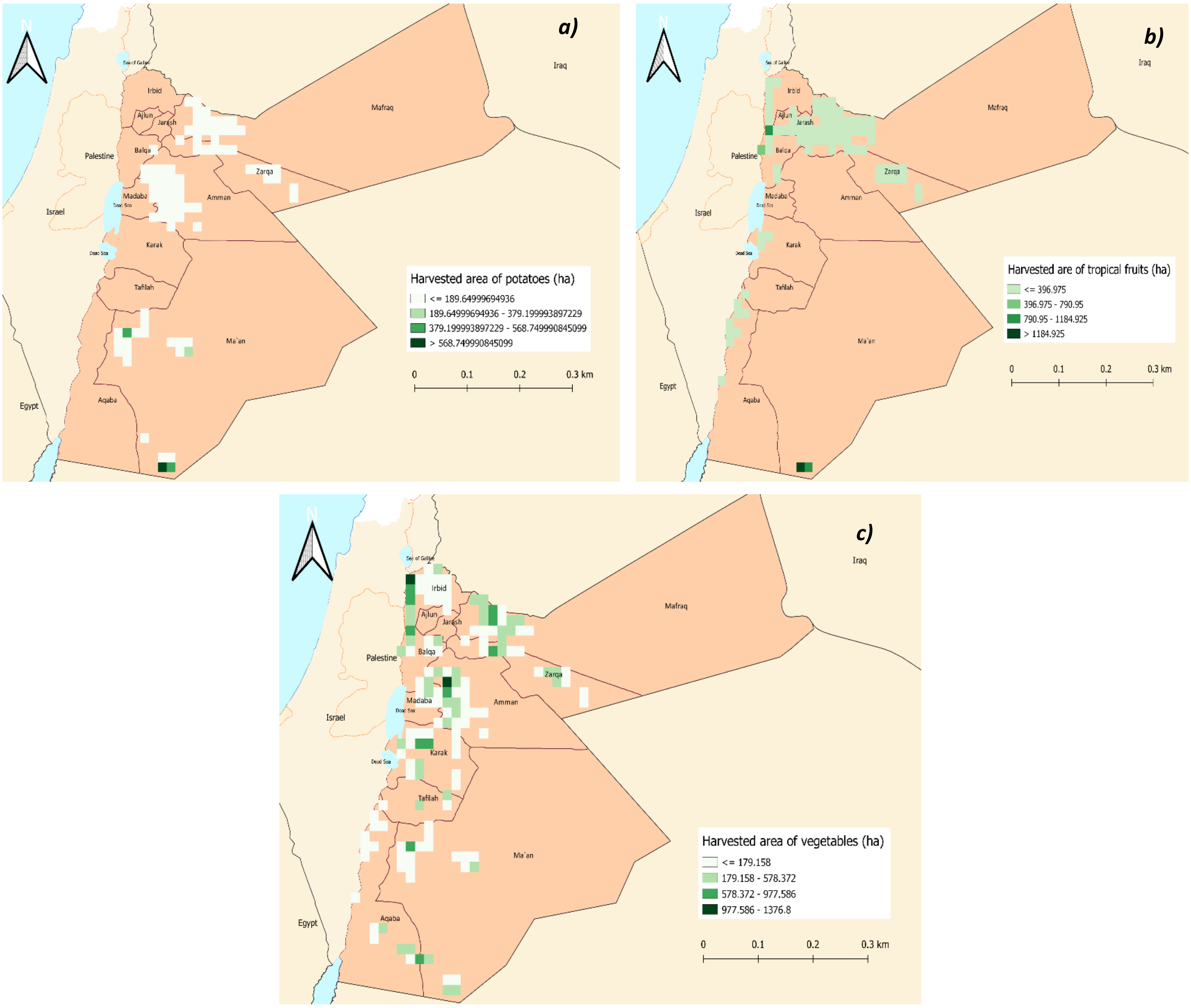


Map 9 - Location of selected crops, own visualization based on Wood-Sichra et al., 2016

As can be seen in Map 10, the harvested area under irrigation that account for the three most-produced foods (vegetables, potatoes, tropical fruits) is located in the central and northern regions of Jordan. Irrigated areas that cultivate potatoes located primarily in the central part of Jordan and have less than 190 hectares in their majority. In the irrigated areas in the southern part is noticed an increased harvested area under irrigation control which can be

[37] https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/PRFF8V
[38] https://www.mapspam.info/
[39] Based on (Mekonnen & Hoekstra, 2011)

associated with the increased production. Regarding the geospatial distribution of the harvested areas under irrigation for tropical fruits, there are considerable quantities of areas along the Jordan river as well as the surface basin of Jordan and Azraq and groundwater basins of Zarqa and Jordan valley. The harvested areas under irrigation for the cultivation of vegetables spanning from south to north locations while along the Jordan river is noticed the most populous cultivated areas. Moreover, there is harvested areas are located in the Yarmouk river basin as well as in places with tropical fruits and potatoes.



Map 10 - Harvested area under irrigation control of a) Potatoes, b) Tropical fruits, c) Vegetables in 2010.
Source: Wood-Sichra et al., 2016

The intensified production of vegetables, tropical fruits and potatoes could be inextricably linked with the water deficit in the relevant groundwater basins. As were noticed previously, the groundwater basins where these crops are cultivated present a historical deficit.

One more factor that frames the level of the interdependence between the water and food sector is the irrigation system. Irrigation systems could be related to three major types. Surface or flood irrigation, which is the most inefficient method. Sprinkler irrigation which is more efficient than flood and drip irrigation which is the most efficient method in relation to the other two. According to the documentation from the national authorities, drip irrigation covers approximately 93% of all vegetable crops, while flood irrigation around covers 5% and the rest is covered by the sprinkler on the national level for 2017. Vegetable production is strongly dependent on irrigation systems, since only 2% is rainfed[40]. In contrast, the field crops are highly dependent on rainfall since only around 10% receives water from irrigation systems. More specifically, 27% is using sprinkler irrigation, 23% drip irrigation, while about 50% used flood irrigation[41].

4.3.7. Electricity use for agricultural production

Concerning the electricity needs for water in 2017 based on (MWI, 2017) but also the electricity needs per demand sector for 2017 based on (NEPCO, 2018), it can be estimated that agriculture has a share of around 6% of the total electricity consumption. Despite the relatively low electricity share, if we consider the external drivers pressure on agriculture but also the projection of (NEPCO, 2018) for an increase in electricity generation, this amount will grow in the future.

4.3.8. Contribution of agriculture to the power system

As expressed in chapter 4.1.3.1, biomass contribution to the electricity mix is at significantly low levels (NEPCO, 2018, 2019). Concerning the electricity potentials that were estimated by Al-Hamamre (2017), biomass could be an alternative to fossil fuel power generation technologies. Moreover, it is interesting to estimate whether the maximum potential from agriculture biomass could cover the electricity demand of the entire agricultural sector, preserving its autonomy.

[40] http://www.dos.gov.jo/dos_home_e/main/agriculture/census/tables1/tab6_1.pdf

[41] http://www.dos.gov.jo/dos_home_e/main/agriculture/census/tables1/tab6_4.pdf

5. Development of the Model

This chapter describes the elements of the model used to generate the mid-term projections. As mentioned before, OSeMOSYS is a linear cost optimization problem and consists of sets, parameters, variables, constraints and objective function. The sets are the inputs that remain constant across all scenarios. The parameters are those inputs that differ between the scenarios. The variables formulated by mathematical equations combining the necessary sets and parameters. The result of a variable could be determined as the output of the model. The constraints are inputs that limit the upper or lower value of a specific variable. In this chapter, the sets, the parameters and the constraints of the model have reported. The OSeMOSYS script thas contains the details for each function is presented in Appendix B.

5.1. Sets

The modelling period starts in 2020 and ends in 2050. The model consists of particular technologies, fuels and emissions that are described in more detail in the next chapters. Each year consists of three seasons: Winter, Summer and Intermediate. The day type is assumed to be one without classifications on weekdays and weekends. For this reason, the number of days that form the day type is seven. The days are split into two categories: Mornings and Nights. This way, it is easier to capture the real-life performance of solar technologies. By the combination of the above six timeslices have formed, naming: Intermediate Days, Intermediate Nights, Summer Days, Summer Nights, Winter Days and Winter Nights.

5.2. Parameters

A brief description of the modelling framework has presented in Fig. 33 through the Reference Energy System (RES). Its purpose is to demonstrate the interconnectedness of the system and its elements. The lines represent the parameters that have modelled as fuels while the boxes represent parameters that have modelled as technologies. Each technology has an input fuel and an output fuel. The first technologies represent extraction/imports technologies. They use the raw material to produce a combustible fuel. Electricity generation technologies use combustible fuel to produce electricity. In the case of renewables, no input fuel is required to produce electricity. After its production, electricity is directed from the power plants to the transmission lines, to the distribution grid, and then to the final demand sectors. It is important to model both the transmission and distribution grid in order to capture the relevant losses. In 2019, the losses in Jordan were 2.18% for transmission and 12.35% for distribution, respectively (NEPCO, 2019). Due to data scarcity, only two technologies were modelled to bypass the transmission links. The small-scale hydro units are connected to the distribution grid, and the PV in rooftops are connected directly to the domestic sector.

As can be seen through Fig. 33, the water resources were modelled as an extraction technology which is an approach that Sridharan (2020) also applied. This is done since the units in OSeMOSYS are defined manually by the user. The water resources reflect how much water is needed (million m^3) to flow into the hydroelectric turbine and produce electricity (PJ).

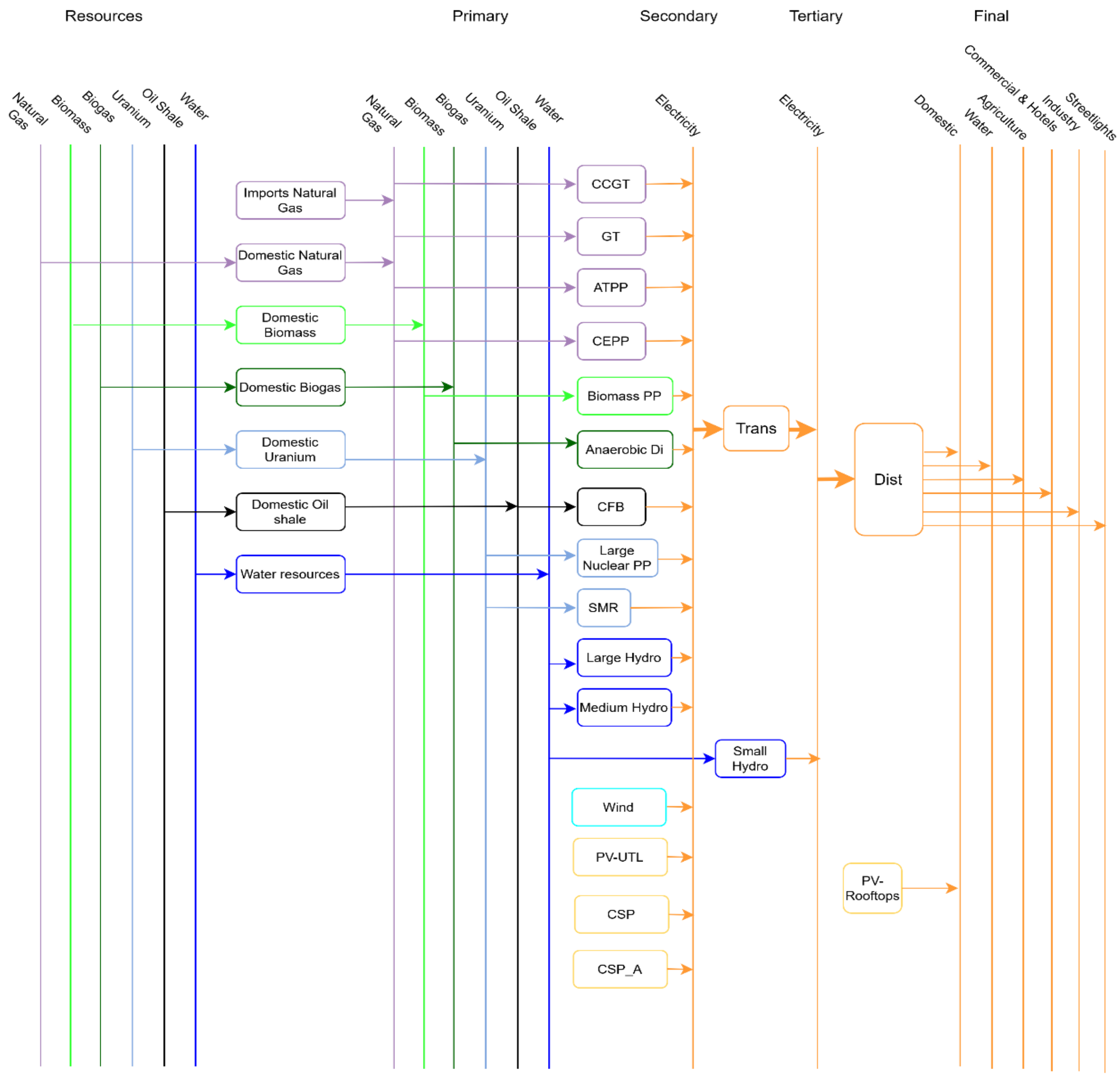


Figure 33- Reference Energy System (RES)

5.2.1. Technologies

Table 15 presents the energy technologies until 2020. Natural gas combustion technologies dominate the fossil fuel generation with Combined Cycle Gas Turbine (CCGT) and the Combustion Engine power plant (CEPP) that could generate electricity from three different fuels. The Aqaba Thermal power plant, due to the advancements made, can generate electricity from both natural gas and fuel oil. Considering the planned commissioning of fossil-based power plants, in 2020 it is scheduled to start operating a power plant for oil shale combustion. The power plant uses a circulating fluidized bed (CFB) technology for the combustion.

Combustion Technology	Capacity (MW)	Power Plant name	Capacity (MW) by PP	Source
CCGT	2796	Al Qatrana (IPP2)	373	(Al Qatrana IPP — Xenel, n.d.)
		Amman East (AES Jordan) (IPP1)	400	(AES Jordan PSC (IPP1), n.d.)
		Rehab CCGT	297	(CEGCO Rehab, n.d.)
		Zarqa	485	(General Electric, 2019)
		Samra CCGT	1241	(SEPCO TPI, n.d.)
GT	210	Rehab GT	60	(CEGCO Rehab, n.d.)
		Risha	150	(General Electric, n.d.)
CEPP	814	IPP3	573	(Wartsila IPP3, n.d.)
		IPP4	241	(Wartsila IPP4, n.d.)
Steam Turbine	650	Aqaba Power Plant	650	(CEGCO ATPP, n.d.)
Circulating Fluidized-bed (CFB)	470	Attarat Power Company Oil shale Power Plant	/	(Enefit, n.d.)
PV-Utility	925.5	/	/	(EIS-MEMR, 2020)
Wind Turbines	369.6	/	/	(EIS-MEMR, 2020)
Hydro	16.5	King Talal dam	6	(NEPCO, 2018)
		Aqaba Power Plant	6	(CEGCO ATPP, n.d.)
		As-Samra WWTP	3.5	(Suez, 2017)
Anaerobic digestion	9.5	As-Samra WWTP	/	(Suez, 2017)
Biomass	6	Al-Ghabawi Landfill	/	(Al-Hamamre et al., 2017)
	4	Rusaifeh Landfill	/	(Zafar, 2020)

Table 15-Energy technologies until 2020

Additionally, new nuclear power plants are in the plans of the national policy-makers[42,43]. According to these plans, two nuclear technologies is possible to be deployed depending on the size of the power plant. The first one is about the commissioning of a large nuclear reactor while the second is about the commissioning of small modular reactors (SMR).

Concerning the renewable technologies, wind, PV utility-scale (PV-UTL) and hydropower in medium-scale are operating in the country, as well as an insignificant amount of biomass and biogas. The model has expanded the solar technologies, such as PV in rooftops, CSP without storage and CSP with eight-hour storage. Regarding hydropower, two new technologies introduced and are about the capacity scale of each power plant. The summary for the plans until 2030 presented in Table 16.

[42] http://www.jaec.gov.jo/Pages/viewpage?pageID=33
[43] https://www.world-nuclear.org/information-library/country-profiles/countries-g-n/jordan.aspx#ECSArticleLink1

Combustion Technology	Capacity (MW)	Commissioning	Source
Nuclear- Large reactor	1000	2028	(Sinamees, 2019)
Nuclear-SMR	300	2029	
		2030	
PV-rooftops	/	/	/
CSP	/	/	/
PV-UTL	200	2020	(NEPCO, 2018, 2019)
	250	2021	
	100	2024	
Wind	418	2020	
	50	2021	
Hydropower-Medium	33	2021	(ESIA, 2017)
Hydropower small scale	/	/	(Jaber, 2012)
Hydropower Large scale	200	2024	(GIZ[44];Hydropower & Dams International, 2020)

Table 16- Planned capacities until 2030

5.2.2. Fuels

Based on (NEPCO, 2019) the fuels used in the energy sector in 2019 were fuel oil with 0.45% share, diesel with approximately 0.05% share, and natural gas with about 99.5% share of the total fuel mix. As for 2018, fuel oil was used with a share of about 3.4%, diesel with a share of 0.12% and natural gas with a share of approximately 96.5%. The fuel oil was used as secondary fuel in the fossil power plants and for this reason it is not modelled. It was assumed that the shares of oil products were covered by natural gas. The national strategy for the power sector is to reduce the use of oil products from 3% in 2020 to 1% in 2030 (MEMR, 2020).

Fuel	Cost (M$/PJ)	Sources/Notes
Natural gas imports	2.306	World bank both initial costs and trend[45]
Natural gas Domestic	3.778 in 2020 5.333 thereafter	The values are taken from the Risha landfill, which also produces biogas. The 2020[46] value is decreased due to corona. The other value is from 2019[47] and it used for the rest years.
Biomass/biogas		
Oil shale	2.722	Oil shale[48]
Uranium	0.5	Uranium[48]

Table 17- Fuel costs per energy technology

[44] https://www.hydropower-dams.com/news/studies-sought-for-pumped-storage-project-in-jordan/
[45] http://pubdocs.worldbank.org/en/633541587395091108/CMO-April-2020-Forecasts.pdf
[46] https://www.memr.gov.jo/ebv4.0/root_storage/en/eb_list_page/retail_prices_of_petroleum_products_for_2020.pdf
[47] https://www.memr.gov.jo/ebv4.0/root_storage/en/eb_list_page/year_2019.pdf
[48] https://www.entsos-tyndp2020-scenarios.eu/fuel-commodities-and-carbon-prices/

Considering the modelled fuels, these were split into two categories: imported vs. domestic. Regarding the fuel imports, only natural gas has included considering its dominant contribution in previous years. The domestic fuels include the uranium, oil shale and biomass for the combustion of the MSW, crop residues and biogas concerning the anaerobic digester (Table 17).

The latest energy strategy published by the MEMR (MEMR, 2020) sets targets to increase the share of electricity generation from domestic resources to 48% in 2030. Additionally, natural gas was planned to contribute to not more than 53% in 2030. Oil shale was intended to contribute at a minimum with 15% to the total electricity mix.

5.2.3. Costs

The cost parameters were incorporated into the model for each energy technology. Three related costs have included namely capital costs, variable costs[49] and fixed costs[50] (Table 18).

Energy technology	Capital cost M$/GW	Fixed cost M$/GW	Variable cost (M$/PJ)	Sources
GT	768	14.592	1.139	(Timilsina, 2020)
CCGT	1028	17.476	1.028	(Timilsina, 2020)
CEPP	1552	24.1	2.111	(Graham et al., 2020)
Steam Turbine	2500	32.175	1.167	(Timilsina & Deluque Curiel, 2020)
CFB	3250	48.75	0.5	(Lako, 2010b)
Nuclear-Large reactor	6765	128.5	1.3	(Timilsina, 2020)
Nuclear-SMR	16304	200	5.5	(Graham et al., 2020)
HYDRO_LARGE	4000	64	0.386	(IEA, 2010)
HYDRO_MED	4500	72	0.386	
HYDRO_SMALL	5000	80	0.386	
PV_UTL	1706	18.7	0.028	(Timilsina, 2020)
CSP	3704	66.672	0.004	(IRENA, 2020)
CSP_A	6670	120.06	1.5	(Graham et al., 2020)
PV_ROF	2200	18.8	0.042	
WIND	1761	45.773	0.1	(Timilsina, 2020)
Anaerobic digester	2140	98.37	1.74	(IRENA, 2020)
Biomass	4115.5	148	1.53	(Timilsina, 2020)

Table 18- Relevant costs per energy technology

For capital, or investment, costs, the starting value of an energy technology was obtained from the relevant literature while the mid-term trends obtained from Graham (2020). The capital costs for GT, CCGT, large nuclear reactor, PV-UTL wind power and biomass were obtained from mean values presented in Timilsina (2020) considering different sources. According to Graham (2020), natural gas combustion technologies are mature, and their future prices will not differ significantly by 2050. Considering the CEPP's both capital and price forecast, information obtained from Graham (2020) for gas reciprocating turbines (Azzam et al., 2014). The price for the power plant, which will combust oil shale through CFB, obtained from Lako (2010b) and assumed that the technology is mature and the price will not decrease considerably by 2050. The selected price for nuclear was the mean values from those reported

[49] The cost with variations during the operation of the power plants such as fuel costs
[50] The costs that remain constant after the comissioning and during the operation of the power plant.

in Timilsina (2020) while for the SMR, the price obtained from Graham (2020). The trend of the cost for both of nuclear technologies obtained from Graham (2020).

Regarding hydropower technologies, prices have obtained from IEA (2010) and the technologies considered as mature. Regarding the rest of the renewables, the price forecast was obtained from Graham (2020). The capital cost for the steam turbine of Aqaba Power Plant was obtained from (Timilsina & Deluque Curiel, 2020), and its price forecast assumed to follow similar trends for natural gas and coal technologies that have reported in Graham (2020).

5.2.4. Performance indicators

The efficiency is essential to estimate the fuel needs of each power plant to produce a unit of electricity. The efficiency of each PP is divided by one in order to get this value. For example, since CFB technology has a 30% efficiency, the power plant needs 3.333 units of fuel in order to produce one unit of electricity. Regarding hydropower, it is estimated that 260 litres of water could generate 1000KWh of electricity (Al-Bahlawan, 2018). For renewables, no fuel input is needed. Performance indicators presented in Table 19.

Technology	Efficiency (%)	Operational life	Capacity factor (%)	Sources
GT	32.27	30	52.5	(CECGO, 2019; ETSAP, 2010; Graham et al., 2020; Timilsina, 2020)
CCGT	44.525	30	72.5	(Burrow, 2016; Cecgo[51]; ETSAP, 2010;Graham et al., 2020; Timilsina, 2020)
CEPP	47.9	30	60	(Haga, 2011;Wartsila[52])
ATPP	33.18	30		(CECGO, 2019)
CFB	30	40	75	Eesti Energia[53];Aarna, 2013;Lako, 2010b
Nuclear-Large reactor	30	45	90	(Graham et al., 2020; Timilsina, 2020)
Nuclear-SMR	30	30	90	
HYDRO_LARGE	/	50	57	(IEA, 2010; Timilsina & Deluque Curiel, 2020)
HYDRO_MED			47.3	(IEA, 2010;own calculations[54])
HYDRO_SMALL			50	(IEA, 2010)
PV_UTL	/	20	25	(Timilsina, 2020)
CSP		25	50	(Timilsina, 2020)
CSP_A		25	50	(Timilsina, 2020)
PV_ROF		20	15	(Singh & Banerjee, 2015; Timilsina, 2020)
WIND		20	24.464	(Ammari et al., 2015; Timilsina, 2020)
Anaerobic digester	35	20	80	(Fusi, Bacenetti et al., 2016; Kuo & Dow, 2017;Lako, 2010)
Biomass	23	25	75	(Graham et al., 2020)

Table 19- Performance indicators per energy technology

Capacity factor captures the available capacity of each power plant under a certain period of time. For example, the solar technologies have a capacity factor of 0% during the night since

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51 https://www.cegco.com.jo/Rehab-Gas-Turbine-Power-Station

52 http://cdn.wartsila.com/docs/default-source/Power-Plants-documents/reference-documents/reference-sheets/ref-ipp3-jordan.pdf

53 https://investinestonia.com/auvere-power-plant-handed-over-to-eesti-energia/

54 Own calculations for the estimation of the capacity factor considering the electricity production of the last 13 years. The calculation is:

$$Average\ annual\ capacity\ factor = \frac{electricity\ generation\ (MWh)}{Installed\ capacity\ (MW)*8760\ (hours\ in\ a\ year)}$$

they produce electricity only during the sunlight[55]. Availability factors for the transmission and distribution grid obtained from NEPCO (2018) and estimated to be constant values of 99.89% for all years. The availability factors for are the same for all power plants and assumed to be 97.9% in 2020 and reach 100% in 2023 based on Weinstein estimations (2019).

5.2.5. Electricity demand by sector

Based on NEPCO (2018), there are indications for the distribution of the electricity demand across sectors. That said, the electricity demand was split into five sectors presented in section 4.1.2.1. Agriculture, along with water pumping, forms one demand sector. According to the Ministry of Water and Irrigation (MWI), water pumping accounted for approximately 9% of the total electricity consumption in 2017 (MWI, 2017). Considering that the total electricity consumption for agriculture and water sectors was 15.33% in 2017 (MWI, 2017), agriculture's share was approximately 6.33%. Since no data exist for 2020, these shares were used for 2020 too.

Considering the WEA nexus framework presented in this study, the electricity demand has a historical coupling with external drivers of population growth and urbanization. Based on forecasts by the national authorities, the total electricity demand will grow by 3.4% annually NEPCO (2018). Since there is no information about the distribution of the demand per sector, the shares of the previous years were used. Additionally, some assumptions made regarding the demand of each sector. For the streetlights sector, an annual growth rate of 1% was assumed. For the domestic sector, a yearly increase of 4% was assumed, which is slightly higher than the cumulative forecast, since it is related more to demographic trends. For the industrial sector the annual growth rate was assumed to be 4% considering the industrial expansion in the mining sector. The commercial and hotels, the water pumping and the agricultural sectors were assumed to be in the levels of the national forecast. However, for the water sector, major interventions were captured for the deployment of desalination units under the RSDSP. Based on Novosel (2014), the first desalination unit will require 11.916 PJ for its operation. The possible expansions, which are considered for 2030 and 2050, will require additional 11.916 PJ and 35.784 PJ, respectively.

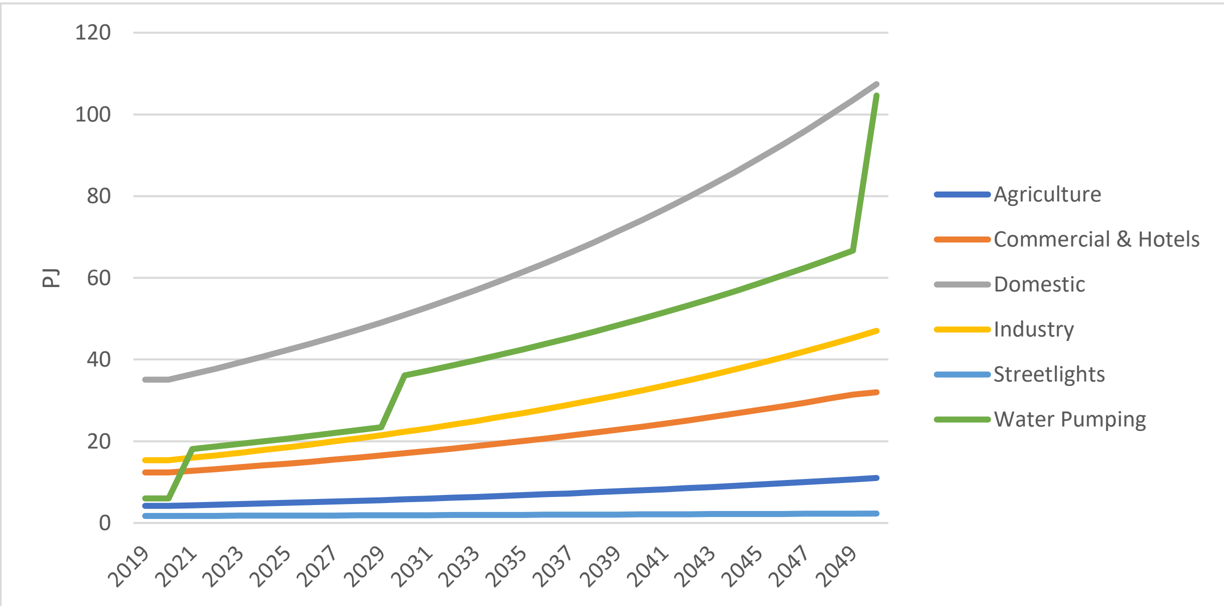

Figure 34- Electricity demand per sector

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[55] Except if there is a storage or battery system integrated

Considering that the MWI has called for tenders in order to construct the unit in 2020[56], it was assumed that the first desalination unit would operate in 2021. As can be seen in Fig. 34, the water sector becomes a significant energy consumer until 2050.

5.2.6. Emission accounting

For fossil power plants, each unit of energy generates a certain amount of CO_2 emissions (Table 20). For the Aqaba Thermal Power Plant (ATPP), a similar amount of emissions was assumed due to the combustion of natural gas but slightly higher since its commissioning was in 1986. Nevertheless, ATPP electricity production is marginalized from the electricity mix while its decommissioning takes place in 2024. The model does not choose technologies such as ATPP after 2024[57]. Lastly, concerning the outputs for the ATPP, its performance does not contribute to frame the insights of the results.

Technology	CO_2 Emissions (Mt/PJ)	Sources
GT	0.0666	(Graham et al., 2020)
CCGT	0.0656	
CEPP	0.067	
ATPP	0.068	Assumed to generate slightly higher CO_2 than CCGT and GT.
CFB	0.135	(Siirde, Eldermann, Rohumaa, & Gusca, 2013)
Biomass	Negligible	(Lako, 2010a)
Anaerobic digestion		

Table 20- CO_2 emissions per energy technology

The model calculates the emissions of each technology using the following equation from Appendix B:

s.t. E1_AnnualEmissionProductionByMode{r in REGION, t in TECHNOLOGY, e in EMISSION, m in MODE_OF_OPERATION, y in YEAR:

*EmissionActivityRatio[r,t,e,m,y] * TotalAnnualTechnologyActivityByMode[r,t,m,y]*

=AnnualTechnologyEmissionByMode[r,t,e,m,y];

Where: In *EmissionActivityRatio[r,t,e,m,y]* the model chooses the emission value presented in Table 20 which is expressed with an “e”, of a specific technology expressed with a “t”, for a specific year expressed with a “y”. The rest sets expresses the region with “r” and the mode of operation expressed with a “m” although they do not contribute to the above calculation since the values for each one is one.

5.2.7. Water accounting

In order to calculate the water quantities needed in power generation, the function of emission accounting was tweaked by changing its units. This means that for each unit of energy produced (PJ) a certain amount of water consumption occurs. That said, water quantities were per unit of energy produced (Table 21) based on information from the

[56] http://www.enicbcmed.eu/call-tenders-construction-desalination-plant-mediss-pilot-site-jordan
[57] The model chose ATPP in years 2021, 2022, 2023 and 2024. The production was 0.85375836 PJ while the annual CO_2 production was 0.058055 Mt/PJ. The max. share of the CO_2 was 0.78%

bibliography. In ATPP, seawater is used for the cooling of the power plant and based on other examples in the Middle East[58] was assumed that once through technology is the most common water cooling technology that exploits seawater for cooling purposes. The value for large hydropower obtained from Mekonnen & Hoekstra (2012) due to its global estimate.

Technology	**Water consumption (million m^3/PJ)**	**Sources**	**Water Technology**
GT	0.053	(Spang et al., 2014)	N/A
CCGT	0.004		Dry cooling
CEPP	0.114	Wartsila[59]	Cooling towers
ATPP	0.305	(Spang et al., 2014)	Once-through
CFB	0.129	(Eesti Energia, 2013; EMD, 2014)	/
Nuclear-Large reactor	0.7167	(Meldrum et al., 2013; Spang et al., 2014)	Mean values
Nuclear-SMR			
HYDRO_LARGE	68	(Mekonnen & Hoekstra, 2012)	Average global
HYDRO_MED	1.25	(Bakken et al., 2013)	/
HYDRO_SMALL	/		It is assumed that no significant water consumption occurs in small hydro schemes
PV_UTL	0.032	(Macknick et al., 2012)	/
CSP	0.435	(Meldrum et al., 2013)	Mean values
CSP_A			
PV_ROF	0.006	(Meldrum et al., 2013)	Flat panels
WIND	/	/	/
Anaerobic digester	0.307	(Spang et al., 2014)	Mean values for biomass
Biomass			

Table 21- Water consumption per energy technology

5.3. Constraints

Various constraints were set in order to capture real-life implications. The constraints have been put to limit, the maximum extraction quantities of domestic fuels, the share of renewables, the lower and upper production of specific energy technologies as well as the Intended Nationally Determined Contributions (INDC) to the Paris Agreement.

First of all, limitations introduced for the extraction technologies. Local information indicated[60] and Weinstein (2019) applied that the domestic production of natural gas from the Risha field would not exceed 16 MMCF/day. Additionally, domestic oil shale production will not exceed 40.000 barrels/day[61]. No limits have placed in domestic uranium production

[58] https://www.utilities-me.com/article-1672-cooling-seawater#:~:text=A%20once%2Dthrough%20seawater%20cooling,turbine)%20back%20to%20the%20sea

[59] https://www.wartsila.com/energy/learn-more/technical-comparisons/combustion-engine-vs-gas-turbine-water-consumption

[60] https://jordantimes.com/news/local/npc-dig-new-wells-risha-gas-field

[61] https://unstats.un.org/oslogroup/meetings/og-11/docs/5al-nugrush.pptx

since nuclear combustion technologies consume an insignificant amount of fuel (Weinstein, 2019).

Constraints were applied to the energy technologies by integrating national policies to the model. The CFB oil shale fired power plant will contribute at minimum 15% to the total electricity mix. From 2030 renewables will contribute at minimum 30% to the total electricity mix and it was assumed to increase at 40% from 2040 and onwards, except the baseline scenario.

Additional constraints were applied concerning electricity production on some energy technologies. PV in rooftops should contribute no more than 1% of the total electricity mix. Small hydropower schemes have a maximum production potential of 200 Gwh/year(Jaber, 2012). Based on Al-Hamamre (2017), MSW, agricultural residues, olive cake and poultry wastes could produce approximately 313 million m^3 of biogas or generate around 3,116 GWh/year. Excluding the MSW, this amount is equal to 1.501,7 GWh/year. This constraint was placed considering only the agricultural potential for electricity generation.

For large scale hydropower, a maximum capacity constraint was used at 800MW (UN-ESCWA, 2017). The same limitation has also used for medium-scale hydropower schemes.

Finally, the model has incorporated across all of the scenarios the INDC[62] which aims to reduce the GHG emissions by 14% until 2030 compared to the baseline scenario presented in HKJ (2014). The limitation placed in the production of CO_2 emissions generated from the power system.

5.4. Scenario development

Three scenarios that were developed in order to capture mid-term insights are presented in Table 22. The BASE scenario does not consider the targets for renewable electricity generation from 2030 and onwards and includes only short-term plans until 2030. The RENEW-BASE scenario integrates the national targets for minimum 30% electricity generation from renewables from 2030 and assumed 40% generation from 2040 and onwards. The WEA scenario sets a constraint for the water consumption of the energy sector and forces the model to use the maximum potential of biomass. Moreover, considering that this limitation will eliminate large hydropower units to operate, a constraint placed for medium scale hydro schemes to operate at their maximum level. The water constraint limits the total water consumption of the power sector to 16 million m^3 per year. This value was the minimum allowed, since lower values prevented the model from solving.

[62]https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Jordan%20First/Jordan%20INDCs%20Final.pdf

Name	Aim	Share of Renewables (inputs)	Water sector constraints (input)	Biomass contribution (input)
BASE	BAU	/	NO	NO
RENEW-BASE	National targets	30% -2030 40%- 2040	NO	NO
WEA	Minimize water consumption/Maximize biomass production	30% -2030 40% - 2040	yes	yes

Table 22- Scenarios developed

6. Results

The context of this study focuses on the analysis of electricity production and water consumption under each scenario. Additional information for the capital costs are presented in Appendix A. Considerable insight is that domestic resource use targets are met without forcing the model to use domestic resources. As presented in Table 23, only the BAU scenario does not meet this target for 2030.

Scenario	Share of domestic resource use (output)	
	2030	2040
BASE	31%	65%
RENEW-BASE	65%	61%
WEA	55%	55%

Table 23- Share of domestic resource use for each scenario

6.1. BASE scenario

Figure 35 presents the results of the baseline scenario (BASE). In this scenario, natural gas combustion technologies such as CEPP, CCGT, GT and the steam turbine of the Aqaba Thermal Power Plant remain the dominant pillars for electricity generation until 2027. In 2028, a large nuclear power plant starts its operation, and small-scale nuclear reactors are deployed in 2028 and 2029. Since their operation, electricity generation from natural gas combustion technologies fluctuates between 2027 and 2034, which is sensible as no constraints are used on these technologies. After 2034, it was noticed that the model does not choose renewable technologies to support electricity generation, but relies mainly on nuclear and natural gas, even though wind and PV in utility-scale are much cheaper. This is associated with the performance indicators that were used on renewables. More specifically, the share of nuclear technologies in 2040 is approximately 38% while for natural gas technologies the share is about 50%. For this scenario there is no use of biomass or CSP. Moreover, the share of renewables is decreasing throughout the period 2020-2050.

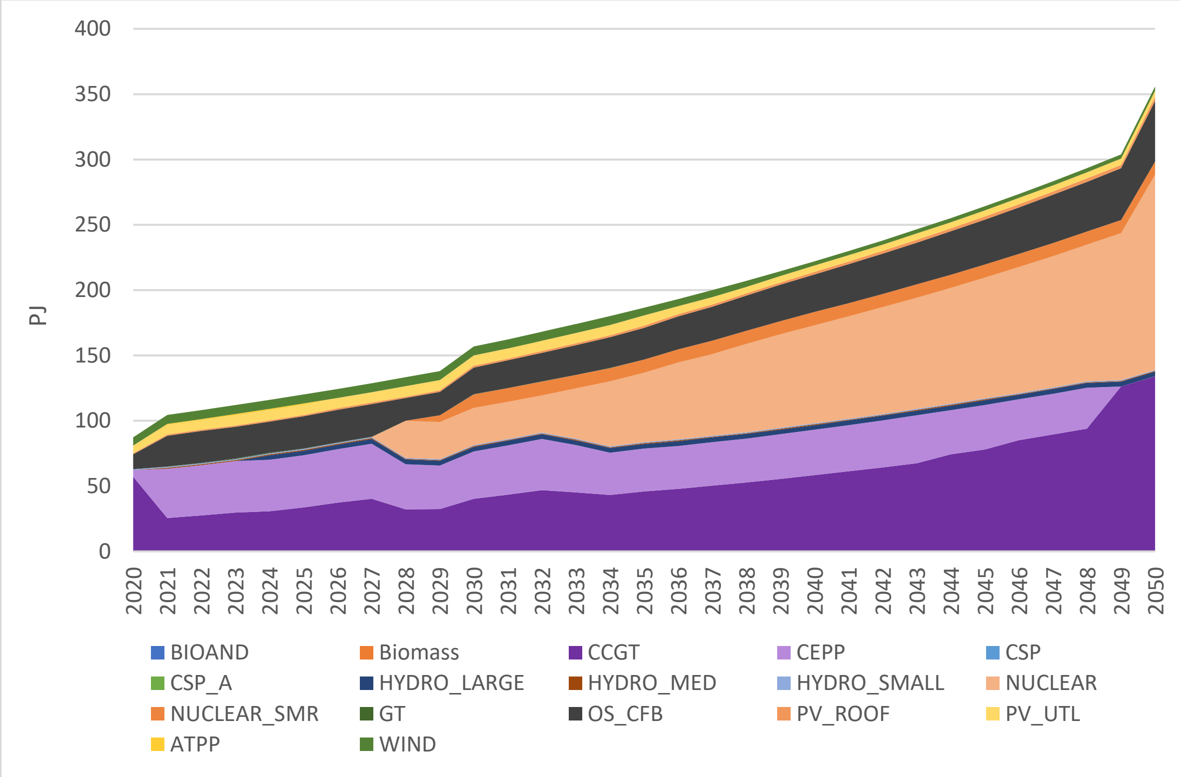

Figure 35- Electricity generation under the BASE scenario

Figure 36 shows the dominant contribution of nuclear technologies to the energy supply creates significant water demands. From the first year of its operation in 2028, the large nuclear power plant is projected to consume approximately 20 million m^3 of water. The deployment of the SMR adds another 7 million m^3 to this amount in 2030. While the water consumption for the SMR remains stable throughout the entire modelling period, the large reactor is projected to consume 53 million m^3 in 2040 and around the double in 2050. The water consumption for large hydropower plants is not included in the below figure because the value is significantly high. The water losses due to the operation of large hydropower is projected to consume approximately 244 million m^3 yearly through evaporation from 2024 until 2050.

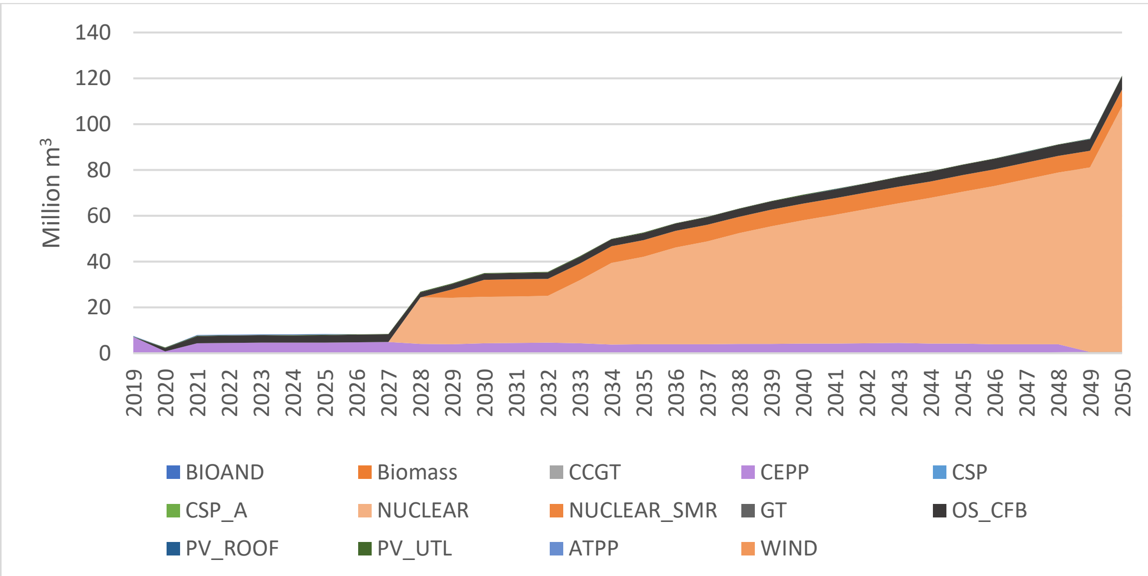

Figure 36- Water consumption per technology according to BASE scenario

6.2. RENEW-BASE scenario

In Fig.37 , the results for electricity generation under the RENEW-BASE scenario are presented. There is a much more diverse electricity mix compared to the BASE scenario. The national policies for the contribution of 30% of renewables force the model to use more technologies to meet the demand. More specifically, hydropower units operate at considerable levels. Large hydropower operates since 2021 when a 200MW hydro unit is deployed, and in 2030 medium-scale hydropower units start their operation. Additionally, wind power in 2030 has produced around 12PJ with a share of approximately 8% while in 2040 the production is around 36 PJ and the share is 16%. For PV-UTL, in 2030 could provide 7 PJ with a 5% share while in 2040 generates around 27PJ with a 12% share. PV in rooftops operates in its maximum, having a stable share of 1% throughout the entire modelling period. The rest solar technologies are not chosen by the model.

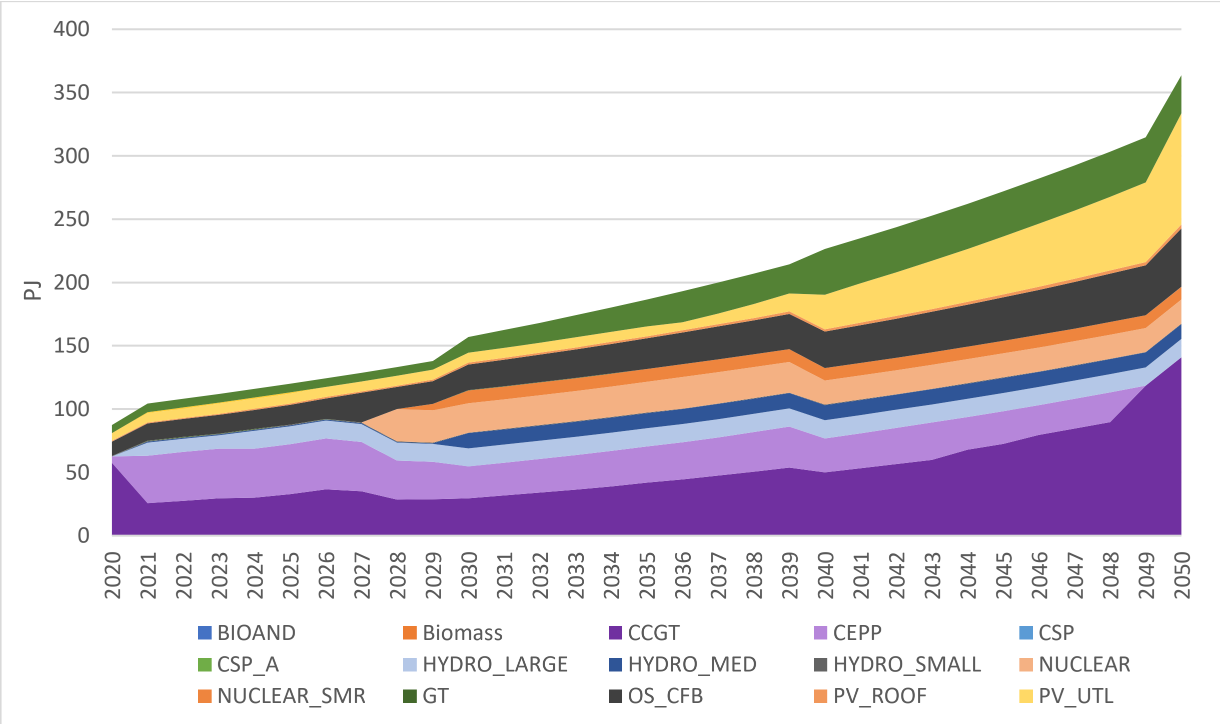

Figure 37- Electricity generation under the RENEW-BASE scenario

The decrease in nuclear power production also depicts in the water consumption for RENEW-BASE scenario. Fig. 38 shows that the total water consumption is much lower than the BASE scenario. This could be attributed mainly to the lower production levels by nuclear power plants. Another indication is the notable increase in water consumption by the PV-UTL scale after 2040. As can be seen from Fig.37, PV-UTL has an increasing trend after 2040, and their share reaches 24% in 2050. Large hydropower plants contribute much more to the electricity mix than in the BASE scenario. However, this leads to higher water consumption through evaporation. These values were not included in the Fig. 41 because its value was too high compared to the rest power plants. More specifically, large hydropower plants under the RENEW-BASE scenario will lead to losses through the evaporation between 700 million m^3 in 2021 to more than 975 million m^3 in 2050. These values represent more than 10% of the evaporation occurred in 2017, which were 7.6 billion m^3 (MWI, 2017).

At the same time, the flow requirements for all of the hydropower units will be between 8 million m^3 in 2020 and more than 19 million m^3 in 2050. In 2017, the King Talal dam had about 115 million m^3 of inflows although and ended the season with 28 million m^3 in storage. However, not all of these quantities allocated to hydroelectricity since the dam is used for multiple purposes. The total inflows for all dams in Jordan in 2017 were more than 219 million m^3.

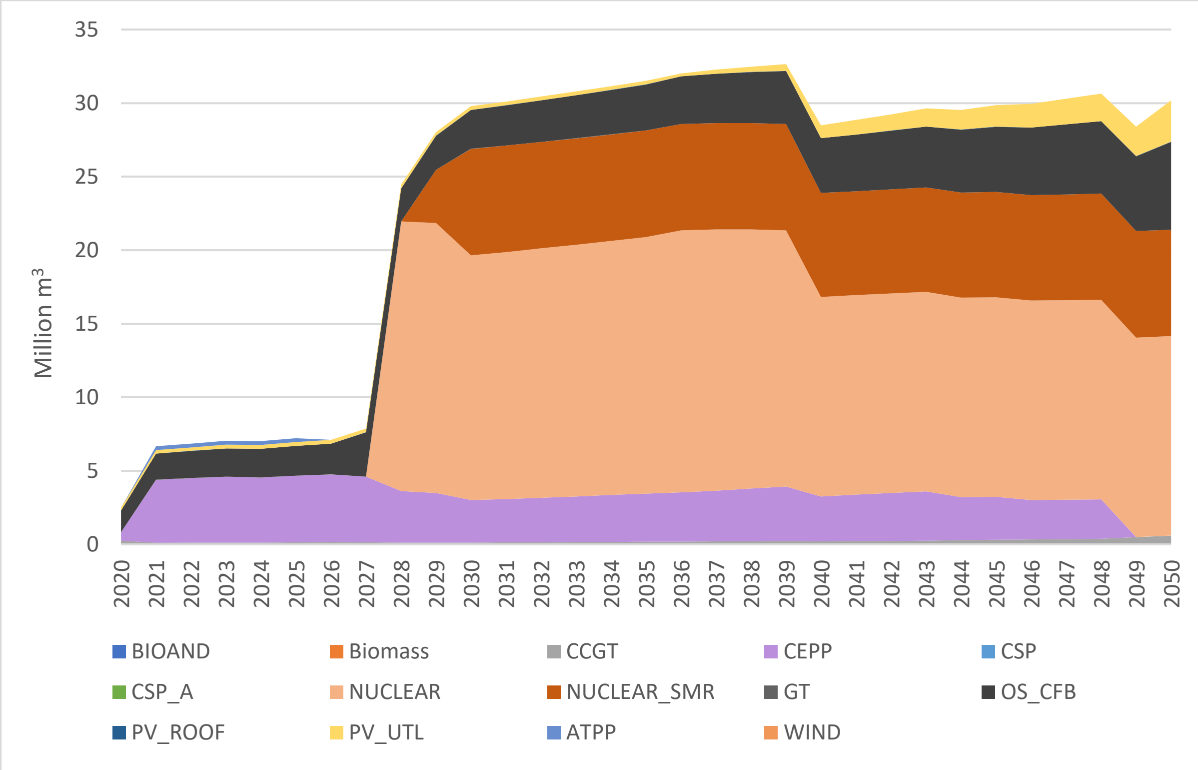

Figure 38- Water consumption under the RENEW-BASE scenario

6.3. WEA scenario

In Fig. 39, the results for the electricity generation under the WEA scenario are presented. It can be seen that CCGT has eliminated the production from CEPP. Additionally, the constraints on water consumption prevent the model from choosing hydropower and nuclear technologies. The electricity generated from these technologies is replaced primarily by wind and CCGT, and secondly by PV and biomass. More specifically in 2030, wind power has a share of around 15.32%, almost double compared to the RENEW-BASE scenario, CCGT has a share of 40% which is 5.5% higher than the total of CEPP and CCGT under the RENEW-BASE scenario. Biomass has a contribution of 3% for the same year while PV-UTL contributes with 5.6%. From 2040 and onwards, when the contribution of renewables should be at least 40%, Wind and PV-UTL scale present a significant contribution to the grid. Another insight of the model is that PV-UTL has surpassed the share of the wind energy after 2048.

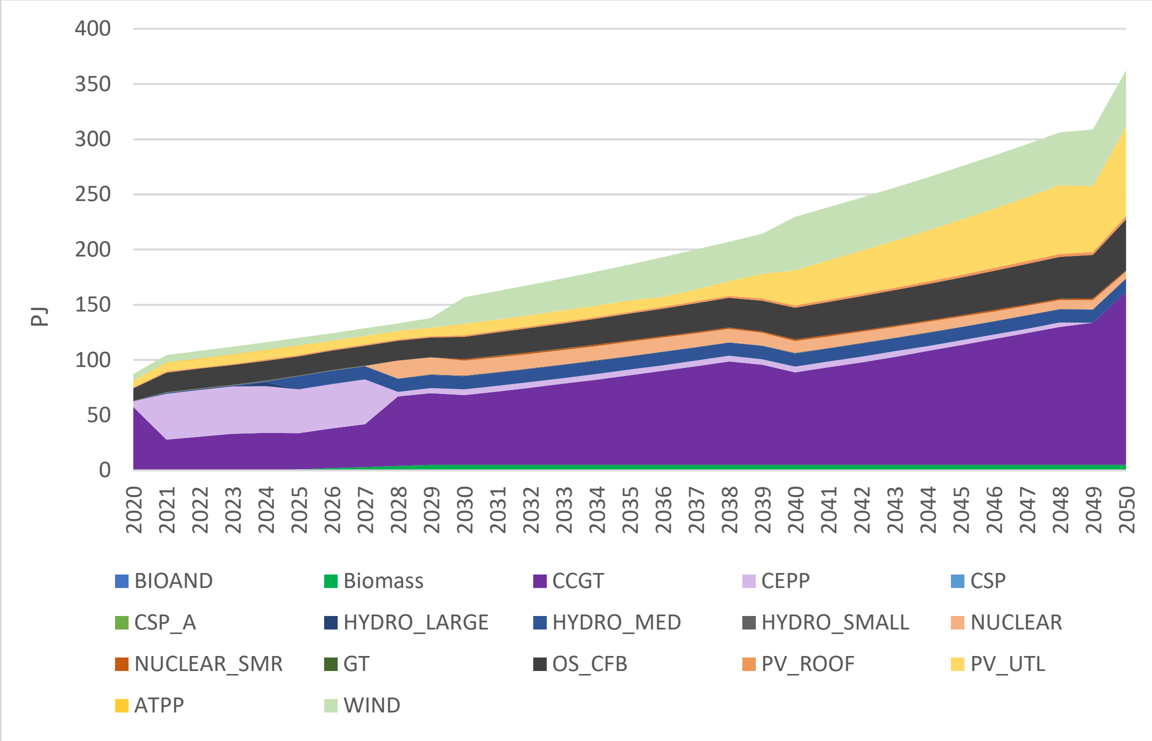

Figure 39- Electricity generation under the WEA scenario

Fig. 40 presents the water consumption for each energy technology under the WEA scenario. It can be seen that the total water consumption has reduced to 16 million m^3 after 2027. Moreover, the water consumption for nuclear technologies is declining from 2028 and onwards as a result of the water constraint. Another indication has to do with biomass water consumption. Even though biomass contributes to the electricity mix between 3% in 2028 and 1% in 2050, its share for water consumption is considerably higher. More specifically, biomass technology contributes to around 9% of the total water consumption for the power sector after 2028, when its maximum activity has deployed.

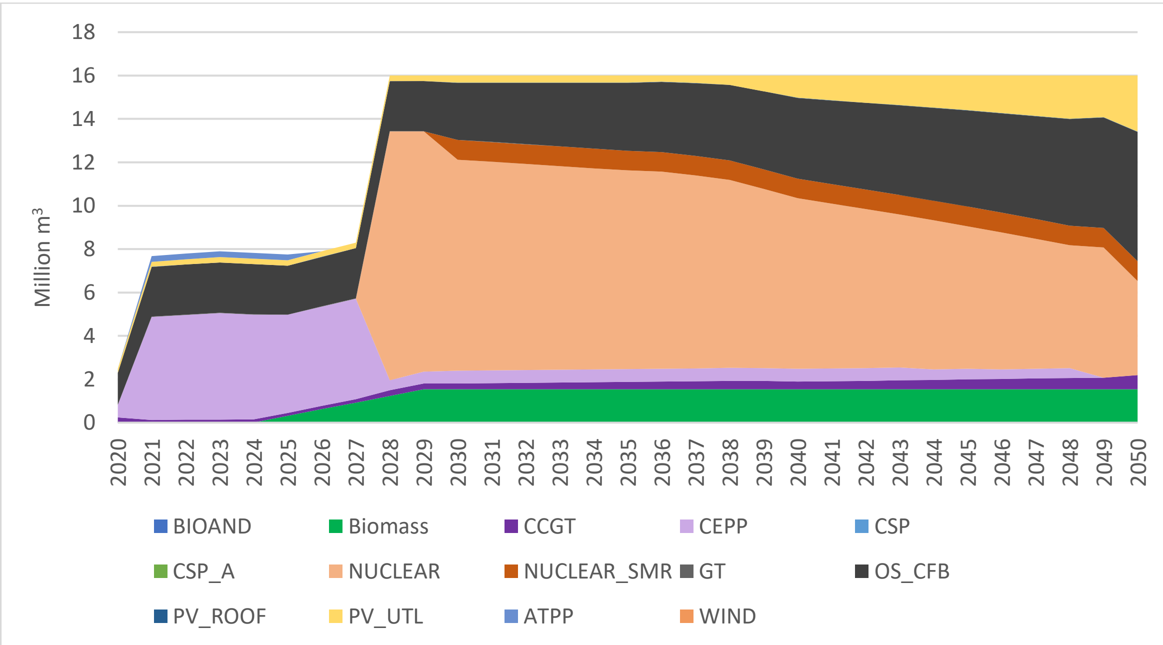

Figure 40- Water consumption for power sector under the WEA scenario

6.4. Comparison of the results

As can be seen in Fig. 41, even if the maximum potential of agricultural biomass exploited to generate electricity, this would not be enough to cover the increasing demand of the entire agricultural sector. More specifically, the maximum electricity that can be produced is about 5.4 PJ, according to Al-Hamamre (2017). The annual growth of the electricity demand in the agricultural sector assumed to be a constant 3.4% which is the mean estimate for the growth of the total electricity generation by NEPCO (2019). Such an increase could be attributed to the technological advancements could be made concerning machinery and farming methods but also the growing demand for agricultural products as a result of population and urbanization growth. It can be noticed that even if a lower annual growth increase was selected, the demand for the agricultural would undoubtedly surpass the maximum electricity supply from agricultural biomass. Concerning the above, a trade-off occurs between the agricultural supply and demand sector.

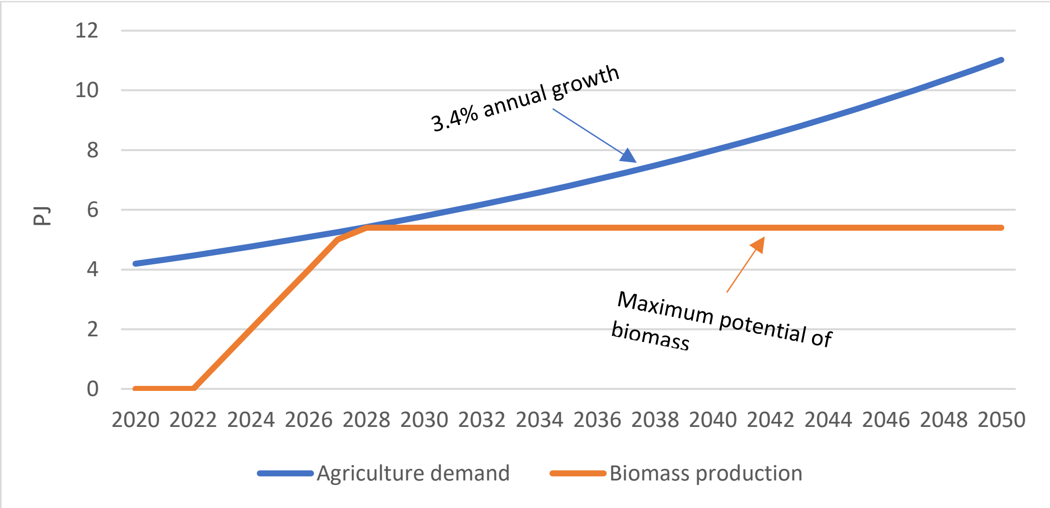

Figure 41- Agriculture demand and biomass electricity production

Fig. 42 presented the energy technologies that are estimated to consume vast quantities of water. Based on the National Water Strategy 2016-2025 issued by the MWI (2016), oil shale will require significantly higher quantities of water than in the scenarios presented in this study. Based on the available information, the power plant of oil shale will integrate air condensers for the cooling of the power plant and for this reason the water consumption will be minimized (Eesti Energia, 2013). On the other hand, water will be required for processes within the extraction and production of oil shale, which was captured by this study.

For nuclear power plants, there are noticed more diverse conditions of water needs. The MWI estimates that the first nuclear power plant will operate in 2024 and will require an additional 22 million m^3 of water for its operation. In this study, the operation of the first nuclear power plant assumed to be in 2028 (MWI, 2016b). The deployment of the nuclear power plant, for BASE and RENEW scenarios, will create an additional water requirement of about 18 million m^3. In 2030, under the BASE scenario, nuclear dominates the power generation since no constraints have been applied for renewables sources; thus, its high water consumption. More specifically, the water demand will exceed 70 million m^3 in 2043 and will climb to more than 120 million m^3 in 2050. When considering the national targets for 30% share of renewables starting from 2030, the nuclear power plant has reduced its water consumption as a result of the reduced energy production. When minimizing the water consumption of the energy sector under the WEAS scenario, the nuclear power plant will require not more than 14 million m^3 of water.

Based on the MWI the total water demand will grow from 1053.6 million m^3 in 2017 to around 1500 million m^3 in 2025. The industrial sector has a historical share of 3% of the total water demand. Considering the above, if the nuclear power plant operates without restrictions in its production levels, has the potential to surpass the share of 3% of the total water demand. Additionally, even if nuclear power plants are restricted but not operate efficiently, this will have a considerable water footprint in Jordan.

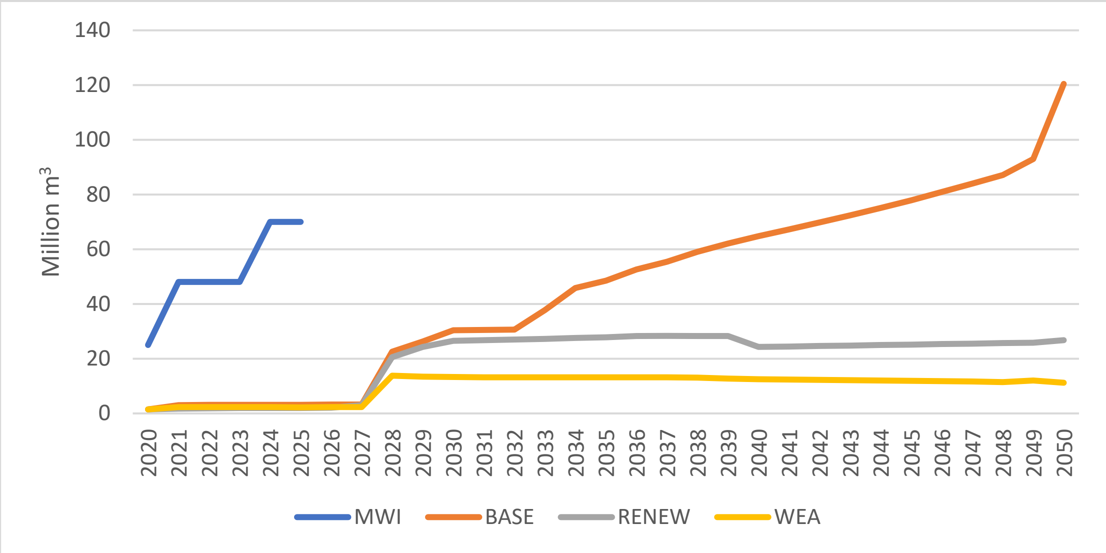

Figure 42- Water consumption of oil shale and nuclear across different scenarios

For hydropower generation, three power plants incorporated into the model. Large hydropower (>12 MW), small hydropower (<1 MW) and medium-scale hydropower units (between 1 MW and 12 MW). When large hydropower units are deployed, vast quantities of water losses occur through evaporation. This is caused due to the open reservoir of the dam. This is the case for the RENEW scenario when 800 MW of large hydropower units operate between 2025 and 2050 respectively and lead to water losses between 700 million m^3 and 975 million m^3. Even when only 200 MW operate under the BASE scenario, the water losses accounted for approximately 244 million m^3. Due to substantial uncertainties for the operation of large hydropower units, medium-scaled hydropower has replaced the large hydropower under the WEA scenario. This leads to water losses through evaporation in the scale of 14 million m^3 yearly under the WEA scenario.

Despite the water losses, water flow needs have been accounted for the generation of hydroelectricity. More specifically, the flow requirements are much more in RENEW base scenario when both large and medium scale hydro units operate and its between 10 to 20 million m^3 between 2025 and 2050. The situation in WEA scenario is reversed when only medium-scale hydro units operate with flow needs of approximately 8 million m^3 per year after 2025. Considering the above, the deployment of large hydropower units have the potential to lead to significant water losses since the reservoirs are much bigger than in smaller units. For this reason, medium-scale and small-scale hydro schemes could be deployed in order to minimize such water losses.

7. Conclusions

This thesis set out to answer three research questions. The main findings that were achieved by answering each research question are presented below, followed by the relevance of the findings for other countries and directions for future research.

The first research question was as follows: *What are the most critical nexus interlinkages for the case of Jordan?* Four critical interlinkages were identified by this study: 1) Water consumption for power generation. The power sector's expansion will require additional water quantities. An oil shale power plant operates from 2020 while national planning aims to include several nuclear power plants to ensure the security of the energy sector. 2) Energy demand for the water sector. The deployment of desalination units to support the increasing water demand will require additional quantities of energy for their operation. 3) Agriculture demand vs. agriculture biomass contribution to the electricity mix. This interlinkage identified in order to examine whether the agriculture sector could cover its own electricity needs. 4) Water needs for irrigation. While the agricultural sector produces about 5% of the total GDP, it consumes about 45% of the total water withdrawals, which constitutes an interconnection between water and agriculture sectors.

The second question was formulated as follows: *Concerning the identified interlinkages, how much energy, water and agriculture will be needed in Jordan by 2050?* The quantities of water, energy and food were examined under three different scenarios. 1) The water quantities needed for the power sector and each energy technology were identified. The nuclear power plant and large hydropower units are the most water-intensive technologies. The nuclear power plants need water for its operation process, while large hydropower units lead to high water losses due to evaporation due to the open reservoirs. 2) Desalination is the main driver for the increased electricity demand in the water sector. Such increase in the electricity demand, would require additional capacities and energy technologies to be deployed. 3) The maximum electricity that can be generated from biomass is about 5.4 PJ while the agricultural demand estimated to grow annually by 3.4%, which is the average annual growth for the electricity demand used by the national authorities. 4) Due to limitations on data and time, this study was not able to dive into a detailed analysis regarding the water demand for irrigation. Although based on the National Water Strategy, the irrigation demand is projected to remain at constant levels between 2016 and 2025.

Considering the answers given to the first and second questions, the third and last question was: *What are the trade-offs and synergies concerning the WEA nexus in Jordan?* Based on the analysis of the results, trade-offs and synergies were identified for each interconnection. 1) Regarding the water needs for power generation, nuclear power plants are the main driver for water consumption in the power system. Nuclear energy contributes to increasing the energy security of the country, although it has the potential to consume water quantities far beyond the maximum levels that the country can provide to the industrial sector (BASE scenario). For this reason, it is essential to put restrictions on electricity generation from nuclear power plants in order to avoid relevant trade-offs. As examined by the RENEW and WEA scenarios, renewable sources could play a pivotal role in this direction. 2) While desalination is a key contributor in meeting the water demand, such technologies will require vast quantities of energy to operate, and this will lead the water sector to become one of the major energy consumers by 2050. 3) The electricity potential from agricultural biomass examined to be not enough to cover the electricity demand of the agricultural sector. Considering this, a trade-off was identified between the energy-agriculture sectors.

Given the findings and limitations of this thesis, five directions can be discerned for future research. Firstly, this study did capture the water requirements for the power sector. However, the development of a model that captures the demand and supply necessities of the entire water sector could deliver a more detailed overview of this sector as well as linkages to other sectors in the mid-term. Secondly, while the model captures the flow requirements for hydropower to generate electricity, did not incorporate changes due to climate-driven implications. The incorporation of climate-relevant parameters such as the decrease of precipitation and streamflow is essential to examine whether climate change will have a significant impact on hydro-electricity. Thirdly, this study did not capture decentralized energy technologies except the PV in rooftops and the small-scale hydropower schemes. Decentralized PV-UTL or wind technologies could play an essential role in the flexibility of the power system by the creation of mini-grids. Such an option could decrease the electricity demand from the grid without compromises to electricity supply for the desalination units and the agricultural sector. Decentralized renewable energy systems could be a solution to compensate for the limitations that the transmission lines could have to support additional loads of electricity. Fourthly, regarding the agricultural sector, the information for the electricity potential from agricultural biomass was obtained in PJ. A more detailed analysis could be conducted regarding the electricity potential of biomass per unit of cultivated crops either by examining the official documentation or geospatial sources. Fifthly, the information used in this study were based on desk research. Concerning the real-life context of the research objectives but also limitations on data availability, direct interactions with the official authorities could provide more articulate information on the relevant subjects.

The relevance of the findings presented in this study extends to other spatial settings where climate change effects and population growth will intensify in the future. The MENA region defines a geographical context where these changes will strain the natural resources without immediate climate action. The findings of this study aim to support the research conducted towards the energy and water security of Jordan by various national and international institutions.

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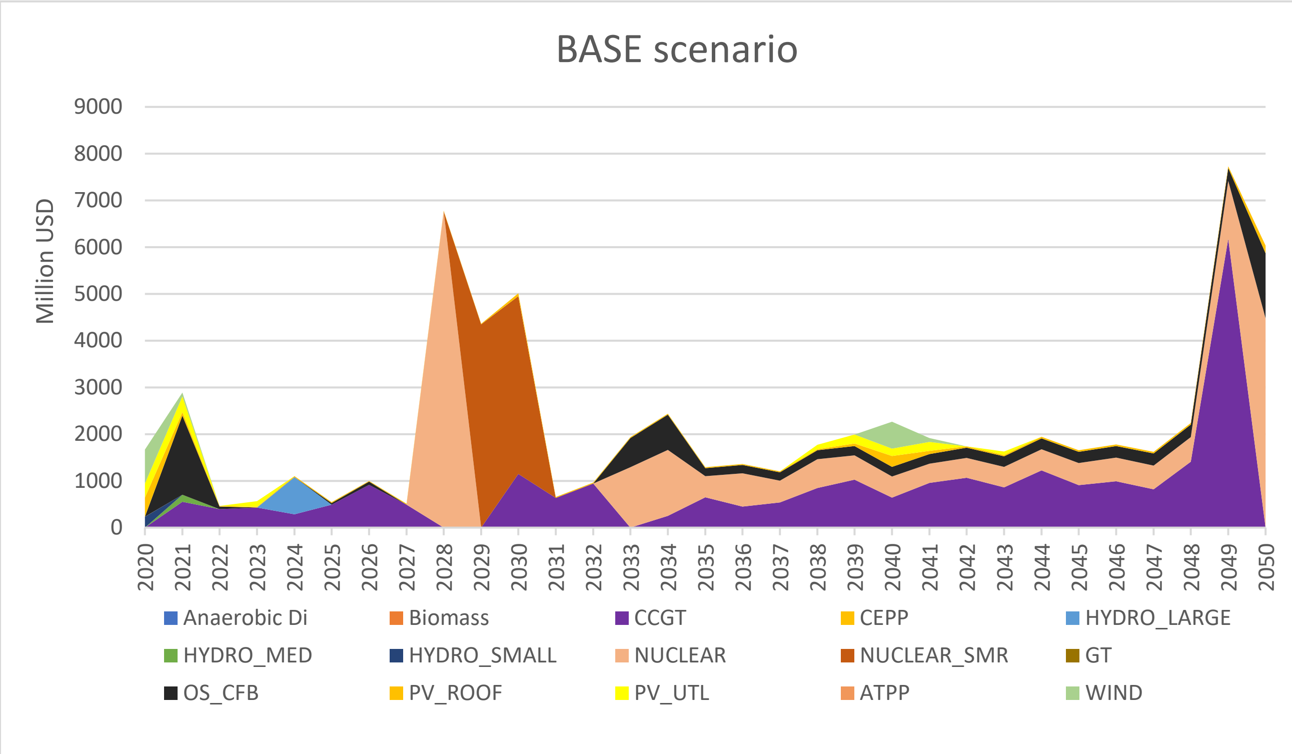
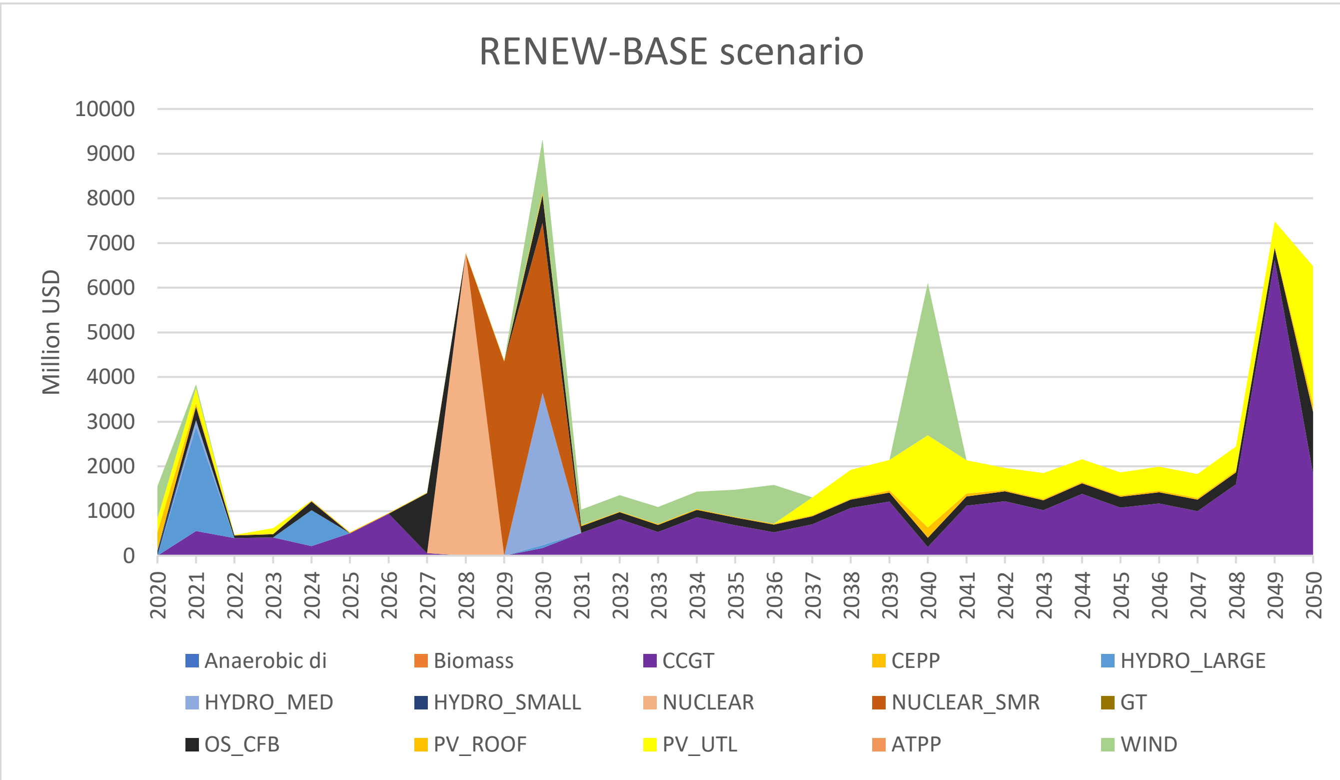
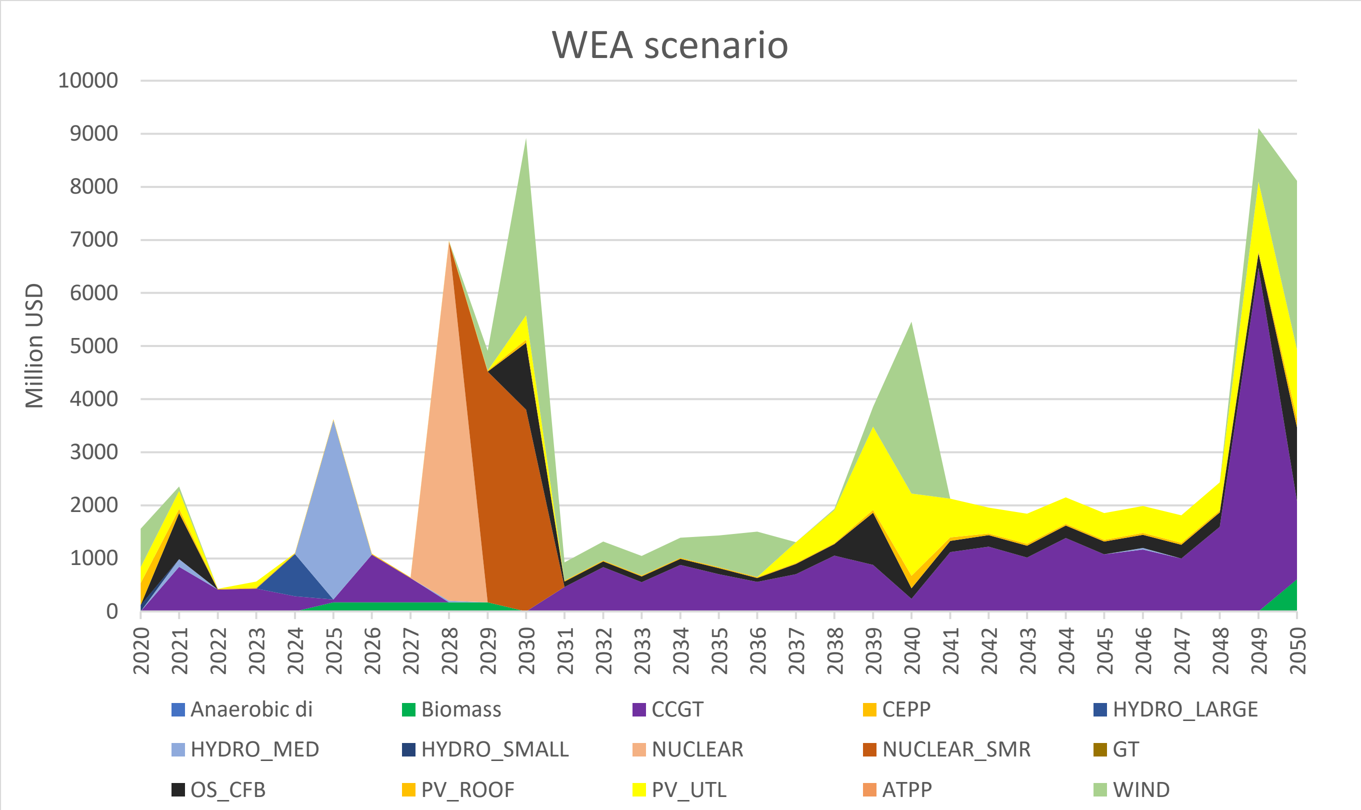
APPENDIX A Capital Investments for each scenario






WEA scenario
Million USD
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
2020
2021
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Anaerobic di
Biomass
CCGT
CEPP
HYDRO_LARGE
HYDRO_MED
HYDRO_SMALL
NUCLEAR
NUCLEAR_SMR
GT
OS_CFB
PV_ROOF
PV_UTL
ATPP
WIND

```
###############
#    Sets     #
###############
#
set DAILYTIMEBRACKET;
set DAYTYPE;
set EMISSION;
set FUEL;
set MODE_OF_OPERATION;
set REGION;
set SEASON;
set STORAGE;
set TECHNOLOGY;
set TIMESLICE;
set YEAR;
#
#####################
#    Parameters     #
#####################
#
########            Global                      #############
#
param YearSplit{l in TIMESLICE, y in YEAR};
param DiscountRate{r in REGION, t in TECHNOLOGY};
param DaySplit{lh in DAILYTIMEBRACKET, y in YEAR};
param DaysInDayType{ls in SEASON, ld in DAYTYPE, y in YEAR};
param DepreciationMethod{r in REGION};
#
########            Demands                     #############
#
param SpecifiedAnnualDemand{r in REGION, f in FUEL, y in YEAR};
param SpecifiedDemandProfile{r in REGION, f in FUEL, l in TIMESLICE, y
in YEAR};
#
#########           Performance                 #############
#
param CapacityToActivityUnit{r in REGION, t in TECHNOLOGY};
param CapacityFactor{r in REGION, t in TECHNOLOGY, l in TIMESLICE, y in
 YEAR};
param AvailabilityFactor{r in REGION, t in TECHNOLOGY, y in YEAR};
param OperationalLife{r in REGION, t in TECHNOLOGY};
param ResidualCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};
param InputActivityRatio{r in REGION, t in TECHNOLOGY, f in FUEL, m in
MODE_OF_OPERATION, y in YEAR};
param OutputActivityRatio{r in REGION, t in TECHNOLOGY, f in FUEL, m in
 MODE_OF_OPERATION, y in YEAR};
#
#########           Technology Costs            #############
#
```

```
param CapitalCost{r in REGION, t in TECHNOLOGY, y in YEAR};
param VariableCost{r in REGION, t in TECHNOLOGY, m in MODE_OF_OPERATION
, y in YEAR};
param FixedCost{r in REGION, t in TECHNOLOGY, y in YEAR};
#
#########            Capacity Constraints        #############
#
param CapacityOfOneTechnologyUnit{r in REGION, t in TECHNOLOGY, y in YE
AR};
param TotalAnnualMaxCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalAnnualMinCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};
#
#########            Activity Constraints        #############
#
param TotalTechnologyAnnualActivityUpperLimit{r in REGION, t in TECHNOL
OGY, y in YEAR};
param TotalTechnologyAnnualActivityLowerLimit{r in REGION, t in TECHNOL
OGY, y in YEAR};
param TotalTechnologyModelPeriodActivityUpperLimit{r in REGION, t in TE
CHNOLOGY};
param TotalTechnologyModelPeriodActivityLowerLimit{r in REGION, t in TE
CHNOLOGY};
#
#########            RE Generation Target        #############
#
param RETagTechnology{r in REGION, t in TECHNOLOGY, y in YEAR} binary;
param RETagFuel{r in REGION, f in FUEL, y in YEAR} binary;
param REMinProductionTarget{r in REGION, y in YEAR};
#
#########            Emissions & Penalties       #############
#
param EmissionActivityRatio{r in REGION, t in TECHNOLOGY, e in EMISSION
, m in MODE_OF_OPERATION, y in YEAR};
param AnnualEmissionLimit{r in REGION, e in EMISSION, y in YEAR};
#
##############
######################
#   Model Variables  #
######################
#
########             Demands                     #############
#
var RateOfDemand{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}>= 0
;
var Demand{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}>= 0;
#
#########            Capacity Variables          #############
#
var NumberOfNewTechnologyUnits{r in REGION, t in TECHNOLOGY, y in YEAR}
 >= 0,integer;
var NewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
```

```
var AccumulatedNewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR} >=
0;
var TotalCapacityAnnual{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
#
#########          Activity Variables          #############
#
var RateOfActivity{r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in M
ODE_OF_OPERATION, y in YEAR} >= 0;
var RateOfTotalActivity{r in REGION, t in TECHNOLOGY, l in TIMESLICE, y
 in YEAR} >= 0;
var TotalTechnologyAnnualActivity{r in REGION, t in TECHNOLOGY, y in YE
AR} >= 0;
var TotalAnnualTechnologyActivityByMode{r in REGION, t in TECHNOLOGY, m
 in MODE_OF_OPERATION, y in YEAR}>=0;
var TotalTechnologyModelPeriodActivity{r in REGION, t in TECHNOLOGY};
var RateOfProductionByTechnologyByMode{r in REGION, l in TIMESLICE, t i
n TECHNOLOGY, m in MODE_OF_OPERATION, f in FUEL, y in YEAR}>= 0;
var RateOfProductionByTechnology{r in REGION, l in TIMESLICE, t in TECH
NOLOGY, f in FUEL, y in YEAR}>= 0;
var ProductionByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY
, f in FUEL, y in YEAR}>= 0;
var ProductionByTechnologyAnnual{r in REGION, t in TECHNOLOGY, f in FUE
L, y in YEAR}>= 0;
var RateOfProduction{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}
 >= 0;
var Production{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR} >= 0;
var RateOfUseByTechnologyByMode{r in REGION, l in TIMESLICE, t in TECHN
OLOGY, m in MODE_OF_OPERATION, f in FUEL, y in YEAR}>= 0;
var RateOfUseByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY,
 f in FUEL, y in YEAR} >= 0;
var UseByTechnologyAnnual{r in REGION, t in TECHNOLOGY, f in FUEL, y in
 YEAR}>= 0;
var RateOfUse{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}>= 0;
var UseByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in
FUEL, y in YEAR}>= 0;
var Use{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}>= 0;
var Trade{r in REGION, rr in REGION, l in TIMESLICE, f in FUEL, y in YE
AR};
var TradeAnnual{r in REGION, rr in REGION, f in FUEL, y in YEAR};
#
var ProductionAnnual{r in REGION, f in FUEL, y in YEAR}>= 0;
var UseAnnual{r in REGION, f in FUEL, y in YEAR}>= 0;
#
#########          Costing Variables          #############
#
var CapitalInvestment{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
var DiscountedCapitalInvestment{r in REGION, t in TECHNOLOGY, y in YEAR
}>= 0;
#
var SalvageValue{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
```

```
var DiscountedSalvageValue{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0
;
var OperatingCost{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
var DiscountedOperatingCost{r in REGION, t in TECHNOLOGY, y in YEAR}>=
0;
#
var AnnualVariableOperatingCost{r in REGION, t in TECHNOLOGY, y in YEAR
}>= 0;
var AnnualFixedOperatingCost{r in REGION, t in TECHNOLOGY, y in YEAR}>=
 0;
#
var TotalDiscountedCostByTechnology{r in REGION, t in TECHNOLOGY, y in
YEAR}>= 0;
var TotalDiscountedCost{r in REGION, y in YEAR}>= 0;
#
var ModelPeriodCostByRegion{r in REGION} >= 0;
#
#########           RE Gen Target              #############
#
var TotalREProductionAnnual{r in REGION, y in YEAR};
var RETotalProductionOfTargetFuelAnnual{r in REGION, y in YEAR};
#
#########           Emissions                  #############
#
var AnnualTechnologyEmissionByMode{r in REGION, t in TECHNOLOGY, e in E
MISSION, m in MODE_OF_OPERATION, y in YEAR}>=0;
var AnnualTechnologyEmission{r in REGION, t in TECHNOLOGY, e in EMISSIO
N, y in YEAR}>=0;
var AnnualTechnologyEmissionPenaltyByEmission{r in REGION, t in TECHNOL
OGY, e in EMISSION, y in YEAR}>=0;
var AnnualTechnologyEmissionsPenalty{r in REGION, t in TECHNOLOGY, y in
 YEAR}>=0;
var DiscountedTechnologyEmissionsPenalty{r in REGION, t in TECHNOLOGY,
y in YEAR}>=0;
var AnnualEmissions{r in REGION, e in EMISSION, y in YEAR}>=0;
var ModelPeriodEmissions{r in REGION, e in EMISSION}>=0;
#
######################
# Objective Function #
######################
#
minimize cost: sum{r in REGION, y in YEAR} TotalDiscountedCost[r,y];
#
#####################
# Constraints       #
#####################
#
s.t. EQ_SpecifiedDemand{r in REGION, l in TIMESLICE, f in FUEL, y in YE
AR:
                        SpecifiedAnnualDemand[r,f,y] <> 0}:
```

```
    SpecifiedAnnualDemand[r,f,y] * SpecifiedDemandProfile[r,f,l,y] / Ye
arSplit[l,y]
    =
    RateOfDemand[r,l,f,y];
#
#########           Capacity Adequacy A         #############
#
s.t. CAa2_TotalAnnualCapacity{r in REGION, t in TECHNOLOGY, y in YEAR}:
    AccumulatedNewCapacity[r,t,y] + ResidualCapacity[r,t,y]
    =
    TotalCapacityAnnual[r,t,y];

s.t. CAa3_TotalActivityOfEachTechnology{r in REGION, t in TECHNOLOGY, l
 in TIMESLICE, y in YEAR}:
    sum{m in MODE_OF_OPERATION} RateOfActivity[r,l,t,m,y]
    =
    RateOfTotalActivity[r,t,l,y];

s.t. CAa4_Constraint_Capacity{r in REGION, l in TIMESLICE, t in TECHNOL
OGY, y in YEAR}:
    RateOfTotalActivity[r,t,l,y]
    <=
    TotalCapacityAnnual[r,t,y] * CapacityFactor[r,t,l,y] * CapacityToAc
tivityUnit[r,t];

s.t. CAa5_TotalNewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR: Cap
acityOfOneTechnologyUnit[r,t,y]<>0}:
    CapacityOfOneTechnologyUnit[r,t,y] * NumberOfNewTechnologyUnits[r,t
,y]
    =
    NewCapacity[r,t,y];

#
# Note that the PlannedMaintenance equation below ensures that all othe
r technologies have a capacity great enough
# to at least meet the annual average.
#
#########           Capacity Adequacy B         #############
#
s.t. CAb1_PlannedMaintenance{r in REGION, t in TECHNOLOGY, y in YEAR: A
vailabilityFactor[r,t,y] < 1}:
    sum{l in TIMESLICE} RateOfTotalActivity[r,t,l,y] * YearSplit[l,y]
    <=
    sum{l in TIMESLICE} (TotalCapacityAnnual[r,t,y] * CapacityFactor[r,
t,l,y] * YearSplit[l,y])
    * AvailabilityFactor[r,t,y] * CapacityToActivityUnit[r,t];
#
#########           Energy Balance A            #############
#
s.t. EBa1_RateOfFuelProduction1{
```

```
    r in REGION, l in TIMESLICE, f in FUEL, t in TECHNOLOGY, m in MODE_
OF_OPERATION, y in YEAR:
    OutputActivityRatio[r,t,f,m,y] <> 0}:
    RateOfActivity[r,l,t,m,y] * OutputActivityRatio[r,t,f,m,y]
    =
    RateOfProductionByTechnologyByMode[r,l,t,m,f,y];

s.t. EBa2_RateOfFuelProduction2{r in REGION, l in TIMESLICE, f in FUEL,
 t in TECHNOLOGY, y in YEAR
                                # : (sum{m in MODE_OF_OPERATION} Output
ActivityRatio[r,t,f,m,y]) <> 0
                                }:
    sum{m in MODE_OF_OPERATION: OutputActivityRatio[r,t,f,m,y] <> 0} Ra
teOfProductionByTechnologyByMode[r,l,t,m,f,y]
    =
    RateOfProductionByTechnology[r,l,t,f,y];

s.t. EBa3_RateOfFuelProduction3{r in REGION, l in TIMESLICE, f in FUEL,
 y in YEAR:
                                (sum{t in TECHNOLOGY, m in MODE_OF_OPER
ATION} OutputActivityRatio[r,t,f,m,y]) <> 0}:
    sum{t in TECHNOLOGY} RateOfProductionByTechnology[r,l,t,f,y]
    =
    RateOfProduction[r,l,f,y];

s.t. EBa4_RateOfFuelUse1{r in REGION, l in TIMESLICE, f in FUEL, t in T
ECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR:
                         InputActivityRatio[r,t,f,m,y] <> 0}:
    RateOfActivity[r,l,t,m,y] * InputActivityRatio[r,t,f,m,y]
    =
    RateOfUseByTechnologyByMode[r,l,t,m,f,y];

s.t. EBa5_RateOfFuelUse2{r in REGION, l in TIMESLICE, f in FUEL, t in T
ECHNOLOGY, y in YEAR:
                         sum{m in MODE_OF_OPERATION} InputActivityRatio
[r,t,f,m,y] <> 0}:
    sum{m in MODE_OF_OPERATION: InputActivityRatio[r,t,f,m,y] <> 0}
    RateOfUseByTechnologyByMode[r,l,t,m,f,y]
    =
    RateOfUseByTechnology[r,l,t,f,y];

s.t. EBa6_RateOfFuelUse3{r in REGION, l in TIMESLICE, f in FUEL, y in Y
EAR:
                         sum{t in TECHNOLOGY, m in MODE_OF_OPERATION} I
nputActivityRatio[r,t,f,m,y] <> 0}:
    sum{t in TECHNOLOGY} RateOfUseByTechnology[r,l,t,f,y]
    =
    RateOfUse[r,l,f,y];

s.t. EBa7_EnergyBalanceEachTS1{r in REGION, l in TIMESLICE, f in FUEL,
y in YEAR:
```

```
                                (sum{t in TECHNOLOGY, m in MODE_OF_OPERA
TION} OutputActivityRatio[r,t,f,m,y]) <> 0}:
    RateOfProduction[r,l,f,y] * YearSplit[l,y]
    =
    Production[r,l,f,y];

s.t. EBa8_EnergyBalanceEachTS2{r in REGION, l in TIMESLICE, f in FUEL,
y in YEAR:
                                (sum{t in TECHNOLOGY, m in MODE_OF_OPERA
TION} InputActivityRatio[r,t,f,m,y]) <> 0}:
    RateOfUse[r,l,f,y] * YearSplit[l,y]
    =
    Use[r,l,f,y];

s.t. EBa9_EnergyBalanceEachTS3{r in REGION, l in TIMESLICE, f in FUEL,
y in YEAR:
                                SpecifiedAnnualDemand[r,f,y] <> 0}:
    RateOfDemand[r,l,f,y] * YearSplit[l,y]
    =
    Demand[r,l,f,y];

#
#########           Energy Balance B            #############
#
s.t. EBb1_EnergyBalanceEachYear1{r in REGION, f in FUEL, y in YEAR}:
    sum{l in TIMESLICE} Production[r,l,f,y]
    =
    ProductionAnnual[r,f,y];

s.t. EBb2_EnergyBalanceEachYear2{r in REGION, f in FUEL, y in YEAR}:
    sum{l in TIMESLICE} Use[r,l,f,y]
    =
    UseAnnual[r,f,y];

s.t. EBb3_EnergyBalanceEachYear3{r in REGION, rr in REGION, f in FUEL,
y in YEAR}:
    sum{l in TIMESLICE} Trade[r,rr,l,f,y]
    =
    TradeAnnual[r,rr,f,y];

s.t. EBb4_EnergyBalanceEachYear4{r in REGION, f in FUEL, y in YEAR}:
    ProductionAnnual[r,f,y]
    >=
    UseAnnual[r,f,y] + sum{rr in REGION} TradeAnnual[r,rr,f,y] * TradeR
oute[r,rr,f,y] + AccumulatedAnnualDemand[r,f,y];

#
#########           Accounting Technology Production/Use    ###########
##
#
```

```
s.t. Acc1_FuelProductionByTechnology{r in REGION, l in TIMESLICE, t in
TECHNOLOGY, f in FUEL, y in YEAR}:
    RateOfProductionByTechnology[r,l,t,f,y] * YearSplit[l,y]
    =
    ProductionByTechnology[r,l,t,f,y];

s.t. Acc2_FuelUseByTechnology{r in REGION, l in TIMESLICE, t in TECHNOL
OGY, f in FUEL, y in YEAR}:
    RateOfUseByTechnology[r,l,t,f,y] * YearSplit[l,y]
    =
    UseByTechnology[r,l,t,f,y];

s.t. Acc3_AverageAnnualRateOfActivity{r in REGION, t in TECHNOLOGY, m i
n MODE_OF_OPERATION, y in YEAR}:
    sum{l in TIMESLICE} RateOfActivity[r,l,t,m,y]*YearSplit[l,y]
    =
    TotalAnnualTechnologyActivityByMode[r,t,m,y];

s.t. Acc4_ModelPeriodCostByRegion{r in REGION}:
    sum{y in YEAR}TotalDiscountedCost[r,y] = ModelPeriodCostByRegion[r]
;

#########           Capital Costs              #############
#
s.t. CC1_UndiscountedCapitalInvestment{r in REGION, t in TECHNOLOGY, y
in YEAR}: CapitalCost[r,t,y] * NewCapacity[r,t,y] = CapitalInvestment[r
,t,y];
s.t. CC2_DiscountingCapitalInvestment{r in REGION, t in TECHNOLOGY, y i
n YEAR}: CapitalInvestment[r,t,y]/(CapitalRecoveryFactor[r,t,y]) = Disc
ountedCapitalInvestment[r,t,y];
#
#########           Operating Costs            #############
#
s.t. OC1_OperatingCostsVariable{r in REGION, t in TECHNOLOGY, l in TIME
SLICE, y in YEAR: sum{m in MODE_OF_OPERATION} VariableCost[r,t,m,y] <>
0}:
    sum{m in MODE_OF_OPERATION}
    TotalAnnualTechnologyActivityByMode[r,t,m,y] * VariableCost[r,t,m,y
]
    =
    AnnualVariableOperatingCost[r,t,y];

s.t. OC2_OperatingCostsFixedAnnual{r in REGION, t in TECHNOLOGY, y in Y
EAR}:
    TotalCapacityAnnual[r,t,y]*FixedCost[r,t,y]
    =
    AnnualFixedOperatingCost[r,t,y];

s.t. OC3_OperatingCostsTotalAnnual{r in REGION, t in TECHNOLOGY, y in Y
EAR}:
```

```
    AnnualFixedOperatingCost[r,t,y] + AnnualVariableOperatingCost[r,t,y
]
    =
    OperatingCost[r,t,y];

s.t. OC4_DiscountedOperatingCostsTotalAnnual{r in REGION, t in TECHNOLO
GY, y in YEAR}:
    OperatingCost[r,t,y] / CapitalRecoveryFactorMid[r, t, y]
    =
    DiscountedOperatingCost[r,t,y];

#
#########           Total Discounted Costs      #############
#
s.t. TDC1_TotalDiscountedCostByTechnology{r in REGION, t in TECHNOLOGY,
 y in YEAR}: DiscountedOperatingCost[r,t,y]+DiscountedCapitalInvestment
[r,t,y]+DiscountedTechnologyEmissionsPenalty[r,t,y]-
DiscountedSalvageValue[r,t,y] = TotalDiscountedCostByTechnology[r,t,y];
s.t. TDC2_TotalDiscountedCost{r in REGION, y in YEAR}: sum{t in TECHNOL
OGY} TotalDiscountedCostByTechnology[r,t,y]+sum{s in STORAGE} TotalDisc
ountedStorageCost[r,s,y] = TotalDiscountedCost[r,y];
#
#########           Total Capacity Constraints  ##############
#
s.t. TCC1_TotalAnnualMaxCapacityConstraint{r in REGION, t in TECHNOLOGY
, y in YEAR: TotalAnnualMaxCapacity[r,t,y] <> -
1}: TotalCapacityAnnual[r,t,y] <= TotalAnnualMaxCapacity[r,t,y];
s.t. TCC2_TotalAnnualMinCapacityConstraint{r in REGION, t in TECHNOLOGY
, y in YEAR: TotalAnnualMinCapacity[r,t,y]>0}: TotalCapacityAnnual[r,t,
y] >= TotalAnnualMinCapacity[r,t,y];
#
#########           New Capacity Constraints    ##############
#
s.t. NCC1_TotalAnnualMaxNewCapacityConstraint{r in REGION, t in TECHNOL
OGY, y in YEAR: TotalAnnualMaxCapacityInvestment[r,t,y] <> -
1}: NewCapacity[r,t,y] <= TotalAnnualMaxCapacityInvestment[r,t,y];
s.t. NCC2_TotalAnnualMinNewCapacityConstraint{r in REGION, t in TECHNOL
OGY, y in YEAR: TotalAnnualMinCapacityInvestment[r,t,y]>0}: NewCapacity
[r,t,y] >= TotalAnnualMinCapacityInvestment[r,t,y];
#
#########           Annual Activity Constraints ##############
#
s.t. AAC1_TotalAnnualTechnologyActivity{r in REGION, t in TECHNOLOGY, y
 in YEAR}: sum{l in TIMESLICE} RateOfTotalActivity[r,t,l,y]*YearSplit[l
,y] = TotalTechnologyAnnualActivity[r,t,y];
s.t. AAC2_TotalAnnualTechnologyActivityUpperLimit{r in REGION, t in TEC
HNOLOGY, y in YEAR: TotalTechnologyAnnualActivityUpperLimit[r,t,y] <> -
1}: TotalTechnologyAnnualActivity[r,t,y] <= TotalTechnologyAnnualActivi
tyUpperLimit[r,t,y] ;
s.t. AAC3_TotalAnnualTechnologyActivityLowerLimit{r in REGION, t in TEC
HNOLOGY, y in YEAR: TotalTechnologyAnnualActivityLowerLimit[r,t,y]>0}:
```

```
TotalTechnologyAnnualActivity[r,t,y] >= TotalTechnologyAnnualActivityLo
werLimit[r,t,y] ;
#
#########           Total Activity Constraints   ##############
#
s.t. TAC2_TotalModelHorizonTechnologyActivityUpperLimit{r in REGION, t
in TECHNOLOGY: TotalTechnologyModelPeriodActivityUpperLimit[r,t]<>-
1}: TotalTechnologyModelPeriodActivity[r,t] <= TotalTechnologyModelPeri
odActivityUpperLimit[r,t] ;
s.t. TAC3_TotalModelHorizenTechnologyActivityLowerLimit{r in REGION, t
in TECHNOLOGY: TotalTechnologyModelPeriodActivityLowerLimit[r,t]>0}: To
talTechnologyModelPeriodActivity[r,t] >= TotalTechnologyModelPeriodActi
vityLowerLimit[r,t] ;
#
#########           RE Production Target        ############## NTS: Sho
uld change demand for production
#
s.t. RE1_FuelProductionByTechnologyAnnual{r in REGION, t in TECHNOLOGY,
 f in FUEL, y in YEAR}: sum{l in TIMESLICE} ProductionByTechnology[r,l,
t,f,y] = ProductionByTechnologyAnnual[r,t,f,y];
s.t. RE2_TechIncluded{r in REGION, y in YEAR}: sum{t in TECHNOLOGY, f i
n FUEL} ProductionByTechnologyAnnual[r,t,f,y]*RETagTechnology[r,t,y] =
TotalREProductionAnnual[r,y];
s.t. RE3_FuelIncluded{r in REGION, y in YEAR}: sum{l in TIMESLICE, f in
 FUEL} RateOfProduction[r,l,f,y]*YearSplit[l,y]*RETagFuel[r,f,y] = RETo
talProductionOfTargetFuelAnnual[r,y];
s.t. RE4_EnergyConstraint{r in REGION, y in YEAR}:REMinProductionTarget
[r,y]*RETotalProductionOfTargetFuelAnnual[r,y] <= TotalREProductionAnnu
al[r,y];
s.t. RE5_FuelUseByTechnologyAnnual{r in REGION, t in TECHNOLOGY, f in F
UEL, y in YEAR}: sum{l in TIMESLICE} RateOfUseByTechnology[r,l,t,f,y]*Y
earSplit[l,y] = UseByTechnologyAnnual[r,t,f,y];
#
#########           Emissions Accounting        ##############
#
s.t. E1_AnnualEmissionProductionByMode{r in REGION, t in TECHNOLOGY, e
in EMISSION, m in MODE_OF_OPERATION, y in YEAR:
                                       EmissionActivityRatio[r,t,e,m,y]
 <> 0}:
    EmissionActivityRatio[r,t,e,m,y] * TotalAnnualTechnologyActivityByM
ode[r,t,m,y]
    =
    AnnualTechnologyEmissionByMode[r,t,e,m,y];

s.t. E2_AnnualEmissionProduction{r in REGION, t in TECHNOLOGY, e in EMI
SSION, y in YEAR}:
    sum{m in MODE_OF_OPERATION}
    AnnualTechnologyEmissionByMode[r,t,e,m,y]
    =
    AnnualTechnologyEmission[r,t,e,y];
```

```
s.t. E6_EmissionsAccounting1{r in REGION, e in EMISSION, y in YEAR}:
    sum{t in TECHNOLOGY}
    AnnualTechnologyEmission[r,t,e,y]
    =
    AnnualEmissions[r,e,y];

s.t. E7_EmissionsAccounting2{r in REGION, e in EMISSION}:
    sum{y in YEAR} AnnualEmissions[r,e,y]
    =
    ModelPeriodEmissions[r,e] - ModelPeriodExogenousEmission[r,e];

s.t. E8_AnnualEmissionsLimit{r in REGION, e in EMISSION, y in YEAR: Ann
ualEmissionLimit[r, e, y] <> -1}:
    AnnualEmissions[r,e,y] + AnnualExogenousEmission[r,e,y]
    <=
    AnnualEmissionLimit[r,e,y];

s.t. E9_ModelPeriodEmissionsLimit{r in REGION, e in EMISSION: ModelPeri
odEmissionLimit[r, e] <> -1}:
    ModelPeriodEmissions[r,e]
    <=
    ModelPeriodEmissionLimit[r,e];
#
#######################################################################
####################
#
# Solve the problem
solve;
```