STUDY

The Water-Energy Nexus in Iran

Water-Related Challenges for the Power Sector

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- Around the world, electricity generation requires water for cooling, running turbines, cleaning processes and power plant operation. Accordingly, the globally increasing demand for electricity produces a growing demand for water. Particularly in Iran, and other parts of the Middle East and North Africa, diminishing water resources are very likely to adversely affect not only the primary energy production, but also the operation of electricity generation capacities, putting energy security at risk while jeopardizing the region's social and economic development.

- In Iran, the increasing depletion of the country's water resources is becoming a serious issue. Among other consequences, water scarcity has already affected the Iranian power sector, which depends heavily on water-intensive thermal and hydro-power generation technologies. At the same time, the already fast-paced growth in electricity demand is expected to further accelerate in the future, if the nation's demand for water is to be satisfied by the application of energy-intensive desalination and water re-use technologies. Thus, Iran's power sector is not only affected by, but contributes to the country's water stress.

- This publication intends to provide a comprehensive overview of the water-energy nexus' relevance to the Iranian electricity sector, by illustrating key trends, analysing water-related challenges and identifying knowledge gaps. It summarises the results of a workshop, and a series of dialogues with Iranian energy and water experts, in which both the current situation and future water-related risks and impacts on the Iranian power sector were discussed. Based on those results, it highlights research needs and further options for scientific collaboration.

Contents

1. Introduction

Water and energy are closely interlinked. Water is needed at every stage of the energy supply chain, and energy is needed to extract, distribute, treat and desalinate water. These complex interdependencies and trade-offs between water and energy are part of the so-called water-energy nexus.

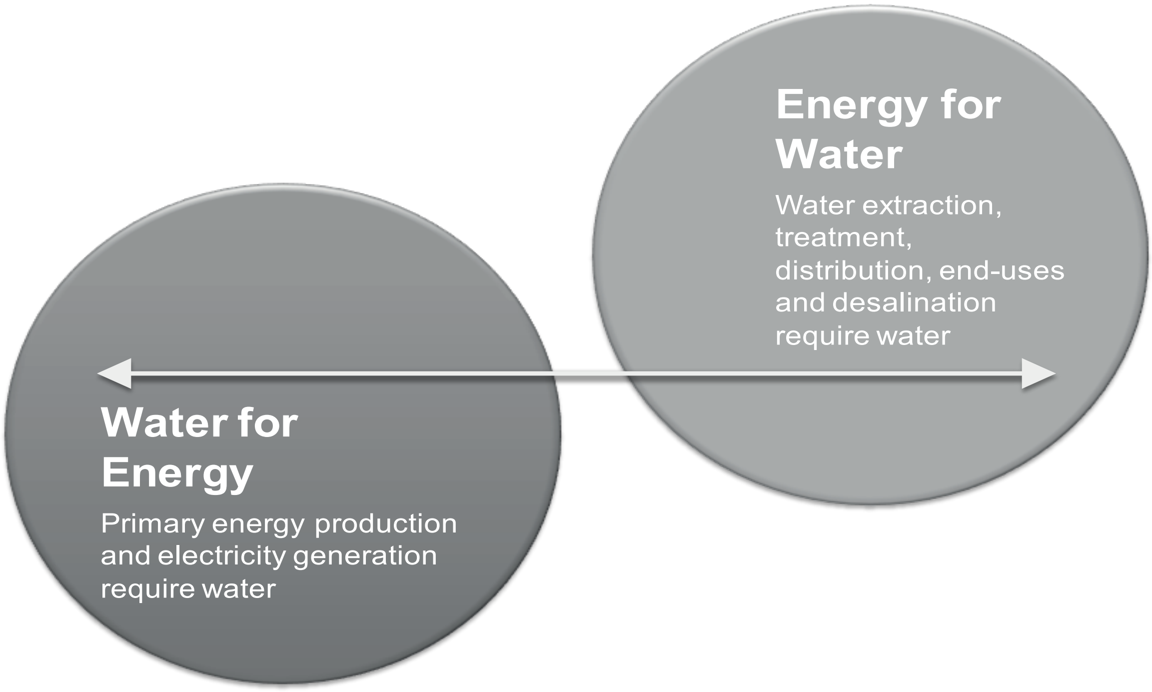
Particularly in regions affected by water stress, the increasing demand for energy can lead to greater water scarcity, just as the energy sector can be affected by reduced water availability. At the same time, the decreased availability of both ground and surface water encourages the use of energy-intensive desalination and water re-use technologies, especially in the dry areas of the Middle East and North Africa (MENA).

Iran faces just such a situation. It is affected by a growing depletion of its water resources, due to both a changing climate, and the growth of water demand in the agricultural, industrial and residential sectors. Against the background of increased energy demand, depleted water resources could adversely affect the fossil fuel industry, as well as the operation of electricity generation capacities. This could put Iran's energy security at risk and jeopardise the country's social and economic development.

The risks of water stress to energy security, in general – and to the power sector in particular – have thus far been barely examined. A deeper understanding of water's role in Iran's current and future energy system is needed. Electricity generation infrastructures are designed to last for decades, and influence the energy sector's long-term water requirements. To lower the risks of competition for water across sectors, the future availability of water should be taken into account in today's energy planning.

This study provides a first comprehensive overview of the water-energy nexus' relevance for energy security in the Iranian electricity sector. The assessment is based on the results of a workshop, and a series of dialogues with Iranian energy, water and agriculture experts, in which both the current situation and future challenges related to the water-energy nexus were discussed.

Figure 1. Schematic overview Water-Energy Nexus



Source: based on World Bank 2013

2. Overview of the Water-Energy Nexus

Water and energy are essential to sustain and enhance economic growth and social development. Yet, due to their uneven geographical distribution, the resources needed to ensure reliable supply of both water and energy services are becoming increasingly scarce in many countries and regions worldwide. Today, 2.8 billion people – more than a third of the world's population – live in areas of high water stress. If present trends continue, the number is expected to rise to 3.9 billion by 2030 (OECD 2011). On the energy side, an estimated 1.1 billion people – 14 percent of the global population – lack access to electricity, and even more have only an unreliable supply of modern energy services (OECD/IEA 2017). In addition, increasing temperature and reduced precipitation levels, as well as extreme weather events associated with climate change (like heat waves, floods, droughts and storms), add to the pressure on energy and water resources. At the same time, the demand for water and energy is increasing due to population growth, economic development, urbanisation and changing consumer habits. Securing the supply of water and energy under these circumstances poses severe challenges on both the national and international levels, due to the high interconnectedness of both energy and water systems.

Energy and water resource systems are not only linked within themselves. Far-reaching interdependencies between the two systems also exist. Water is required to generate energy, and energy is needed to extract, distribute and treat water. Actions and decisions in one of the sectors can significantly affect the other. The complex interdependencies, trade-offs and synergies that exist between the water and energy systems are commonly referred to as the water-energy nexus (WE-Nexus).

Historically, around the world, water and energy systems have been planned, developed, regulated and managed separately. Today, the interdependencies between water and energy are widely recognised, and the concept of the water-energy nexus has become increasingly prominent among international organisations, development agencies, academics, policy analysts and other stakeholders. However, on the ground, a so-called »silo mentality« still prevails. Typically, water and energy challenges continue to be addressed within sectorial boundaries particularly in terms of project, investment and policy decisions (Bhattacharyya et al. 2015). In consequence, knowledge gaps regarding the extent of linkages between water and energy systems hinder integrated planning.

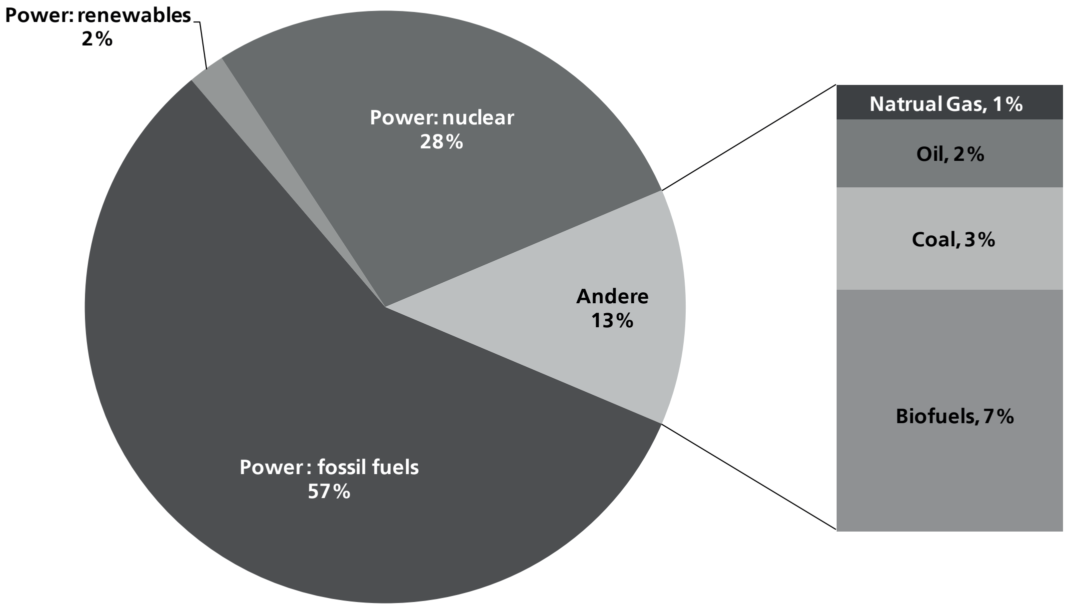
A deeper understanding of the risks and opportunities is particularly needed on the energy side of the nexus (IRENA 2015), as water has thus far been prioritised in the mainstream nexus discussions (Allouche et al. 2015). While water security is, in many ways, closely linked to energy security, more detailed knowledge on water's role with regard to energy security in both current energy systems and different future energy development pathways is required. Given the significant energy investments currently being made in many countries, now is a crucial time to ensure that the most efficient and effective pathways for the water and energy sectors are chosen to meet sustainability goals.

Besides the potential effects of water constraints on energy security, the decreasing availability of ground and surface water may significantly increase energy demand for energy-intensive desalination and water re-use technologies. Particularly in the Middle East and North Africa, the use of unconventional water sources with such technologies is expected to be a significant driver of energy demand, which needs to be taken into account when addressing the water-energy nexus.

2.1 Water for Energy

Water is needed at every stage of the energy supply chain, from the extraction and processing of energy carriers (nuclear-, fossil-, and biofuels), to power and heat generation, and cooling. Moreover, both the manufacture of energy systems and the construction and operation of power plants also require significant amounts of water. Depending on the energy source, and the conversion technology, water requirements vary significantly. Conventional fuels require water for extraction, transport and processing; thermal power plants using nuclear sources or fossil fuels require large amounts of water for cooling and generating electricity, while large-scale hydropower plants are only viable if rivers or reservoirs have sufficient water levels and water inflows (World Bank 2013). Renewable energy resources also require water. For example, the operation of concentrated solar power (CSP) plants requires water for

Figure 2. Overview distribution of water withdrawals in the global energy sector in 2014



Notes: Renewables includes solar PV, CSP, wind, geothermal and bioenergy. Water requirements are quantified for »source-to-carrier« primary energy production (oil, gas, coal), a definition which includes extraction, processing and transport. Water withdrawals and consumption for biofuels account for the irrigation of dedicated feedstock and wa-ter use for processing. For electricity generation, freshwater requirements are for the operational phase, including cleaning, cooling and other process related needs; water used for the production of input fuels is excluded. Hydropower is excluded.
Source: OECD/IEA 2016

cooling and mirror cleaning, while solar photovoltaic plants require water mainly for cleaning (IRENA 2015). Bioenergy generation requires water for both feedstock production and power plant operation (either for cooling in thermal plants, or in biogas plants as input for the anaerobic digestion process).

In the electricity sector, both generation technology and energy source influence the water requirements. In particular, for the large share of thermal power plants, water requirements depend strongly on the cooling technology employed. Wet-cooling technologies, for example, generally require more water than dry-cooling options. However, given the fact that some advanced cooling technologies withdraw less water from the water source, but consume more water overall (OECD/IEA 2016), both water withdrawals and water consumption need to be taken into account when evaluating water use.

Globally, the energy sector accounts for an estimated 10-15 percent of global freshwater withdrawals, and 3 percent of total water consumption (OECD/IEA 2016; IRENA 2015).[1] At 88 percent, the largest amounts of water are used for electricity generation (Fig. 2). Electricity generation requires water mainly for cooling purposes, with 70 percent of the total installed capacity worldwide being thermal power plants (OECD/IEA 2016). In primary energy production, the major share of water is used for the extraction of fossil fuels, and as input in feedstock production for biofuels.

2.2 Energy for Water Desalination and Re-use

Water is not only needed in the energy supply chain, but energy is also needed to extract, distribute and treat water. The water sector uses energy, to a large extent, in the form of electricity. The amount of energy required for the provision of water strongly depends on the wa-

1. Water withdrawals refer to the amount of water removed from, but later returned to, the water source. Water returns can affect the water quality of the water source. For example, cooling water often has higher temperatures on its return to the water source, which can result in thermal pollution. Water consumption refers to the amount of water that is permanently removed from the water source.

ter source, the transport distance, the relief of the terrain and the type of treatment facility (OECD/IEA 2016). Groundwater extraction generally requires more energy than surface water supply. Most energy-intensive by far, however, is the supply of non-traditional water sources with desalination or re-use technologies.

Although today the majority of water is supplied from surface- and groundwater sources, with increasing levels of water stress, non-traditional water sources are progressively gaining importance, especially in the Middle East and North Africa (ibid.). Water desalination is already substantially increasing the energy demand in the MENA region (Delgado et al. 2017). While the water sector accounts for about 4 percent of world electricity consumption, in the Middle East it already accounts for 9 percent, with a quarter of water-related energy consumption being attributable to desalination (OECD/IEA 2016).

In the future, the share of non-traditional water from desalination in the overall water supply is expected to increase significantly. Accordingly, the electricity demand for desalination is also expected to increase. Today, 5 percent of the electricity consumed by the water sector is used for desalination. Projections by the International Energy Agency (OECD/IEA 2016) indicate that the share of electricity consumed by desalination will quadruple to more than 20 percent by 2040. Today, about 30 terawatt hours of electricity are used, worldwide, for desalination; in 2040, it is projected that, depending on the scenario, 295 to 345 terawatt hours will be consumed for desalination. By 2040, the lion's share of 250 terawatt hours of electricity is expected to be used for desalination in the Middle East and North Africa (ibid.). The increasing energy demand for desalination must be considered when analysing current and future water demand for energy generation. Moreover, in countries with high shares of desalination, one must also consider the extent to which water constraints affecting energy security may also, indirectly, affect the future supply of non-traditional water resources.

2.3 Climate Change and Its Effects on Water-Related Risks to Energy Security

In addition to increased demand for water in all sectors, the impacts of climate change are expected to put further pressure on water resources worldwide. The main climate-related drivers influencing water availability are precipitation, temperature and evaporative levels (Bates et al. 2008). Potential negative impacts from future changes in precipitation, temperature and evaporative levels include increased frequency and duration of droughts and floods, decreased water quality (due to higher water temperatures), longer periods of low flows and increased erosion and sedimentation levels (ibid.). Although it is expected that changes in climate and weather will affect all regions of the globe, the degree to which different regions and countries are impacted will vary significantly.

As one of the most water-stressed regions in the world today, the Middle East and North Africa is projected to be among the regions most severely impacted by the negative effects of climate change, namely increased aridity and higher temperatures (IPCC 1997). It has been projected that the annual water discharge in the MENA region, which is already critically low, will drop by another 15–45 percent in a 2 degree Celsius warmer world (and by 75 percent in a 4 degree Celsius warmer world) (Lelieveld et al. 2016). In addition, climate change projections foresee heat extremes with higher maximum temperatures during the hottest days (e. g., a rise from today's baseline of 43 degrees Celsius to about 46 degrees Celsius by mid-century, and almost 50 degrees Celsius by the end of the century) (Waha et al. 2017). Such challenges will put the region's future ability to provide water to its population, and to its different economic sectors, to the test (World Bank 2018).

Accordingly, reduced water availability has been named by the International Energy Agency (OECD/IEA 2015) as one of the major climate change-related risks to the energy sector, not only in the MENA region, but worldwide. Most energy systems are sensitive in terms of both the amounts and quality of the water they require (IRENA 2015). Reduced water availability, as well as changes in temperature, volume flow rates and water density can have substantial effects on energy systems. This is especially the case for the electricity sector. Hydropower production can, for example, be affected by decreasing water levels, low flow rates and reservoir sedimentation. Thermal power plants, which need large amounts of water for cooling, can likewise be affected by reduced water availability and higher water temperatures, which can reduce cooling efficiency and lead to increased cooling water demand (OECD/IEA 2015). The cultivation of feedstock to produce biofuels could also be negatively impacted by reduced water availability, as could fossil fuel production, given the fact that extraction and processing of fossil fuels, such as oil products and natural gas, require large amounts of water (ibid.). It should be noted that nearly all onshore oil reserves in the Middle East are located in areas at risk of water scarcity (SBC 2014).

Water availability is not only a concern for the future of the energy sector. Limitations in water supply are already restricting the development and operation of conventional and renewable energy sources (SBC 2014). In the United States, for example, limited water availability due to droughts constrained the operation of power plants and other energy production activities in 2012 (DOE 2014). In 2015, droughts in Brazil restricted hydropower production, necessitating a switch to back-up fossil-fuelled power generation (OECD/IEA 2015). In France, one third of nuclear capacity was offline in 2009 because of high water temperatures; in 2015, heat waves led to a lack of cooling water, and the consequent reduction of thermal power generation in several European countries (Fernández-Blanco et al. 2017). In the same year, a coal-fired power plant in India had to be shut down due to water shortages, which also caused the commissioning of a new unit at the same plant to be postponed (PEI 2015). These examples show that – worldwide – water limitations have already constrained power generation and capacity expansions. With water-related risk to energy supply and electricity generation expected to increase, we need to assess how these developments might affect energy security on both the national and international levels, not only in terms of existing energy systems, but future energy infrastructure developments as well.

2.4 The Water-Energy Nexus and the Agricultural and Food Sector

Despite the increased demand for water, and coinciding decline of both water availability and water quality worldwide, the energy system is not the major consumer of water. Globally, the agricultural sector is the sector with the highest water requirements, accounting for about 70 percent of all freshwater withdrawals worldwide (FAO 2016a). The agricultural and food sector also accounts for about 30 percent of global energy demand (FAO 2014). This demand is only projected to increase, as roughly 60 percent more food must be produced by 2050 to meet the growing global demand (ibid.). Accordingly, the nexus debate is often extended from water and energy to the agricultural and food sector (Water-Energy-Food Nexus). While focusing on the water-for-energy link in the nexus, the water requirements of the agriculture and food sector need to be taken into account, as allocation of water resources to the energy sector can result in an increase of water security-related risks in other sectors (IRENA 2015). Thus, the aim should be to avoid trade-offs and potential conflicts over water between the energy and food sector, wherever possible. However, given diminishing water resources, governments (especially in regions affected by water scarcity) will likely have to com-promise between water, energy and food security (ibid.).

This will likely also be the case in Iran, where the agricultural sector is, by far, the largest and least efficient consumer of water (FAO 2016b). As water becomes a scarce resource, the extensive water use for farming is having direct consequences for other sectors, including the energy sector. Measures taken in the agricultural sector to reduce the pressure on the country's water resources could therefore also help mitigate some of the water-related risks to and impacts on other sectors. Nevertheless, the energy sector should also actively seek solutions to reduce its own water consumption, to help ensure energy security and improve the overall water situation in Iran.

3. The Water-Energy Nexus in the Islamic Republic of Iran – An Analysis of the Status Quo

The public awareness of water scarcity in Iran has significantly increased in recent years. Since the beginning of 2018, the topic has garnered more attention in the public debate, due to the challenges that are increasingly being felt as a consequence of water shortage in the country. Declining water levels in various lakes and wetlands, such as Lake Urmia, are frequently discussed. Although this year, at lake Urmia, there have been initial signs of recovery, the water levels of this important water body have been falling for over 20 years (Jalili et al. 2016). Climate change and increasing water demand from the agricultural sector have further worsened the situation. Those worst affected by this trend are local farmers, as disruption of the water supply directly affects their livelihoods. This is not only the case for those farmers who depend on water from lake Urmia. It is an overarching development, as over 90 percent of the annual water withdrawal in Iran is used by the agricultural sector for irrigation and livestock farming. The agricultural sector is the major water consumer in Iran, and consequently, the sector most affected by water stress. Accordingly, the link between water and agriculture in Iran is, and has already been, widely discussed.

Compared to the agricultural sector, the share of water consumed by the energy sector is much lower. Yet, this year, the shortage of water has already affected the electricity supply in Iran. With decreasing water resource availability, aspects of energy security and water allocation will become even more important in the near future. This is especially true given the fact that Iranian energy demand – particularly the demand for electricity – is expected to increase significantly from 253 terawatt hours in 2016 to over 350 terawatt hours in 2040 (OECD/IEA 2018; Azadi et al. 2017). The growing electricity demand has various causes, some of which relate to the region's changing climate; increasing temperatures, for example, can result in a growing electricity demand for cooling. In turn, the growing electricity demand drives the demand for water in the power sector. Meanwhile, the supply of unconventional water through energy-intensive seawater desalination techniques, or waste water recovery methods, is expected to stimulate de-mand for electricity in the water sector. All these different driving forces fuel the demand for electricity, generating a surge in water demand for electricity generation. Such interdependencies will likely lead to new dynamics in the Iranian water-energy nexus.

As energy is fundamental for social and economic development, increasing disruptions and rising costs are critical. By strengthening awareness of the inter-linkage between the Iranian energy and water systems, trade-offs might be considered in decision-making processes today, in order to avert any future lock-in effects and adverse impacts on the Iranian economy and population. In particular, renewable energies like wind and photovoltaic hardly require any water resources to operate, and could furthermore support the creation of local employment in affected areas. Such aspects should be considered today, when making decisions regarding future energy infrastructures.

3.1 Iran's Energy Sector and Resulting Implications for Water Demand

The Islamic Republic of Iran is rich in energy sources, and a net energy exporter. Iran has the fourth-largest proven oil reserves, and the second-largest proven natural gas reserves, in the world (IEA 2017). Accordingly, the oil and gas industry plays a key role in the country's economy, and contributes significantly to Iran's financial revenues. On the demand side, the country has experienced a very rapid increase in domestic energy demand in the last decades, due not only to high population growth, increased urbanisation and changing consumer habits, but also to subsidy-induced overuse and high inefficiencies in energy production, transport and consumption (Moshiri and Lechtenböhmer 2015). Currently, more than 95 percent of Iran's gas production is used domestically (IEA 2018a). Despite the country's large fossil fuel resource deposits, the continuous increase in domestic energy demand could reduce the country's future capacity to export fossil fuels. Such a development would be critical for the Iranian economy, which is strongly dependent on fossil fuel exports.

In order to limit wasteful energy use and slow demand growth, reforming the domestic energy market has been central on the political agenda; over the last two decades, the country has pursued a range of energy subsidy reforms. But state-controlled electricity prices remain low, in large part due to extreme inflation, making the modernization of the energy sector and extensions to capacity challenging. In addition to domestic difficulties, Iran's energy sector has also been affected by international sanctions. As a result, current energy production falls short of the country's potential (Ahmadi 2018). In particular, Iran's crude oil production declined during the previous period of international sanctions, but quickly recovered, in 2016, with the implementation of the JCPOA (IEA 2018b; FES 2017). Natural gas production, on the other hand, was not affected in the same way by the previous sanctions (IEA 2018a). Today, growth is already slowing because of the second round of economic sanctions, put in place by the USA against the Iranian oil industry, which come into effect in November 2018. These sanctions adversely affect both technology investments and trade, placing severe constraints on necessary investments, and limiting the country's ability to import renewable energy and water-conserving technologies. This lack of access to technologies and financing hinders the energy sector's modernization efforts, and indirectly affects that sector's future water de-mand.

Iran is among the countries with the highest amounts of water used in the energy sector (Spang et al. 2014). Water demand in the energy sector comprises water consumption and withdrawal in both the primary energy sector and electricity sector. The former includes the exploration and processing of fossil fuel resources, such as crude oil and natural gas.

Primary Energy Production

In Iran, the major share of water consumed by the energy sector is utilized in primary energy production (Spang et al. 2014). Crude oil exploration and processing is especially water-intensive (on average, water consumption in oil exploration ranges from 15–78 cubic meters per terajoule; in crude oil refinement the average is 16 cubic meters per terajoule); in conventional gas production, water consumption is generally lower (on average, 1.6 cubic meters per terajoule) (OECD/IEA 2016; Williams and Simmons 2013; Wu et al. 2009). Accordingly, in the Iranian energy sector, most water consumed for fossil fuel extraction and processing is used in crude oil production and oil refining (Spang et al. 2014). Crude oil recovery can be differentiated between primary, secondary and enhanced oil recovery (EOR). Usually, these methods are applied in stages, beginning with primary and secondary extraction. Only once these methods are exhausted, do EOR methods come into consideration. Today, only a minor part of crude oil production still belongs to primary recovery, which is less water intensive. The prevailing secondary recovery methods and enhanced oil recovery (which comprises a number of different methods) are, by contrast, more water-intensive (Wu et al. 2009).

In 2017, Iran's crude oil production stood at about 3.86 million barrels per day (OPEC 2018). Since the lifting of sanctions in 2016, over half of Iran's crude oil production (56 percent) is exported (IEA 2018b). In the future, it may be expected that the water demand for crude oil production will further increase. To date, many Iranian oil fields have already been exploited for decades, and have high decline rates (Azadi et al. 2017). To sustain its crude oil production capacities in the future, Iran will have to employ more water-intensive EOR technologies. By contrast to oil, Iran's natural gas production is almost completely used domestically (IEA 2018a). At 44 percent, the highest share of gas is used in industry (including fuel and feedstock use in the petrochemical industry), followed by residential electricity and heat generation (42 percent) (MOE 2017).

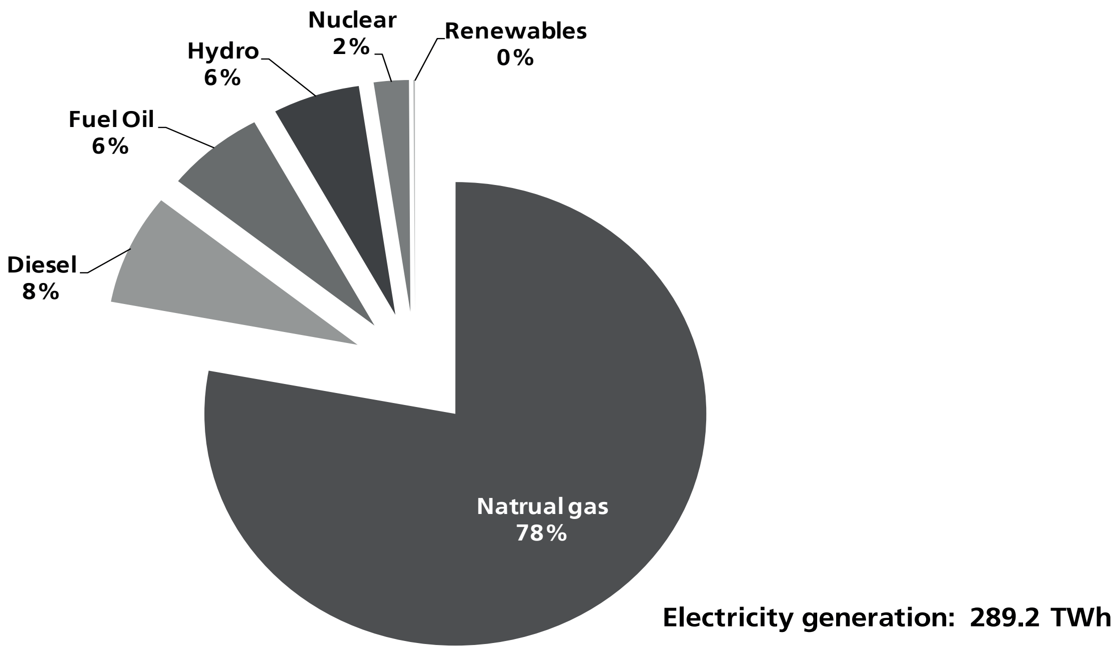
Electricity Generation

With about 78 percent of Iran's electricity generated from natural gas, in 2016, gas is the dominant fuel type in the Iranian electricity sector, followed by diesel-oil (8 percent), fuel-oil (6 percent), hydro (6 percent), nuclear (2 percent) and renewables (0.1 percent) (Fig. 3). Apart from hydropower (11,278 megawatts installed capacity), renewable energies still play a minor role in the Iranian electricity system. The dominant share of the electricity generation portfolio belongs to fossil fuel fired steam, gas and combined cycle power plants (52,391 megawatts). By the end of 2015, Iran had produced 86,968 gigawatt hours of electricity based on steam power plants, 75,423 gigawatt hours based on gas power plants, and 100,936 gigawatt hours based on combined cycle power plants (MOE/Tavanir 2016).

By comparison, water withdrawal and consumption in Iran's electricity sector is much lower than water demand for primary energy generation (Spang et al. 2014). Nevertheless, water is becoming a critical factor for the power sector, which is already facing occasional blackouts during peak demand periods, due to water shortages (especially in the summer time). With the major share of electricity in Iran generated by water-intensive thermal power plants, most of the water is used for cooling systems. The type of cooling systems installed significantly influence water withdrawal and consumption. Classical cooling systems include once-through cooling systems, closed-loop (or wet-recirculating systems, e.g., cooling tower systems) and dry-cooling systems. In particular, once-through cooling systems are very water intensive, as are cooling towers. Only the later, dry-cooling, systems need almost no water for cooling purposes, although they generate lower plant efficiencies. In Iran, regulations are already in place that require new power plants to use dry-cooling systems. To date, however, the Iranian power sector is still characterized by aging and inefficient power infrastructures, with a high number of water-intensive cooling systems.

Notwithstanding the country's increasing water challenges, water aspects' relation to electricity generation technologies are, with the exception of hydropower, rarely discussed. Shrinking water resources, decreasing precipitation and higher temperatures have already resulted in declining electricity outputs, due to lower levels of saved water in dams. At the same time, the govern-

Figure 3. Shares of electricity generation in Iran by source 2016



Source: Jorli et al. 2017 based on Tavenir 2017

ment plans to expand Iran's electricity generation capacities to meet the fast-paced growth in demand, and to increase its exports. In 2015, a total electricity generation capacity of 74,103 megawatts was installed, which already represents a 20 percent increase over 2010 (MOE/Tavanir 2016). With further expansions planned, this is a critical time to ensure that the most efficient and effective pathways for electricity generation and water use are chosen, with an eye to preventing future technological lock-in effects. One promising option to reduce the water-intensity in the electricity sector could be the expansion of renewable energies like solar photovoltaic (19 cubic meters per terajoule) or wind (0.2 cubic meters per terajoule). The operation of solar PV and wind power plants is, by far, less water-intensive compared to thermal power generation based on fossil fuels (the average water con-sumption thermal electricity generation with oil is 485 cubic meters per terajoule; with gas, 267 cubic meters per terajoule) (Mekonnen et al. 2015). Moreover, for solar and water energy sources, water consumption for the fuel supply is nonexistent. In any case, water-related risks and impacts to the power sector ought to be placed high on the country's power sector modernization and capacity expansion agenda.

3.2 The Challenging Water Situation in Iran

With a water crisis looming, the power sector is well-advised to become less reliant on water. Water stress levels in Iran are anticipated to increase significantly in the coming decades (Luck et al. 2015). While Iran has a more advanced water management system than most countries in the region, and a long tradition of innovative water management reaching back to the ancient Persians, water shortage has become a serious issue for the country (Madani 2014). The reasons for the intensifying water challenges in Iran are manifold; though some are periodic, or repairable (like summer droughts, or damaged pipes), other drivers are structural and long-term. On the one hand, rapid population growth and socio-economic development have fuelled water demand in the last decades. On the other, inefficiency and mismanagement (particularly in the agricultural sector) have contributed to current water difficulties.

The agricultural sector in Iran relies heavily on irrigation, and consumes over 90 percent of the country's limited water resources (Madani 2014). Inefficient water use in this sector was encouraged by high subsidies for water and energy, which were granted to achieve the nation's goal of food self-sufficiency – a high priority on the Iranian political agenda for decades (ibid.). International sanctions have also played a role, preventing the necessary investment in essential infrastructures, in both the water and agricultural sectors (Beevor 2018).

These structural weaknesses are aggravated by ecological factors. The country has been experiencing severe droughts for several years. In the future, this trend is expected to continue, due to climate change. Annual precipitation is expected to decrease, and temperatures to increase, making the already mostly arid and semi-arid country even drier and warmer (Amiri and Eslamian 2010). As a result, the level of water stress in most areas of the country will increase to a very high level (Luck et al. 2015).

Today, lakes and rivers are drying, and groundwater resources are declining. Iran currently uses more than 80 percent of its renewable freshwater resources, although international standards recommend the use of no more than 40 percent, to ensure environmental sustainability (Fanack 2017). In the last 50 years, water availability per capita has drastically decreased, from over 4,800 cubic meters in 1970, to about 1,640 cubic meters in 2014 (FAO, 2016b). And yet, at an average of 250 liters per day per capita, water consumption remains twice as high as the world average (Madani 2014). If the country's current and future water demands are to be met, far-reaching measures will have to be taken, including the reduction of water use inefficiencies in the agricultural sector, the reduction of household water consumption and a commitment to the protection of both surface and groundwater sources. In addition, desalination of seawater and re-use of waste water are being considered as emerging solutions to the country's growing water demand gap.

3.3 Growing Energy Requirements for Water Desalination in Iran

Seawater desalination is a promising future strategy to overcome water gaps, as the method has the capacity to make seawater suitable for potable use at large scale. However, seawater desalination is a very energy-intensive process, and its large-scale application will result in increased energy demand. Today, only about 1 percent of global water demand is met by desalination, and yet, it already accounts for roughly one quarter of the total energy consumption in the water sector (OECD/IEA 2016). By 2040, desalination capacities worldwide are projected to quadruple, and will account for 60 percent of the water sector's energy consumption (ibid.). Particularly in the Middle East, desalination capacities are expected to increase significantly, accounting for over 10 percent of final energy consumption in the region by 2040 (ibid.).

Today, about 73 desalination plants are operating in Iran, with a capacity to treat 420,000 cubic meters of saline water per day, or 148 million cubic meters per year (Financial Tribune 2018). Though in 2004, the desalination plant size in Iran ranged between 100 and 10,000 cubic meters per day (Madaeni and Ghanei 2004), plant sizes have since evolved. This year, the construction of a desalination complex with a total capacity of 1,000,000 cubic meters per day began in Bandar Abbas (DesalData 2018). To meet the electricity demand of these desalination facilities, a power plant with a 300-400 megawatt capacity will be built.

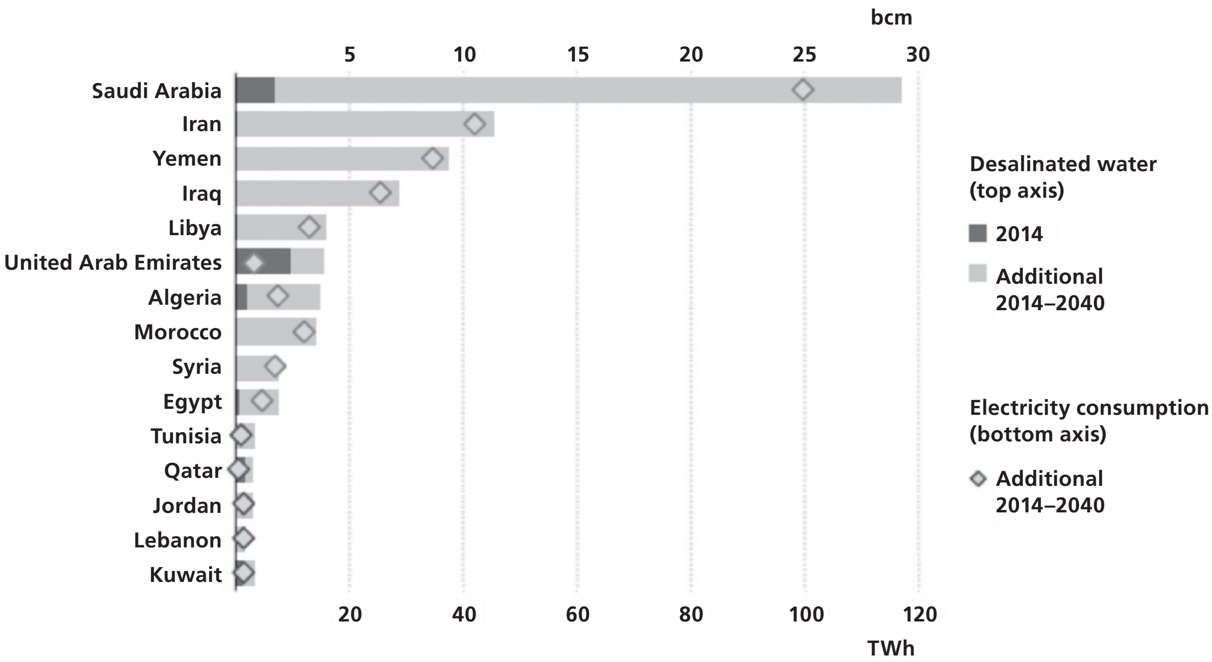
In keeping with its current increase in desalination capacity, Iran is ranked second among all MENA countries in terms of future planned installation of additional desalination capacities. By 2040, Iran's water desalination capacity is expected to increase to over 10 billion cubic meters. This will require more than 40 terawatt hours of electricity. (Fig. 4)

Today, desalination in Iran is predominantly powered by fossil fuels; planned capacity expansions likewise focus on conventional fossil fuel power plants as sources of electricity. However, studies have shown that desalination plants in Iran could also be cost-effectively powered by renewable energy systems, which could significantly increase the sustainability of the country's desalination efforts (Caldera et al. 2016).

4. Identification of Water-Related Risks and Potential Impacts on the Iranian Power Sector

This chapter presents and discusses water-related risks to and potential impacts on the Iranian power sector. In a first step, water-related risks to the Iranian power sector were debated by experts from research institutions and ministries at an interdisciplinary workshop in Tehran, in

Figure 4. Additional desalination capacity and electricity demand in the MENA region, 2014–2040



Source: OECD/IEA 2016.

September 2018. There, experts evaluated the identified risks with regard to the level of risk they posed for the Iranian power sector, and the timeframe in which those risks are expected to occur. In a second step, potential impacts stemming from the identified water-related risks were discussed individually with Iranian stakeholders, and evaluated according to their current and future relevance for the Iranian power system. Both the results of the evaluation of water-related risks and the assessment of associated impacts on the Iranian power sector were subsequently analysed, to identify future research needs with respect to the Iranian water-energy nexus.

4.1 Water-Related Risks to the Iranian Power Sector

Most electricity generation technologies need water for cooling, steam turbines, cleaning processes and power plant operation. The amount of water required by different types of electricity generation technologies varies. Today, the majority of power plants worldwide (including thermal and hydropower) are water-intensive power plants. Limitations on water availability and quality can challenge the reliability of current electricity generation, as well as the feasibility and sustainability of future power sector extensions.

In Iran, electricity generation relies primarily on thermal power plants (at over 92 percent of electricity generation), including a higher share of older power plants with water-intensive wet-cooling technologies. In addition, Iran also generates electricity with a number of water-reliant hydropower plants (5.7 percent of electricity generation) (Jorli et al. 2017). This water dependence makes the Iranian power sector vulnerable to water constraints such as drought, precipitation changes and competition over water resources with other sectors – such as the agricultural, industrial and residential sectors. The main risks for the power sector stemming from these constraints include decreasing water availability, seasonal variability of water availability, changes in water quality, changes in water temperature, sea level rise and regulatory uncertainty (Box 1).

A group of Iranian experts was consulted to better evaluate these water-related risks to the Iranian electricity sector. The experts were asked to assess the six water-

Box 1: Water-Related Risks to the Power Sector

- **Decreasing water availability:** Thermal and hydropower plants have high water requirements, and are therefore vulnerable to decreasing water availability. Decreased water availability can negatively affect power plants to varying degrees, resulting in efficiency reductions, capacity cutbacks or even power plant shutdowns. Water availability is a growing concern with respect to meeting future power generation needs.

- **Seasonal variability of water availability:** In most regions, water availability varies throughout the year. This seasonal variability can result in periods in which water resources are insufficient to meet demand, as well as in other periods in which high volumes of water pose a risk to power generation. For example, rapid snowmelt in spring can overload reservoirs, or lead to floods, endangering power plants on riversides. This can result in springtime electricity losses, and inadequate water supply for electricity generation in summer.

- **Changes in water quality:** The quality of water can affect a power plant's operation at both the water intake and water discharge sides. For example, changes in water quality at the intake can lead to increased levels of scaling, corrosion and/or biological growth, which can reduce the efficiency and longevity of cooling systems. Poor quality of the discharge water can adversely affect the ecosystem, if not adequately managed and regulated. In cases where the discharge water requirements cannot be met, the operation of the power plant may be compromised.

- **Changes in water temperature:** An increase in water temperature can reduce cooling efficiency and increase the cooling water demand, negatively impacting power plant operation and electricity generation. Higher temperatures in the discharge water can make it difficult to meet river temperature regulations, which usually require discharge water temperatures to stay below a certain threshold, to protect the ecosystem.

- **Sea level rise:** As a result of global warming, rising sea levels could impact coastal power generation infrastructures. Besides flooding, sea-level rise can also result in saltwater contamination of freshwater sources, while higher salinity may pose problems for power plant operation.

- **Regulatory uncertainty:** Regulatory restrictions may be imposed on water use for electricity generation. Areas of concern are uncertainty regarding future regulatory changes – for example with respect to water prices, or water quality requirements – as well as potential conflicts resulting from water issues.

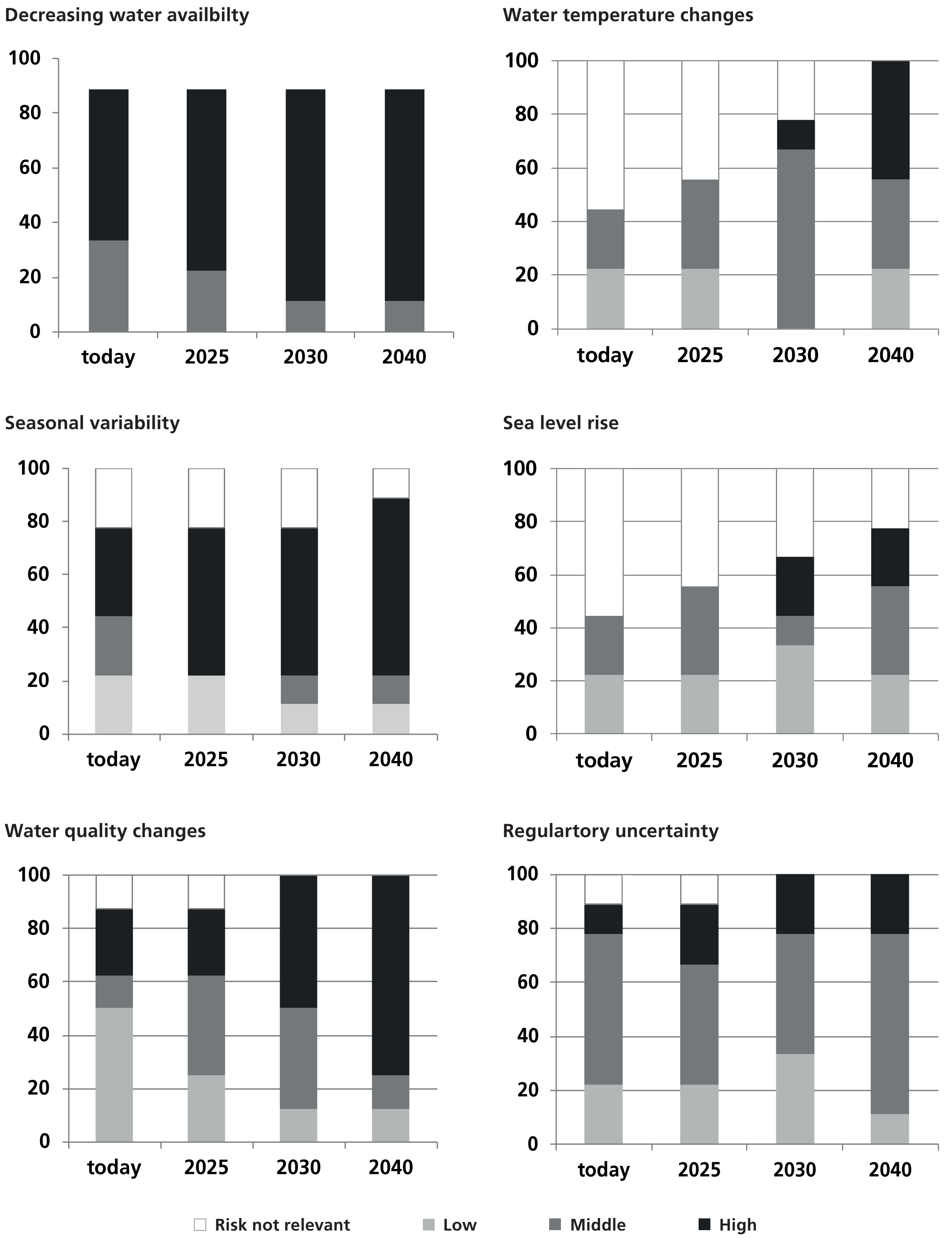
Sources: IRENA/WRI 2018; Rodriguez 2016; World Bank 2014; Gassert 2014; Chien et a. 2013; Feeley et al. 2008

related risks (Box 1) in regard to the level of risk they pose to the Iranian power sector (low/medium/high), and the timeframe in which they expect that risk to occur. The results of this water-related risk assessment are presented in Figure 5. It should be noted that the following overview is just a snapshot of the participating experts' opinions; though it provides initial insights, it should not be taken as representative statements.

The overall assessment of water-related risks to the Iranian power sector reveals that all six predefined risks are either already relevant today, or anticipated to become relevant in the future. In the next two decades, the risk levels of decreased water availability, seasonal variability and changes in water quality are expected to be particularly high. Water temperature changes and sea level rise, on the other hand, are currently envisaged to be of only limited relevance to the electricity sector; by 2040, however, experts anticipate these risk levels to noticeably increase. The following summarizes the expert assessments of the individual risks:

- **Decreasing water availability:** All experts agree that decreased water availability is already a very significant risk to power generation in Iran. All experts rated the risk of »decreasing water availability« as

Figure 5. Evaluation of water-related risks to the electricity sector in Iran today and in the future by Iranian experts



having medium to high relevance, today. In the next 5, 10 and 20 years, experts expect the risks to the power sector stemming from decreased water availability to further increase.

- **Seasonal variability:** Next to the overall decrease in water availability, the seasonal variability of water also poses risks to the energy sector. The majority of experts consulted consider this risk as already relevant to the Iranian power sector, today. A number of experts classified the current risk level as already high, while others assessed the current risk to be of low or medium relevance, but likely to grow over time. By 2040, the majority of experts rated the risk of »varying water availability« to potentially be high.

- **Changes in water quality:** The majority of experts surveyed think that changes in water quality are currently either irrelevant, or of only low relevance to the Iranian power sector. Only a small number of experts classified the risk stemming from changes in water quality to be high today; looking to the future, however, experts expect the risk to become increasingly relevant by 2040. From 2030 onwards, all experts supported the assumption that decreased water quality will pose a risk to power generation; by 2040, the majority of experts anticipate that risk to be high.

- **Changes in water temperature:** By comparison to the other water-related challenges, the Iranian experts rated the risk of changes in water temperature as either irrelevant, or of only low to medium relevance for the power sector today. The future risk assessment, however, clearly showed that rising water temperatures entail increasing risk levels for Iranian power generation. By 2040, all experts anticipated that rising water temperature would constitute a risk to the Iranian power sector; the majority classified that risk as medium to high.

- **Sea level rise:** Only a few experts estimated the risks associated with sea level rise to be relevant to the Iranian power sector today. However, by 2040, more experts envision rising sea levels to be a relevant risk to the power sector, and they anticipate the risk level to increase with time.

- **Regulatory uncertainty:** Yet another potential water-related risk to the power sector is regulatory uncertainty, for example, with respect to the share and amount of water available to the power sector, or the future price of water. The experts' discussion frequently addressed the topic of water distribution between sectors, especially the levels of water use in the agricultural sector, which is much higher than water use for electricity generation. But, as the Iranian power sector remains predominantly state-controlled, the majority of experts expect the risks of regulatory uncertainty to be manageable. Nonetheless, the relevance of regulatory uncertainty with respect to water for the Iranian power sector is expected to increase over the next two decades.

In addition to these six, predefined, general water-related risks, the experts also identified further risks for the Iranian power sector, which may also affect the sector's water withdrawal and consumption. One factor mentioned as a risk to the electricity sector's water consumption was the limited availability of modern power generation technology in Iran. Limited access to modern technologies is closely related to both the previous and current (November 2018) rounds of trade sanctions. Other risks highlighted by the expert discussion were the environmental risks stemming from discharge water, in terms of both thermal, and other varieties of pollution. In this context, the risks to water quality from primary fossil fuel production were also mentioned as relevant. Oil spills, as a cause of water pollution, could also affect the intake water quality for cooling in thermal power plants. Finally, one water-related risk that was highlighted by several experts was the geopolitical risk to Iran's water supply. With the sources of some relevant water bodies located in neighbouring countries, the supply of water can be strongly influenced by these nations' water politics.

4.2 Potential Impacts of Water-Related Risk on the Iranian Energy Sector

In addition to their assessment of water-related risks, experts also discussed potential risk-related impacts on the Iranian power sector. On the supply side, water stress can impact current power generation in the form of either decreased electricity generation, or reduced efficiency levels. Planning and development of future power infrastructures may also be affected by water issues. On the demand side, water-related risks to the power sector might reach electricity consumers in the form of increased electricity prices, or unreliability of supply. This could potentially have larger societal effects, for example, in the form of public discontent, or even protests (Box 2).

Water stress is already significantly impacting Iran's electricity generation infrastructure, which is overly reliant on thermal and hydropower plants. Correspondingly, all experts agreed that decreased power generation and reduced cooling efficiency have already occurred. They likewise agreed that decreased power generation will surely continue to occur, while reduced cooling efficiency will likely remain an issue for the power sector. Decreased power generation is expected to have major consequences. Reduced cooling efficiency, on the other hand, is seen as less critical, and likely to result in only minor operational consequences for power plants. With regard to the geographic extent of such impacts, decreased power generation is expected to affect the national level, while reduced cooling efficiency is expected to occur mainly locally.

Box 2: Potential Impacts of Water-Related Risks to the Power Sector

- **Power Generation**
  - Decreased power generation, or e ven power plant shutdowns (e. g., due to limited availability of cooling water during heat waves)
  - Reduced cooling efficiency due to higher water temperatures
  - Financial losses for power generation companies
- **Electricity consumers**
  - Reduced reliability of power supply, electricity shortages or even blackouts
  - Higher electricity prices (due, e. g., to the possibility of economic pricing of water, leading to higher energy production costs, or reliance on more expensive forms of generation)
- **New electricity infrastructure**
  - Permits to locate power plants denied
  - Energy infrastructure investments suspended
- **Society**
  - Social and political discontent (e. g., conflicts with local communities over access to water)

Sources: World Bank 2014; PWC 2011

Decreased power generation and lower efficiency may result in financial losses for power generation companies. This potential impact was evaluated differently from expert to expert. One the one hand, it was observed that financial losses were irrelevant, as the state owns most of the power infrastructure, and could therefore cover potential losses, provided Iran continues to receive oil export revenue. On the other hand, some experts saw these losses as problematic, if not for the generation companies, than for Iran as a country. They expected financial losses to be most likely, and to have potentially major consequences on the national level.

In regard to the effects of water stress on the planning and development of new power sector infrastructures, experts observed that impacts have already occurred, or will occur in the near future, but that permits to locate power plants were not likely to be denied, nor energy infrastructure investments suspended. Instead, they expected planning and investment to shift (as it already is) to other locations, for example, to areas in southern Iran with lower water stress levels. This impact was estimated as of potentially great consequence, mainly on the district and provincial levels, but not on a national scale.

Regarding impacts on energy consumers, water shortage has already affected Iranian electricity supply. This spring, the country's energy minister, Reza Ardakanian, warned that summer power outages were inevitable across Iran, if electricity consumption was not decreased (Radio Farda, April 9, 2018). Likewise, the Iranian experts agreed that unreliable electricity supply has al-ready resulted from water scarcity in Iran. The probability that this impact will continue to occur was rated to be most likely, while the severity of the impact was estimated to be moderate to major. The impact is expected to affect the local level up to the national level.

The potential for higher electricity prices due to water-related risks was evaluated differently from expert to expert. While some saw the probability of this impact as unlikely, because electricity prices are stipulated by the government, others were certain that an increase would occur in the future. The experts agreed, however, that if it did occur, it would have at least minor to moderate consequences on the national level.

In terms of its effects on society, access to water and water allocation can be sources of tension, either within or between states (OECD 2005). In Iran, water shortages have already resulted in dissatisfaction, and minor protests, as was the case in the southwestern provinces, in mid-2018. Electricity shortage can likewise be a source of tension. Accordingly, the experts anticipated that this impact has already occurred, and will most likely continue to occur, with the potential for major consequences, mainly on the district and provincial levels, but also on the national level.

This impact assessment shows that all impacts were evaluated as either having already occurred, or as likely to occur in the near future. Overall, the severity of the impacts was estimated to be moderate to major, but in most cases, not yet critical. In terms of the impacts' geographic scope, the picture is mixed; some impacts (like reduced cooling efficiency, or effects on the development of new power infrastructures) are expected to occur mainly locally, while others (like decreased power generation, or higher electricity prices) are expected to have effects on all scales, up to the national level.

Beyond these predefined impacts, the experts discussed further potential water-induced impacts on the power sector. One potentially positive impact highlighted was the prospect that renewable energy technologies, like wind and photovoltaic, might be more seriously considered, as such technologies use only very little water. Another physical impact which was raised – although potentially relevant only at the local level – was that water extraction from groundwater wells may destabilize the ground on which the power infrastructures are located. And, while the Minister of Energy, Reza Ardakanian, issued assurances that Iran's water and power industries will not be directly affected by the re-imposed US sanctions (Mehrnews, June 1, 2018), limited access to technology – including renewable energy and water-saving technologies – was seen as posing a potential challenge to the electricity sector's efforts to meet the country's rapidly growing electricity demand.

5. Discussion and Outlook

The share of water consumed by the Iranian power sector is low by comparison to the amount of water used in the energy sector as a whole, and even lower compared to the country's overall water consumption. Yet, even the power sector – which is growing quickly – contributes to, and is affected by, water stress. Our discussions with Iranian experts highlight the extent to which the power sector is already, currently, being affected by water-related risks. According to those experts, the majority of impacts – such as declining power generation, shifting locations of new electricity infrastructures or public discontent over energy and water issues – have already occurred, and are expected to gain relevance in coming years. In light of these findings, and of the political relevance of both water and energy security, one may conclude that, in Iran, the concept of the water-energy nexus is well understood. However, thus far, applications of and research on the concept remain limited, both in the energy sector, generally, and the power sector, in particular. And while both the energy and water sectors are coordinated by the same ministry, the Ministry of Energy and Water, the two sectors are, to a large extent, governed and regulated separately. Choices and decisions concerning electricity infrastructures made today will have decades-long effects on the level of water consumed by the power sector. At the same time, the level of water stress in Iran is expected to increase, potentially adversely affecting both electricity supply and water security. To avoid technology lock-in effects, and unfavourable impacts on the Iranian population and economy, the complexities of the water-energy nexus need to be explored in more detail. Based on the analysis, and the results of the expert evaluation of water-related risks and associated impacts on the Iranian power sector, the following research needs for the Iranian water-energy nexus can be identified:

- Water availability and electricity production are strongly site-specific, making geographical context a critical factor in risk and impact assessment. The water-energy nexus must, therefore, be assessed not only on a national level, but on a sub-national scale as well, to identify the areas in which water use for electricity generation will be most critical. Questions to be addressed include: What percentage of power plants are located in water-stressed locations?

What other water demands exist in the same locations? What are the drivers of local water demand? Is regional demand expected to increase? Is water availability expected to decrease, based on different climate scenarios, and how will this affect power generation? How does power plant water withdrawal and discharge affect local communities and the environment?

- Renewable energies (especially less water-intensive wind and solar photo-voltaic technologies) must be considered, specifically, in their capacity to reduce water demand, and therewith the water-related risks and impacts on the power sector. Expert discussions highlighted the fact that although solar and wind energy are regarded as beneficial, their advantages with respect to water have not yet been considered. Therefore, potential water savings compared to conventional power infrastructure developments should be quantified for different energy scenarios. To compare fossil-fuel and renewable power technologies, new holistic decision-making instruments are needed, which integrate economic, socio-economic, environmental and social aspects in the decision-making process (multi-criteria approaches).

- In regard to the expansion of renewable energy generation, the consequences of the US sanctions against the Iranian economy should also be considered. With the exception of smaller-scale wind turbines, Iran depends on technology imports for renewable energy technology. Experts regarded this as a major barrier for the wider deployment of renewables in Iran.

- To better evaluate the consequences of water use in the energy sector, the external costs of water use in Iran should be analysed. According to the experts, thus far, only the negative consequences of emissions are regarded as environmental costs.

- Planned and future implementations of improved power plant cooling technologies should be analysed, in combination and comparison with renewable energy technologies, and with a focus on costs and environmental impacts. Some of the experts stressed that although improved power plant cooling suffices as an interim solution, it is not a sustainable pathway for the long-term future.

- Although water is already part of a criteria set for the planning of new power plant locations in Iran, future climate-induced changes in both water availability and quality, as well as competing uses (especially in the agricultural sector) have yet to be sufficiently considered. Given the rapidly increasing electricity demand in Iran, the expected expansion and modernization of the electricity infrastructure must take future water demand into consideration. To harmonize the development of energy and non-energy water demands, it would be necessary to analyse institutional set-ups and decision-making procedures, and to enable a dialogue between the different sectors (including the agricultural sector) aimed at integrating planning, and ensuring sustainable development. To enable a meaningful dialogue, political priorities, norms, perceptions and underlying normative assumptions must be reflected. This imperative was highlighted in an example given by one of the experts, who stated that, because electricity supply security takes top-priority for consumers, many in the sector (worried that modifications could negatively affect that supply security) are critical of, or even resistant to change.

- Self-reinforcing dynamics between future electricity demand in the production of unconventional water (desalination and waste-water reuse), and the associated water demand for power generation, need to be studied further, so that they can be taken into account in electricity and water infrastructure planning.

- Beyond the electricity sector, the much higher levels of water withdrawal and consumption in the production of primary energy carriers must be considered and quantified.

- Synthetic fuels offer an innovative means of transforming current fossil fuel-based industries into sustainable business models, as well as the opportunity to strengthen collaboration with Europe, and to open new export markets (as a countermeasure to the US' withdrawal from the JCPOA, and as a joint EU-Iran Collaboration Program). The effects of such developments on water demand in the energy sector would need to be assessed and quantified.

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