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ABSTRACT

Climate change mitigation calls for energy systems minimising end-use demands, optimising the fuel efficiency of conversion systems, increasing the use of renewable energy sources and exploiting synergies wherever possible. In parallel, global fresh water resources are strained due to amongst others population and wealth increase and competitive water uses from agriculture and industry is causing many nations to turn to desalination technologies. This article investigates a Jordanian energy scenario with two different desalination technologies; reverse osmosis (RO) driven by electricity and Multi Stage Flash (MSF) desalination driven by Cogeneration of Heat and Power (CHP). The two systems impact the energy systems in different ways due to the technologies' particular characteristics. The systems are analyses in the energy systems analysis model EnergyPLAN to determine the impacts on energy system performance. Results indicate that RO and MSF are similar in fuel use. While there is no use of waste heat from condensing mode plants, efficiencies for CHP and MSF are not sufficiently good to results in lower fuel usage than RO. The Jordanian energy system is somewhat inflexible giving cause to Critical Excess Electricity Production (CEEP) even at relatively modest wind power penetrations. Here RO assists the energy system in decreasing CEEP – and even more if water storage is applied.

Keywords

Energy systems analysis,
EnergyPLAN,
desalination,
Jordan,
wind power

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1. Introduction

Jordan is a nearly land-locked country of approximately 89000 km^2 in the Middle East with a population of approximately 6.5 million [1]. The country is nearly 100 per cent dependent on imported fossil fuels (cf Section 4) affecting both security of supply, the balance of trade and contributing to the enhanced greenhouse effect. In terms of security of supply, the national energy strategy of Jordan [2] point out some challenges associated with the supply of natural gas and oil from neighbouring Iraq and Egypt.

In terms of water, the country may be characterised as being semi-arid desert, prone to drought and with fresh water resources being strained and with fresh water exploitation exceeding sustainable levels (cf section 5). Water use is particularly high in the agricultural sector, standing at 72 per cent of the water demand in 2005 [2].

As with many other countries with similar fresh water resource issues, Jordan is contemplating desalination as a means for providing adequate fresh water resources in the future, however desalination is associated with significant energy demands and will thus have an impact on Primary Energy Supply (PES).

In general, there are two main categories of desalination plants; plants based on distillation processes and plants based on RO. The former is primarily dependent on heat while the latter is dependent on a pressure difference – typically applied using electricity. The heat may be supplied from different technologies including purpose built boilers but also excess heat from thermal power generation

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(Cogeneration of Heat and Power (CHP) plants) and heat from solar collectors. From an energy systems perspective, these thus have different characteristics. Electricity use for desalination is typically grid-based and thus affects the energy systems as other large scale electricity demands.

In order to reduce the climate change impact of desalination, and to improve the balance of trade and security of supply, focus should be brought to energy efficient desalination which should optimally exploit locally available renewable energy sources.

Previous work has assessed potential renewable energy contributions in Jordan. Hrayshat found that "*Jordan has enormous underground energy resources*" in the form of geothermal energy in the 20° to 65° range [3]. Solar exploitation is limited in Jordan according to Hrayshat [4], though e.g. water pumping [5] and heating are areas with potentials. As Al Salaymeh et al also states, "*It is [..] unlikely that any future energy scenario for Jordan will not include a significant proportion of its energy to come from renewable sources such as solar energy*" [6]. Wind power has also been the centre of attention of a number of studies. Mohsen & Akash [7] investigated wind power for water pumping in different locations in Jordan, though finding only one to be "favourable". Habali et al [8], investigated the regional distribution of wind resources and the match between resource and utilisation in 2004, while Alsaad has made a more recent (2013) publication, locating and analysing four "promising locations" and finding a potential production of these sites of 18.9 TWh [9]. Abu-Ashour et al [10] have investigated and biomass resources and assessing a limited potential of 6.6 PJ including collection losses. Common for these examples of work is that they mainly are from a single-resource perspective.

In addition to a large body of literature on the technical aspects of desalination including reverse osmosis and thermal energy storage [11], solar desalination [12, 13] and combined power and desalination plants [14], and a substantial body of work specifically on desalination in Jordan investigating reverse osmosis of brackish ground water [15–17], solar-driven membrane desalination [18, 19] and the more general role of desalination in Jordan's water supply [15–23] there is some work probing into the energy – water connection mainly from a unit perspective [23, 24] and limited work putting the water – energy connection into a larger energy systems perspective [25]. In the last mentioned work, Novosel et al investigate the interesting prospects of a Red Sea – Dead Sea pipeline exploiting the height difference for power generation and the lower salt-contents of Red Sea water for desalination purposes. They find that such a system can provide fresh water while stopping the recession of the water level in the Dead Sea.

This article explores the field of energy systems impact of the water-energy connection even further with a focus on different technologies' effects on the energy system and the energy system dynamics.

The scope is thus to establish the energy system impacts of two different types of desalination technologies; electricity-based RO and CHP steam-based thermal desalination in terms of PES on thermal power generation plants and the adaptability of the energy system to integrate wind power measure in terms of Critical Excess Electricity Generation.

The article starts by describing the two mentioned desalination methods with a particular focus on their energy characteristics. Secondly, the EnergyPLAN model is introduced – with a particular section on the modelling of desalination systems in EnergyPLAN. Reference energy and water systems for Jordan are established, and scenarios for alternative water supply schemes are established. These are subsequently modelled in the EnergyPLAN model. Lastly, the three systems' energy performance and ability to integrate wind power is analysed.

2. Desalination methods

This section briefly outlines the mode of operation of the investigated desalination methods with a focus on their energy requirements in terms of energy source (electricity, steam at a given temperature, other) as well as in terms of per unit energy use (kWh electricity, MJ steam or other per cubic metre of desalinated water).

2.1. RO desalination

Desalination based on RO exploits the partial-pressure difference between a volume of fresh water and a volume of salt water. The partial pressure difference will inherently seek to equalize the salt concentration difference between the two bodies of water as long as the bodies of water are connected through a membrane permeable to water. Hence, in such a system, the salt water body will lower its salt concentration by attracting water from the other reservoir through the process of osmoses. In RO, an externally applied pressure changes the partial pressure and thus reverses the flow direction of water through the membrane, thus producing fresh water.

This process requires mechanical power and maybe be used in sizes ranging from hand-held emergency devices up to the Israeli plant at Ashkelon which is reported as being the world's largest [26] at 330,000 m^3/day [27] corresponding to approx. 120 M m^3/year.

The mechanical power is typically supplied as electricity, and the demand is potentially large. Peñata & Garcia-Rodriguez report electricity consumptions for state-of-the art applications of seawater RO desalination plants down to 1.8–2.2 kWh/m^3 [28] and more typical specific electricity demands in the range of 2.2–2.5 kWh/m^3 for actual medium and large scale plants.

The Energy Technology Systems Analysis Program (ETSAP) under the International Energy Agency (IEA) reports electricity demands from 3.5 to 5.0 kWh/m^3 for large scale RO [29].

2.2. MSF desalination

Most desalination plants in the word are based on thermal processes utilising the circumstance that water vapours are free from minerals – including salt – so inducing evaporation and subsequent condensation of water vapours result in desalinated water. Making the phase change is energy intensive, so different applications are applied to obtain the optimal performance. In MSF a series of stages involving vaporization and condensation follow one another make use of the condensing heat in heating up feed water.

Semiat reports heat demands for MSF of 55–80 kWh/m^3 plus electricity demands "claimed to be around" 1.2–4.5 kWh/m^3 [30] while reviewing and referencing work with a wider span from 25 to 120 kWh/m^3 plus electricity demands ranging from 2 to 5 kWh/m^3. As a review, the reporting does not detail systems boundaries or details of the quoted specific demands. For CHP–based MSF plants, electricity production drops due to the required temperature of the heat for the MSF plant, causing an indirect electricity consumption of 4-7 kWh/m^3 [30].

The ETSAP-IEA reports electricity demands in the 2.5 to 3.5 kWh/m^3 range for MSF plants plus an additional heat demand of 80.6 kWh/m^3 [29], which are both within the ranges reported by Semiat.

3. The EnergyPLAN model

The analyses of the energy system are carried out using the EnergyPLAN model, which is a model that has been used for regional, national and international energy systems analyses and energy scenario design, as well as for analyses of particular technologies within the energy systems.

3.1. Energy systems analyses in the EnergyPLAN model

The EnergyPLAN model is an analytically programmed, deterministic energy system's analysis model able to model entire energy systems with electricity, heat, cooling, transportation, and industrial fuel demands. The model has specifically been created to enable hourly analyses of energy systems characterised by different energy demands, production units that are either dispatchable or non-dispatchable, and complex correlations between the different energy units and between different energy demands – e.g. heat and electricity. The EnergyPLAN is documented in [31] and compared to other models in [32].

EnergyPLAN has been applied to numerous analyses including analyses of particular focal points in energy systems such as heat pumps [33–35], wind power [36, 37], CHP plants [38, 39], energy savings, transportation [40–42] as well as to more holistic work on scenario development for local areas [43–46], nations [47] or transnational regions. The model has also been applied to provide technology-specific production and consumption data for more detailed analyses of e.g. electric vehicle systems [48, 49] and transmission systems [39, 50–52] and has in a few instances been applied to systems with desalination [25, 53].

EnergyPLAN models one year in hourly steps based on a user-defined energy system composition with dispatchable production units characterised by efficiencies and installed capacities, non-dispatchable production units characterised by installed capacities, efficiencies (where relevant) and yearly distribution profiles with relative productions for each hour of a leap year; i.e. 8784 values.

Heat, electricity, and transportation demands are included as aggregate annual demands combined with hourly distribution profiles for an entire year to disaggregate demands to the hourly level.

The model has an endogenous priority of productions, giving highest priority to use-it or lose it technologies whether this is renewable energy technologies following a climatically given production profile, industrial surplus generation of heat and power or related hereto, electricity and heat production from waste incineration plants. Second follows CHP units due to their high total efficiency and lastly follows condensing mode power generation, in the case of electricity, or boilers, in the case of heat demands that needs to be covered. A number of technologies add flexibility to the system. Apart from the dispatchable production – and consumption – units, these include storage systems (including vehicle to grid technology), heat pumps, and electric heaters.

The model has two general approaches to optimising the modelled system; two so-called Regulation Strategies. In the one, the system is optimising its performance against an external electricity market, i.e. increasing production of electricity with export in mind when deemed economically attractive and conversely, decreasing production when this is deemed favourable. The other general approach consists of a number of technical regulation strategies, where focus is on small CHP units' function in the system; whether they operate solely according to the heat demand, whether they operate according to a fixed electricity production schedule or whether they are actively dispatched to ensure the optimal balance for both heating and electricity systems.

3.2. Desalination in the EnergyPLAN model

The two forms of desalination technologies described in Section 2 are to varying extents integrated into the EnergyPLAN model.

Thermal processes using CHP plants to generate steam or super-heated water for desalination such as multi-stage flash is not modelled explicitly, however such systems may be modelled in the same manner as other CHP applications and thus the CHP – District heating combination that is integrated in the EnergyPLAN model.

The system may both be modelled as a back pressure system or as an extraction system with the added system flexibility. For the back pressure system, the CHP plant is modelled with electric and heat efficiencies, aggregate annual heat demands, hourly heat distribution data, and heat storage size. Using this facility for desalination of water entails establishing the correct ratio between water demands and proxy heat demands.

For extraction plants, the system may be perceived as a back pressure plant combined with a condensing mode plant, where hourly system balance requirements determine the exact operating mode.

RO is explicitly implemented into the EnergyPLAN model. A fresh water demand is given as an annual aggregate, combined with hourly distribution and a fresh water reservoir. The modelling of RO is further refined through coexistence with a pumped hydro plant running on the brine from the desalination unit, although this facility is not employed in the analyses in this article. This facility is utilised by Novosel and colleagues [25] but requires an aquaduct between Aqaba and the Dead Sea – a distance of approx 180 km. Please see [25] for further details on this type of analyses.

4. Reference energy scenario for Jordan

The current energy system of Jordan is characterised by a high reliance on oil products and natural gas supplemented by small shares of renewable energy sources, see Figure 1. Out of the total Primary Energy Supply (PES), the electricity sector accounts for 46% including all natural gas use (based on [54]).

International Energy Agency (IEA) statistics do not list any energy uses or productions on CHP units or heat plants in Jordan, so there is not centralised heating in the country – and nor is the system characterised by dependencies between different energy carriers or the synergies that this might create.

4.1. Generating equipment in the Jordanian energy system

Electricity generation in the Jordanian energy system is characterised by condensing mode power plants based on either natural gas or electricity with smaller fractions

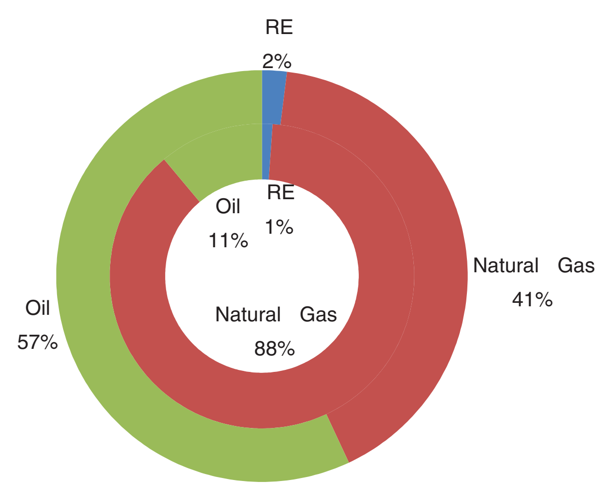

Figure 1: Primary energy supply (outer Circle) and electricity generation (inner circle), Jordan 2009. Data source [54]

Table 1: PES, electricity production and conversion efficiencies in Jordanian power plants. Data in columns 2 & 4 from [54]; columns 3 & 5 are calculated.

Fuel	PES [IEA units]	PES [GWh LCV*]	Electricity production [GWh]	Conversion efficiency [%]
Gas oil/ Diesel	15 kt	174.6	(Included below)	
Fuel oil	332 kt	3744.2	1633	41.7
Natural gas	143542 TJ GCV†	36018.9	12570	34.9
All oil and gas		39937.7	14203	35.6
Hydro	59 TJ	16.4	16.4	100.0
Wind	3 TJ	0.8	0.8	100.0
Biogas	7 TJ	1.9	n.a.	n.a.

* Lower Calorific Value † Gross Calorific Value

of from hydro, wind power and biogas, see Table 1. Conversion efficiencies are relatively low, averaging a modest 35.6 per cent for all oil and natural-based production.

Jordan currently has minor wind farms with approximately 1.5 MW installed capacity, however the *Updated Jordan Master Strategy of Energy Sector in Jordan for the period (2007–2020)* recommends a substantial increase by 600 MW before 2020, as well as expansion in the use of solar cells, and electricity generation from waste – however without actual quantitative targets for the latter [55].

In addition to renewable energy, the Master Strategy also recommends expanding thermal power generation based on oil shale and natural gas as well as commencing the erection of a nuclear power plant. Different sizes are contemplated for oil, oil shale, natural gas and nuclear based power generation but for the reference scenario, 600 MW nuclear power is included. Additional oil, oil-shale and natural gas-based power generation is not included in these analyses.

4.2. Electricity demand of Jordan and electricity distribution

The 2009 electricity demand in Jordan was 14.5 TWh [54], but it is expected to grow by 7.4% annually in the next decade [55], giving a year 2020 demand of 31.8 TWh.

The hourly demand variation is as shown in Figure 2 with lows in the night and peaks in the day. This variation is applied in the energy systems analyses, and it is thus assumed that the current profile also will be valid in a future situation with a higher electricity demand and i.e. that the increase in electricity demand is not due to the addition of particular technologies with unusual demand profiles.

4.2. Distribution profile of wind power generation

An hourly distribution profile of wind power is a prerequisite for energy systems analyses of energy systems with wind power production. This production profile is estimated using satellite-derived Modern Era Retrospective-Analysis for Research and Applications

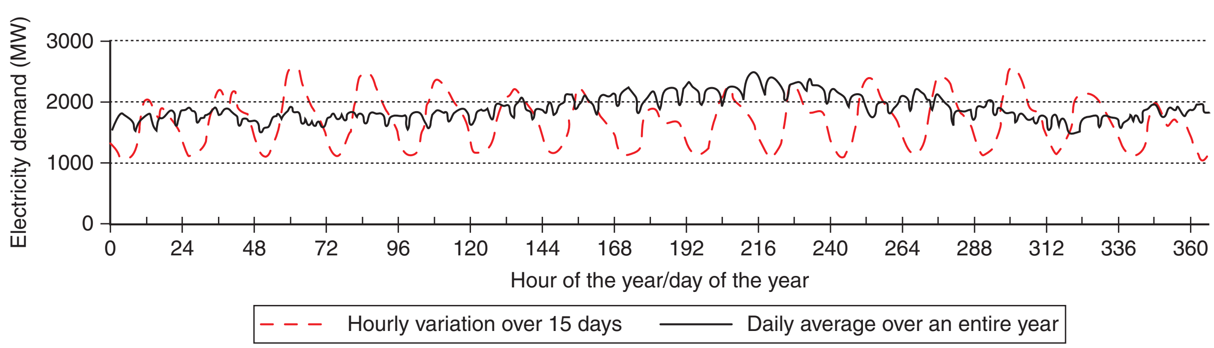

Figure 2: Electricity demand variation for the first 15 days of the year and daily average over the entire year. Based on data from [54] and [56].

(MERRA) data from NASA combined with a wind turbine production profile.

MERRA data are available for a location near Wadi Araba, which is one of the sites anticipated for wind power expansion in Jordan [55]. The MERRA data states wind speeds and directions at a height of 50 meters above ground level, well below the hub height of modern wind turbines. A shear factor of 0.2 has thus been applied to translocate the assessment to a hub height of 90 m and for the wind power assessment, a 3 MW Vestas v90 wind turbine has been used. The entire assessment has been conducted using the wind energy project design and planning software package WindPRO [57].

The assessment results in the production profile shown in Figure 3.

5. Water supply in Jordan

Jordan is in a semi-arid region with rainfall in the capital of Amman of only approx. 273 mm/year [58] or less than half the rainfall of e.g. Copenhagen. Fresh water demand from the growing population is mainly covered by ground water or aquifers at 54% of the total annual demand, where extraction is approximately twice the sustainable replenishing rate [59]. Another 37% is covered [59] [59] [60] [60] by surface waters and the remainder by treated waste water and by desalination [59]. Irrigation is by far the largest fresh water consumer at 72%, industrial demands at 3% and domestic, commercial and tourist industry at 25% [59].

In addition to the unsustainable use of water, Jordan is also facing a series of problems in water supply ranging from illegal wells and un-monitored extraction levels to pollution of aquifers.

5.1. Water demand in Jordan

The Jordanian Ministry of Water and Irrigation projects that the annual demand will increase in the future from 1505 Mm^3 2007 level of up to 1635 Mm^3 in year 2022 putting emphasis on the need for sustainable water supply. One of the means that the Jordanian authorities investigate is the use of desalination, where a present plant with an annual production of 10 Mm^3 should increase to 20 Mm^3 and new plants of 500 Mm^3 should be established based on brackish or on sea water. This would correspond to establishing four Ashkelon size plants.

5.2. Distribution of water demand in Jordan

In order to conduct energy systems analyses of the impact of desalination on energy system performance, it is required to have the hourly distribution of the fresh water demand over the year, however this data is not available, so a qualitative assessment has been made of the distribution of the three consumption categories; agriculture, municipal and industry for a 24 h cycle as well as for the yearly cycle; see Figures 4 & 5.

Agriculture is considered having a flat rate over the 24 h of the day whereas municipal and industrial demands are more aligned with general human activity. On the yearly basis, however, industrial and municipal demands are assumed constant, whereas agriculture is assumed following a typical growing season with low demands during autumn and winter and high demands during spring and summer.

Figures 4 & 5 are assumed numbers. Contacts to Jordanian water authorities have unfortunately not proven fruitful. The general picture has however been deemed reasonable by Jordanian researcher Mohammad Tarawneh from the Hashemite University in Zarqa, Jordan.

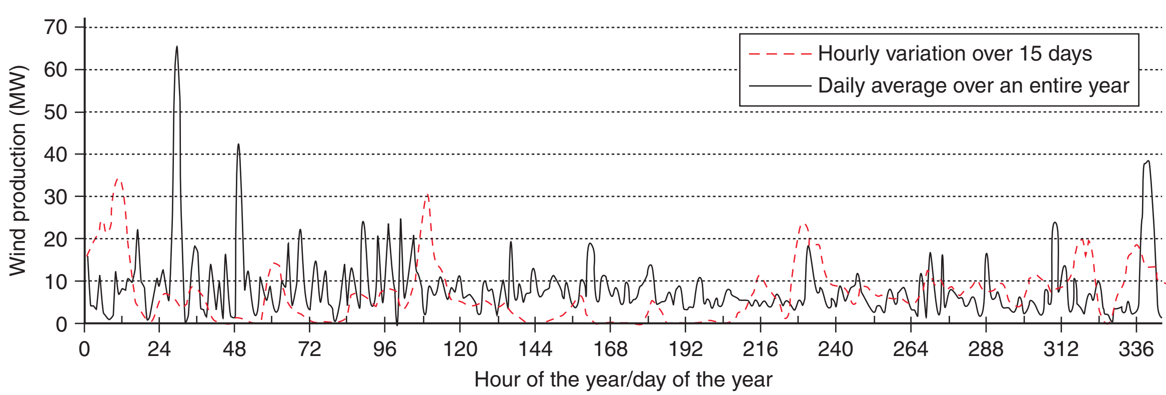

Figure 3: Wind power production the first 15 days of the year and daily average over the entire year.

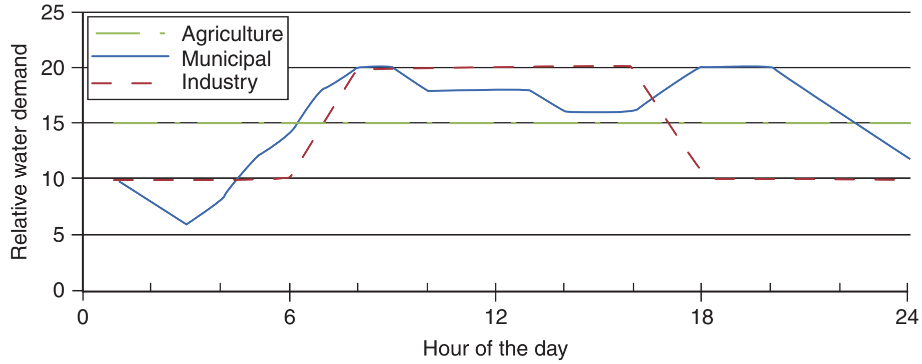

Figure 4: Hourly variation of fresh water demand in Jordan. Each curve is shown as index numbers

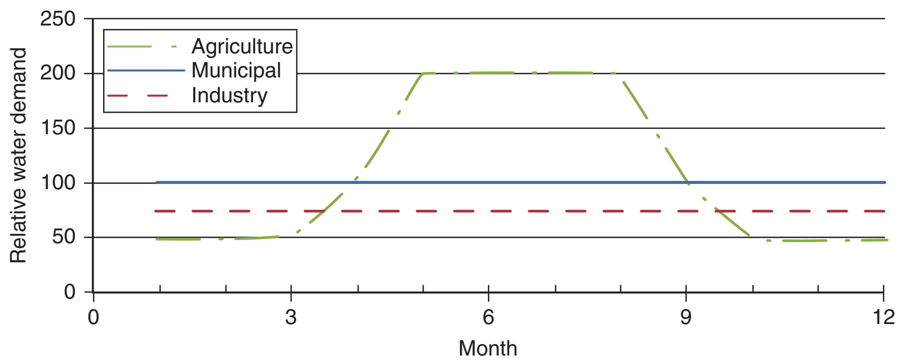

Figure 5: Monthly variation in fresh water demand in Jordan. Each curve is shown as index numbers.

These hourly and monthly distributions are applied to the actual demands of the three consumption sectors to generate the aggregated water demand profile.

6. Energy systems modelling and desalination alternatives

The Jordanian year 2020 system is modelled in the EnergyPLAN model. For the analyses, it is assumed that the efficiency of condensing mode thermal plants will increase from the present level up to 40%, but with the same distribution of fuels as in the present situation.

For CHP units, as noted earlier, the electric efficiency may drop slightly due to the required steam data. CADDET IEA [60] lists an efficiency drop from 40% down to approximately 38% for modest steam data of 5 bar. This value is used in these analyses and with a total efficiency of 90% for the plant.

The planned expansion of wind, solar and waste is not included – the two latter are not quantified in detail and the former is rather used as a factor to vary in the analyses.

The existing hydro power capacity is modelled as a constant 1872 MW production – giving the required output listed in Table 1. The hydro capacity is thus not dispatched actively to assist the integration of wind power in the analyses, which of course is an obvious option depending on the existence of reservoir capacity. For wind power, the existing 1.5 MW stock does not match the production in Table 1 based on the hourly distribution curves. Here an installed capacity of 0.8 MW matches the existing wind production – indicating the existing wind turbines are either having technical problems or are located under poor wind conditions.

The 600 MW nuclear is modelled as having a constant output. For grid stability reasons, EnergyPLAN modellers typically apply a minimum production on condensing mode or on CHP plants as well as a minimum production of 30% from grid supporting technologies [61]. In this case, nuclear will cover the minimum production. The latter restriction is of lesser importance as large-scale CHP units, condensing mode plants as well as wind turbines are assumed grid supporting in the future.

The variation of the electricity demand is assumed having the same distribution profile as the present system – apart from the new demands introduced from desalination.

For the analyses, an annual production of 520 Mm^3 fresh water is modelled. The existing small-scale desalination plant as well as the expansion of this plant is treated congruously with the new plants.

In EnergyPLAN, a Regulation Strategy 2 is applied, in which the model seeks to ensure balance in both electricity and heat.

The specific electricity demand for RO is modelled as 3.5 kWh/m^3 and demands for MSF of 80 kWh heat and 2.5 kWh electricity per m^3 is applied. With the annual fresh water production, this gives an aggregated electricity demand of 1.82 TWh for RO and 1.30 TWh for MSF together with 41.60 TWh of heat.

EnergyPLAN does not permit the modelling of desalination with both heat and electricity demands, so MSF is modelled as a district heating demand of 31.60 TWh and the electric efficiency of the CHP units are reduced by 2.3% to accommodate for the electricity demand of 1.30 TWh.

7. Results of energy systems modelling with increasing wind

In the energy systems modelling, wind power is increased from 0 to 6000 MW corresponding to approximately 20% of the Jordanian electricity demand – excl. demands for desalination – standing at 31.8 TWh in 2020 as indicated previously.

Results show how well the different systems are adapted to increasing levels of fluctuating power in terms of the electricity production that cannot be used within the system in the form of Critical Excess Electricity Production as well as the effects on Primary Energy Supply (PES) for power generation – excluding RES-based PES (see also [62]). Results are included for MSF and RO respectively and in both case without any fresh water storage as well as with fresh water storage corresponding to four weeks of water use

PES for electricity generation decreases with higher penetration of wind power as wind power replaces fossil fuel-based power generation, as shown in Figure 6. The two curves for MSF and RO are very close with a slightly lower PES for the RO alternative.

The performance in terms of CEEP shows an increasing trend as a consequence of increasing wind power penetration as shown in Figure 7. It is notable that from as low as 2500 MW – or approx 7.5% wind power penetration - the systems starts to exhibit CEEP.

In the case of MSF, the storage will be filled by shifting electricity production from condensing mode operation plants to desalination CHP units and again be discharged by reducing desalination CHP operation and running demands on storage contents. Reducing CHP operation is applied to limit Critical Excess Electricity Generation (CEEP) and thus occurs only in hours with CEEP. However, in these hours, CHP production is already at a minimum in the modelled system, hence the storage cannot discharge – and hence, storage size is inconsequential to the operation of the energy system.

In general, CEEP is larger with MSF than with RO due to the extra restriction imposed by the operation of CHP plants that creates an additional electricity generation – as opposed to the RO case, where basically an extra electricity demand is included; an electricity demand which may be more or less flexible depending on the storage included.

It should also be noted, that CEEP in general is at a modest level – even at the maximum level of wind

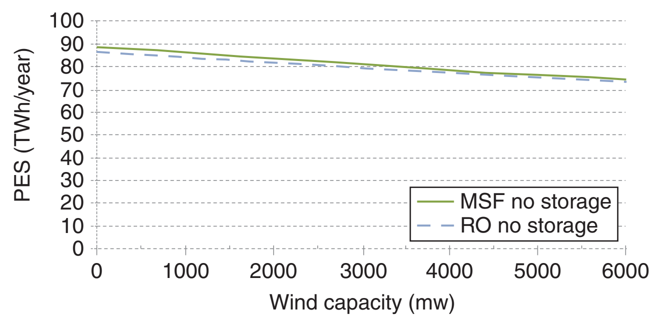

Figure 6: PES for electricity generation – excluding renewable energy sources – as a function of increasing wind power penetration.

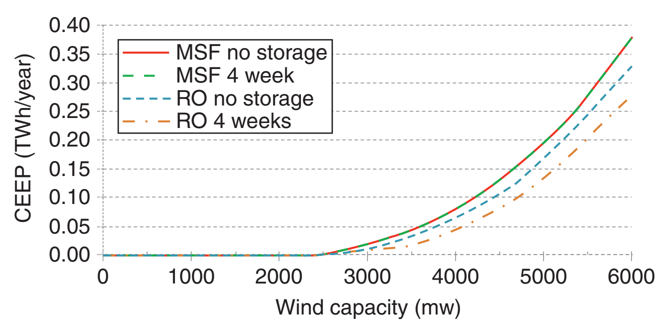

Figure 7: CEEP as a function of increasing wind power penetration.

power penetration modelled. Contributing factors include a fossil system with dispatchable units apart from wind, nuclear and CHP desalination. Furthermore, the electricity demand for desalination is relatively modest at 1.3 TWh (MSF) to 1.82 TWH (RO) compared to a general electricity demand of 31.8 TWh. The heat demand for MSF is 41.6 TWh – approximately 26% higher than the electricity demand incl. demand for MSF. For comparison, the district heating demand in Denmark was 17% higher than the domestic electricity demand in 2012 [63], so the modelled Jordanian system has a higher heat-induced inflexibility than the Danish system, but CEEP in Denmark was at a similar level at 20% wind power penetration – namely very limited [64].

8. Conclusion

This article has analysed the effects of large scale desalination on the Jordanian energy system with a particular focus on the energy systems impacts of the simultaneous large scale introduction of wind power into the energy system.

The Jordanian PES with MSF as well as with RO are of a similar magnitude – particularly when considering the uncertainty in terms of efficiencies of the two technologies, where literature shows large variations in specific electricity and heat demands for desalination.

In terms of the ability to integrate wind power into the power system, the two cases exhibit some difference though. In general, CEEP starts between 2500 and 3000 MW wind power. A contributing fact to the CEEP is the modelled 600 MW nuclear power plant, which is included with a constant production throughout the year. If this was replaced by dispatchable condensing mode power plants, CEEP would be more than halved in the RO No Storage Case.

Water storage has some implication for the system's ability to integrate wind power. For the MSF case, there is no call for operating the storage, however in the RO case, CEEP is reduced by approximately 15%.

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