Integration of renewables and reverse osmosis desalination – Case study for the Jordanian energy system with a high share of wind and photovoltaics

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ABSTRACT

Jordan is a country faced with several environmental and energy related issues. It is the Worlds' fourth most water deprived country with a water consumption of only 145 m^3 per capita annually, less than a third of the established severe water poverty line. Jordan is also a country rich in wind and solar potential but practically no utilization with 99% of the produced electricity coming from imported fossil fuels resulting in high CO_2 emissions and a potential security of supply issue. The utilization of reverse osmosis desalination in a combination with brine operated pump storage units and wind and photovoltaic plants can tackle both issues. The desalination plants can produce the much needed water and act as a flexible demand to increase the penetration of intermittent renewables supported by the brine operated pump storage units. This paper presents six scenarios for the development of the Jordanian energy system until the year 2050. The results have shown that the demonstrated configuration can increase the share of intermittent renewables in the production of electricity up to 76% resulting in a high reduction of fuel consumption, CO_2 emissions and costs. These analyses have been performed using the EnergyPLAN advanced energy system analyses tool.

Keywords:
EnergyPLAN, Jordan, Renewable energy, reverse osmosis desalination

Nomenclature

Abbreviation	Full name	Measuring unit
BOPS	brine operated pump storage	-
c	ionic molar concentration	mol/l
CEEP	critical access of electricity production	-
CHP	combined heat and power	-

E_{tot}	total electricity demand for desalination per cubic meter of fresh water	kWh/m^3 of fresh water
g	standard gravity	m/s^2
GDP	gross domestic product	-
h	height difference	m
IEA	International Energy Agency	-
NEPCO	National Electric Power Company	-
P_p	installed power of pumps for the pumping of salt water	kW
P_{RO}	installed power of pumps for the RO desalination itself	kW
P_{tot}	total installed power of pumps for desalination	kW
PV	photovoltaic	-
R	gas constant	l bar/K mol
RES	renewable energy sources	-
RO	reverse osmosis	-
T	absolute temperature	K
v	volume flow of salt water	m^3/s
V_{fresh}	volume flow of fresh water	m^3
ρ	density of pumped water	kg/m^3

1. Introduction

A high level of water scarcity and heavy dependence on imported fossil fuels are both very serious issues facing Jordan. It is currently the Worlds' fourth most water deprived country with an annual consumption of only 145 m^3 per capita annually [1], less than a third of the established severe water poverty line of 500 m^3 [2]. This is an issue that will only become more serious in the future considering that Jordan's population is predicted to increase by 50% by the year 2030 [3]. It is also a country heavily dependent on imported fossil fuels with 5909 ktoe or 83.6% of the primary energy consumption coming from crude oil or oil products, 872 ktoe or 12.3% from natural gas and only 283 ktoe or 4.1% from renewables and electricity import in 2011 [4]. This represents an enormous expense. The Jordanian fuel bill exceeds 3 billion USD annually which is approximately 20% of its GDP for the year 2011 [5]. As with the water scarcity, this problem is bound to escalate in the upcoming future. The Jordanian official energy strategy predicts an annual increase of the electricity demand by 7.4% annually by the year 2020 [6]. This would double the demand in the period 2011 to 2020.

The utilization of an integrated system combining reverse osmosis (RO) desalination and pump storage systems that utilize brine water (brine operated pump storage or BOPS) with renewable energy sources (RES), namely wind and photovoltaic (PV) energy, can help mitigate all of the aforementioned issues. The benefits of integrated solutions for the reduction of CO_2 emissions and the increase of the utilization of intermittent RES has already been discussed in the past, for example with a focus on wind energy [7] and the integration of the energy and transport sectors [8]. The authors of [9] presented and discussed seven possible technologies mostly focusing on power to heat technologies, flexible electricity demand and electric vehicles while the work presented in [10] focused primarily on the integration of the energy and transport systems. The integration of wind [11] and PV [12] with desalination systems has also been discussed in the past. The authors of [13] have demonstrated that the utilization of RO desalination can reduce the amount of critical excess of electricity production, meaning excess electricity that cannot be stored or exported, (CEEP) by approximately 15% in their scenarios while our previous work demonstrated that the utilization of RO desalination and BOPS could separately increase the penetrations of wind power to roughly 32% and for PV power to roughly 37% of the total annual electricity demand [14]. These papers focused on the technical impact desalination has on energy systems of arid countries but not its cost. This issue is still unexplored. The work performed in [15] demonstrated the economic and environmental benefits of the integration of intermittent RES, pump storage and desalination in an island environment with a potential penetration of wind and hydro energy of up to 36%. The idea of water and energy integration has been discussed in the framework of the energy-water nexus. Work on this topic has demonstrated a positive effect on water and energy consumption as well as a reduction in CO_2 emissions in several case studies like China [16], the MENA region [17] and California [18].

Jordan is a country rich in the potential for economically viable wind, [19] and PV, [20] energy utilization with payback periods being as low as 6 years for wind [21] and 2.3 for PV [22] in some cases. The utilization of these RES could power the RO desalination plants which would in turn, aside from producing fresh water, further increase the potential for their penetration. The desalination system could also be fitted with BOPS to further increase this potential. The importance of energy storage in future energy systems for the purpose of increasing the penetration of renewables [23] as well as its' role in a market environment [24] has already been discussed by several authors in the past. RO desalination is the most widespread sea water desalination technologies in use today and its flexibility makes it suitable for utilization with intermittent energy sources like wind and PV [25]. The benefits of 100% renewable energy systems and systems with a high penetration of renewables are numerous including CO_2 emission mitigation [26], job creation and economic growth amongst others [27].

This paper presents a continuation of previous work where the beneficial influence of RO desalination on the increase of the potential for the penetration of renewables has already been demonstrated in EnergyPLAN [14] and in H2RES [28]. The goal of this work is to use the EnergyPLAN [29] advanced energy system analyses tool to present and compare 6 scenarios for the future development of the Jordanian energy system centred on the utilization of RES and RO desalination. Unlike the previous work, this paper explores the impact desalination and intermittent RES have not only on the energy system from the perspective of CEEP and CO_2 emissions but also on the total cost of the system Two desalination systems have been analysed, one modelled after a system focused on the reduction of energy consumption [30] and one focused on the increase of the potential for the penetration of renewables [14]. The results have shown that the second configuration could support an energy system where 76% of the electricity can be produced from wind and PV alone resulting in a drastic reduction of CO_2 emissions and fuel use and in turn also of the total cost of the energy system.

2. Methodology

The analyses performed in this paper were conducted with the EnergyPLAN advanced energy system analyses tool. EnergyPLAN is a deterministic input output energy system modelling tool able to create annual analyses of different energy systems on an hourly level. It requires a broad range of both hourly and annual aggregated data. The required inputs include the hourly distributions of electricity and heat demand as well as the distributions for the energy productions from wind, PV, river hydro and similar energy sources, the installed capacities of the individual energy producers, energy mix of the thermal power plants and the demand in the building, industry and transport sectors as well as the economic data related to the fuel costs and the costs of the investment and operation of the different systems. The provided results include the total annual CO_2 emissions, total cost of the system, analysis of the energy production, CEEP, fuel consumption and so on.

EnergyPLAN is a well-documented and widely used energy modelling tool that is specialized in the large scale integration of RES in energy systems [31] and optimal combination of RES [32]. It has been used in the past to recreate several different energy systems like Croatia [33], Denmark [35], Macedonia [36],Jordan [14] and so on.

The desalination module has been implemented into the EnergyPLAN version 11. The inputs necessary to run a scenario with desalination include the total annual fresh water demand and hourly demand curve, fresh water storage, energy efficiency of the pumps, efficiency of the desalination process, capacity of the desalination plant and the data regarding the pump hydro storage using the produced brine. It has been used in the past to analyse the impact desalination can have on an energy system [14]. The desalination module, its operation and integration into the electricity system has been described in great detail in the EnergyPLAN manual [37], which is available online.

3. Scenarios

In order to create the future scenarios and analyse the energy system a reference model had to be created first. The year 2011 has been used as a reference point since it is the newest year with available data. The installed capacities of the Jordanian power plants have been taken from the Jordanian National Electric Power Company's (NEPCO) annual energy report for the year 2012 [38], the fuel mix and the total electricity demand from the International Energy Agency (IEA) [39] as well as the energy demands of the building, industry and transport sectors. Due to the way EnergyPLAN handles its inputs, the household and commercial sectors are summed up and added to the model under the individual tab while the agriculture and industry demand are added under the industry tab. The efficiency of the thermal power plants has been calculated based on the electricity production and fuel use data available on the IEA [39] website to be 40%. The hourly distribution of the electricity demand for the year 2010 has been used here and was obtained from NEPCO [40]. The meteorological data including outside temperatures, wind speeds and solar insulations were taken from METEONORM [41]. Figure 1 presents the hourly distributions of electricity demand gathered from NEPCO and the wind speeds and solar insulations gathered from METEONORM. The present and future costs of the fuels and technologies have been taken from [36], the JRC Technology Map [42] and the SETIS Calculator [43].

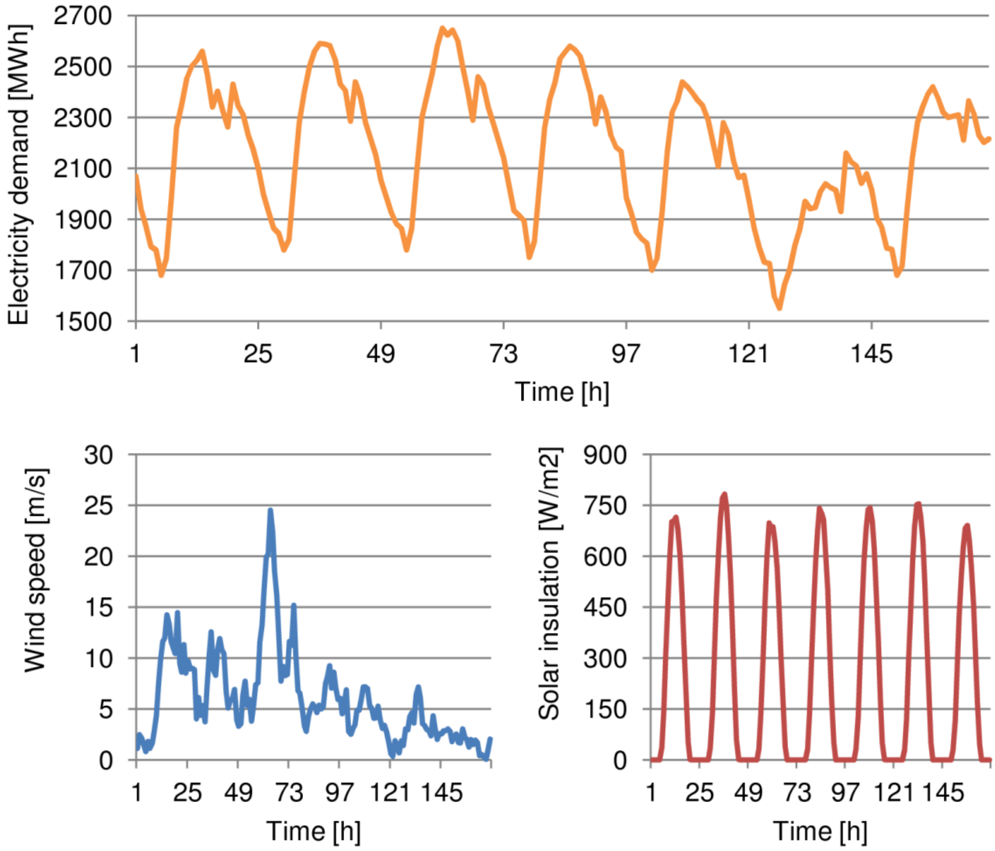

Figure 1 Hourly distributions of electricity demand, wind speeds and solar insulation for Jordan

After the initial creation of the reference model, predictions and analysis of future energy and water demand have been performed. As it was already mentioned, the official Jordanian energy strategy predicts an increase of the electricity demand to be 7.6% annually until the year 2020 [6]. This means that the electricity consumption of the country will increase to 31 TWh in 2020 compared to the 16.3 TWh in 2011 [39]. If this trend would continue until 2050 this would mean a consumption level of 283 TWh, an increase by a factor of 17.4 and an electricity consumption per capita of 24.6 MWh/capita annually in relation to 2.29 MWh/capita in 2011 [39]. The population data and predictions were obtained from the Jordanian Department of Statistics [3]. For comparison, the EU-28 electricity consumption per capita was 6.13 MWh/capita in 2011 [39].

The assumption that the trend of the increase of the electricity demand will continue to rise as steeply after 2020 provided unrealistic results. Alternatively, it was presumed that this increase will begin to slow down after 2020 to result in a consumption level of 6 MWh/capita annually, a value close to the current EU-28 level [39]. Figure 2 presents the assumed increase in the electricity demand and the population in Jordan for the period 2011 to 2050.

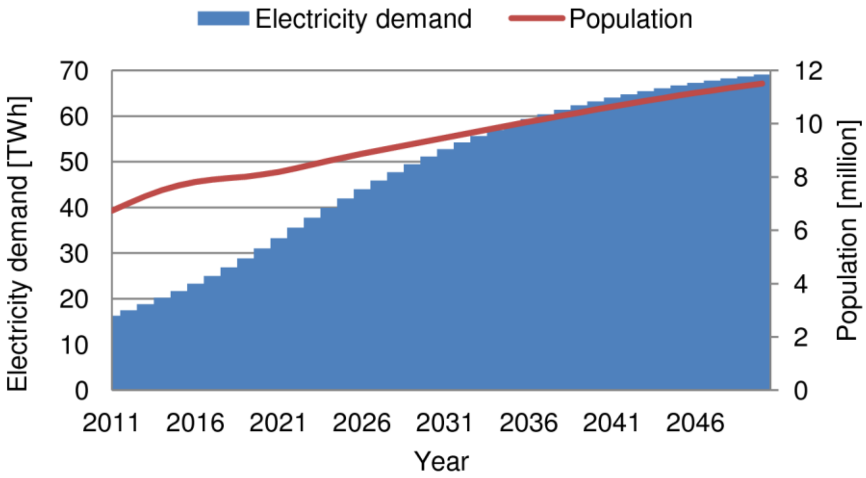

Figure 2 Future electricity demand and population growth in Jordan

Jordan's water supply is predicted to decrease even further to a level of only 91 m^3/capita annually by 2025 [1]. In order to combat this situation, RO desalination systems can be used. For the purpose of this work, a water consumption target of 300 m^3/capita annually by the year 2050 has been presumed. This level is still far below 500 m^3/capita annually but it does represent an increase of more than 100% compared to the level in 2011. Figure 3 presents the increase in the per capita consumption of water

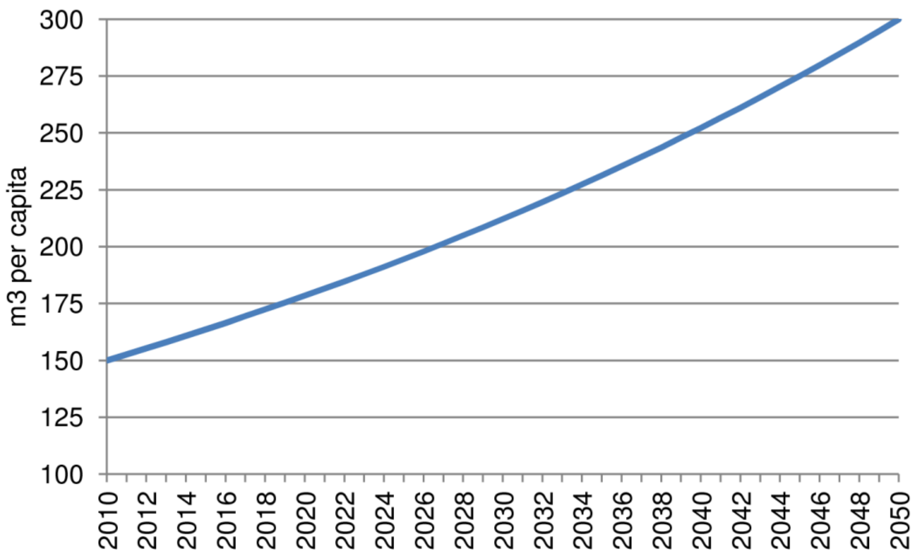

Figure 3 Presumed future water demand per capita in Jordan

In order to satisfy the water demand two desalination systems have been proposed in four of the six developed scenarios according to [30] and [14] both able to produce 570 million m^3 of water annually. This requires a minimum capacity of the desalination plant around 64,960 m^3/h of fresh water. Figure 4 demonstrates the natural supply of fresh water, water supplied through desalination and the total water consumption in Jordan for the period from 2010 till 2050. As it can be seen, by 2020 one such system will be necessary, by 2030 two and by 2050 five. These predictions were made in accordance with the assumption that the per capita consumption should increase to at least 300 m^3/capita annually by 2050. Since there is no data available on the hourly profile of the water consumption in Jordan available a flat constant demand curve has been assumed. This does not pose a significant issue since a fresh water storage unit is incorporated in the desalination system foreseen in the scenarios.

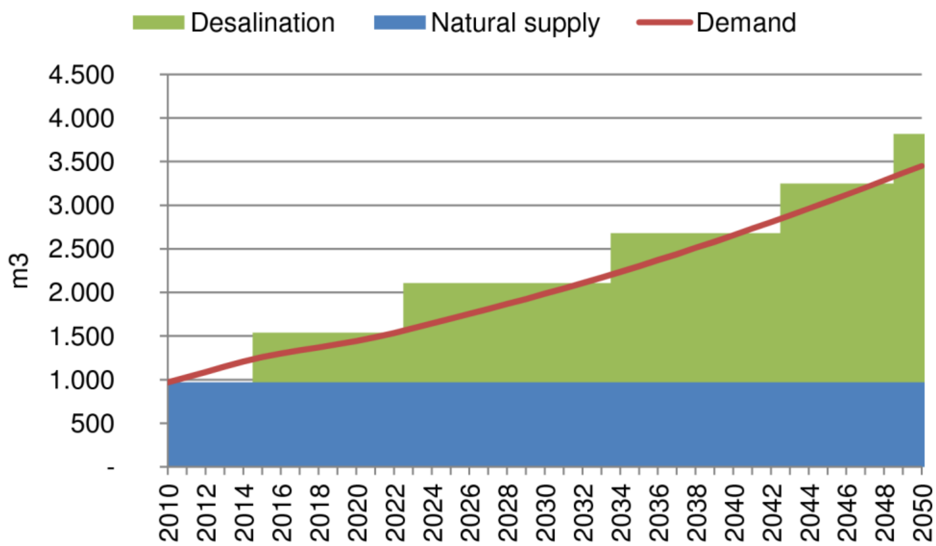

Figure 4 Water demand and supply in Jordan for the period 2010 to 2050

Table 1 represents the energy system of Jordan for the reference year 2011 recreated from the data obtained from [38]. As it can be seen, basically all of the produced electricity in the country comes from thermal power plants (PP) with only 1.4 MW of installed wind. A small amount of hydro power plants that is present in the Jordanian energy system has not been added to the reference scenario since their power (12MW) and production (61GWh) are negligible and there is no real potential in their future expansion.

Table 1 Reference scenario for Jordan for the year 2011

Year	Installed PP [MW]	Installed Wind [MW]	Installed PV [MW]
2011	3298.5	1.4	0

For the purpose of this work, 6 scenarios have been created. The first one, Scenario A, presents a business as usual scenario in which the increased electricity consumption is satisfied with imported fossil fuel and without a desalination system. Scenario B represents a model of the system without a desalination system but with the utilization of RES in the form of wind and PV power. Scenarios C and D include a RO desalination system modelled after the one described in [30] with a capacity of 65,000 m^3/h of fresh water. This desalination system is focused primarily on reducing its energy consumption. The total energy consumption of these systems is 3.31 kWh/m^3 of fresh water. Scenario C is a business as usual scenario that includes the desalination systems and Scenario D a system with desalination and a high level of RES penetration. The minimum grid stabilization shares in Scenarios A trough D has been set to 0.3 meaning that in every hour 30% of the produced electricity has to come from power plants that can provide ancillary services, or in other words, power plants whose output can be regulated freely for example condensing power plants, CHP units, accumulation hydro power plants and so on. Scenarios E and F include a desalination system modelled after the one presented in [14] and a high level of RES penetration. This system is designed to be more flexible and therefore allow for a higher penetration of intermittent RES but with a substantially higher total energy consumption of 7.27 kWh/ m^3 of fresh water. The energy consumption for this case has bene calculated according to the equations 1-4. The energy system described in Scenario E utilizes a desalination system with a capacity of 150% or 97,500 m^3/h of fresh water and a BOPS system. Scenario F incorporates a desalination system with a capacity of 200% or 130,000 m^3/h of fresh water and a BOPS system. The grid stabilization share in Scenario E has been reduced to 10%. For Scenario F this value is set to 10% for 2020 and completely removed in 2030 and 2050. These reduced figures simulate the flexibility of the desalination system and its ability to quickly modulate its energy consumption. This is made possible by the fresh water storage and overcapacity of the desalination unit and with that, the pumps used. The mentioned capacities are for a single system used in 2020. They are increased twofold in 2030 and by a factor of 5 in 2050 as per Figure 4. Table 2 presents the energy systems of the six created scenarios while Table 3 presents the desalination systems. The investment costs of the desalination system has been estimated according to the figures given in [30] for Scenarios C and D. These costs are increased by 20% for Scenarios E and F.

The energy consumption of the flexible desalination system used in scenarios E and F has been calculated according to the following equations (1-4). The total electricity consumption is calculated according to equation 1 and it is equal to the total power of the installed pumps divided by the volume flow of the fresh water. The total power of the pumps, equation 2, is equal to the sum of the installed power of the pumps needed to pump the salt water to the desalination unit, equation 3, and the installed power of the pumps needed to generate the osmotic pressure or in other words to operate the RO desalination unit, equation 4.

$$E_{tot} = \frac{P_{tot}}{V_{fresh} \cdot 3600} \tag{1}$$

$$P_{tot} = P_p + P_{RO} \tag{2}$$

$$P_P = \rho \cdot g \cdot h \cdot v \tag{3}$$

$$P_{RO} = c \cdot R \cdot T \cdot v \tag{4}$$

Table 2 Energy system of the 6 created scenarios

Year	**Scenario**	**Installed PP [MW]**	**Installed Wind [MW]**	**Installed PV [MW]**
2020	A	5400	1.4	0
	B	4900	2500	2500
	C	5775	1.4	0
	D	5200	2800	2800
	E	5400	4800	4500
	F	5380	5000	4500
2030	A	8905	1.4	0
	B	7950	4500	4000
	C	9660	1.4	0
	D	8705	5000	5000
	E	9080	8000	8000

	F	9080	9500	9500
2050	A	12025	1.4	0
	B	10730	6000	6000
	C	13910	1.4	0
	D	12620	7500	7500
	E	13800	14000	14000
	F	14200	18000	18000

Table 3 Desalination system of the 6 created scenarios

Year	**Scenario**	**Fresh water production [Mm^3]**	**Desalination plant [1000 m3/h]**	**Turbine/Pump capacity [MW]**	**Storage capacity [Mm^3]**
2020	A	0	0	0	0
	B	0	0	0	0
	C	570	65	0	0
	D	570	65	0	0
	E	570	97.5	1000	3.2
	F	570	130	1000	3.2
2030	A	0	0	0	0
	B	0	0	0	0
	C	1140	130	0	0
	D	1140	130	0	0
	E	1140	195	2000	6.4
	F	1140	260	2000	6.4
2050	A	0	0	0	0
	B	0	0	0	0
	C	2850	325	0	0
	D	2850	325	0	0
	E	2850	487.5	6000	19.2
	F	2850	650	8000	25.6

Figure 5 presents the two configurations of the RO desalination system used in this analysis. The top figure shows the configuration focussed on the reduction of electricity consumption used in Scenarios C and D and structured based on the system described in [30]. This configuration uses the natural height difference between the Red and the Dead seas and the resulting static pressure of the water column to push the water through the membranes. The bottom figure presents the flexible configuration used in Scenarios E and F based on the system described in [14]. In this configuration the salt water is pumped to a height of 1000 m where it is desalinated. The brine is stored in a storage unit and used by a BOPS system. The produced fresh water is stored in fresh water tanks or lakes and pumped to the consumers.

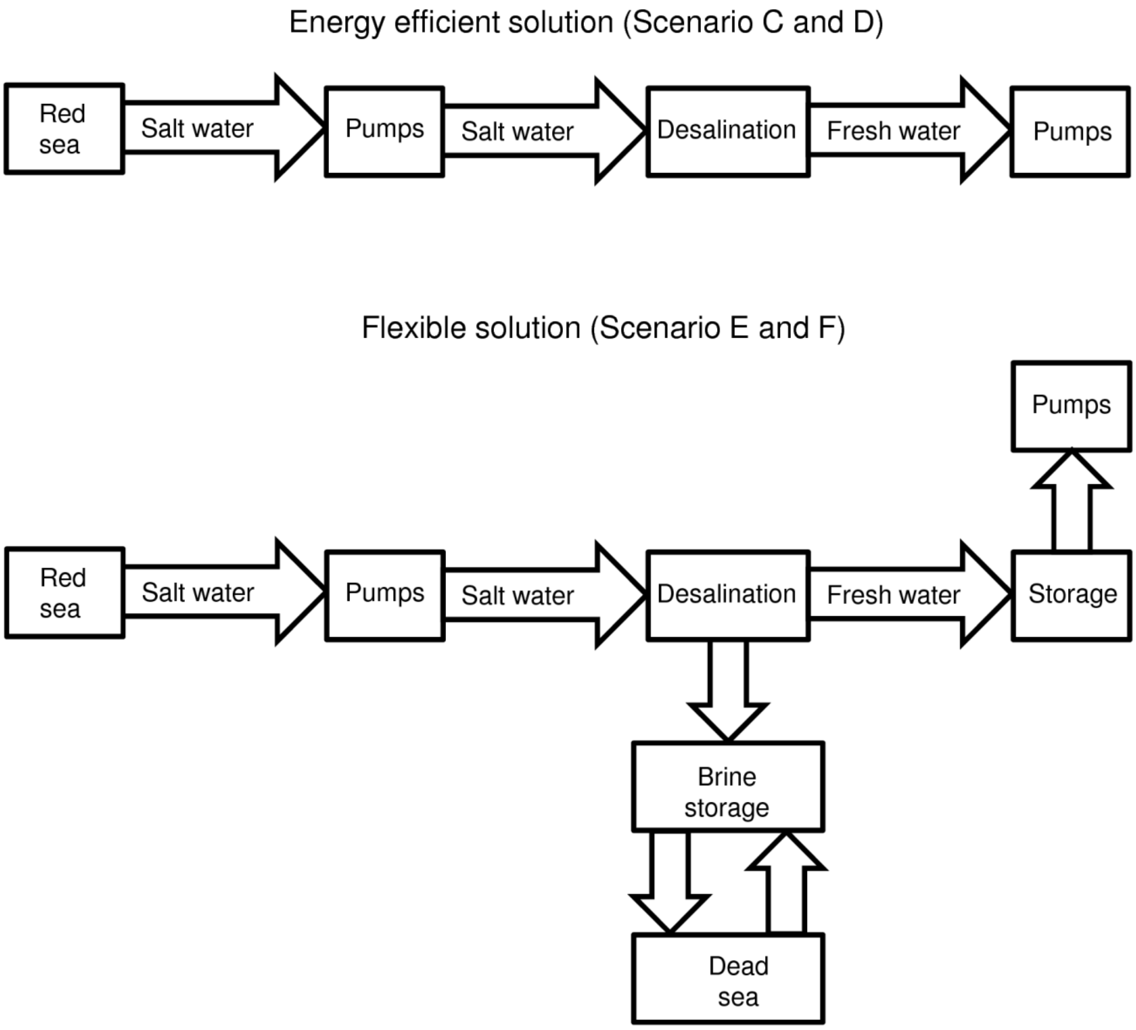

Figure 5 Desalination configuration used in Scenarios C and D (up) and E and F (down)

4. Results and validation

The results obtained from the six scenarios and their comparison is presented in this chapter as well as the model validation presented as a comparison of the reference model and data obtained from the IEA [39].

4.1. Model validation

In order to validate the created reference model the results obtained from it have been compared to the data obtained from the IEA [39]. Table 4 demonstrates this validation. As it can be seen there are no large deviations between the two. All differences are less than 1% except the CO_2 emissions where the difference is 1.22%. This is most likely due to the difference in the emission factors between this model and the ones the IEA uses.

Table 4 Model validation

Energy consumption (TWh annually)	IEA [39]	EnergyPLAN	Difference

PP N. gas	10.14	10.13	0.1%
PP Oil	26.95	26.93	0.07%
PP Biomass	0.02	0.02	0%
Transport	20.84	20.83	0.05%
Residential	9.59	9.59	0%
Industry	7.71	7.71	0%
CO_2 emissions (Mt annually)	18.77	19	1.22%

In order to emphasize the effect the RO desalination and RES have on the energy systems, future energy system analysis have been performed with the exclusion of the building, industrial and transport sectors focusing only on the generation of electricity and it's consumption. This resulted in CO_2 emissions equalling 9.242 Mt annually in 2011 and a total annual cost of the system of 1224 M€ .

4.2.Results

Table 5 demonstrates the total annual electricity demand, electricity consumption of the desalination system and CEEP of the 6 created scenarios for the evaluated years. A small amount of CEEP, up to 5% of the total annual electricity consumption in the case of these scenarios, is tolerated because it is usually more economical to do so than to try and build enough electricity storage to eliminate it completely [44], [45]. It can be seen that the inclusion of the desalination system increases the total electricity demand by 10.7%, 13% and 24% in 2020, 2030 and 2050 respectively for Scenarios C and D compared to Scenarios A and B which don't include desalination. This increase is even bigger for Scenarios E and F with an increase of 23.5%, 28.5% and 52.7% in 2020, 2030 and 2050 respectively. CEEP is lower than the set limit of 5% for all scenarios and it does not appear in Scenarios A and C since they do not utilize intermittent RES which is the cause of its production.

Table 5 Total electricity demand, electricity demand for the desalination and CEEP

Year	Scenario	Total electricity demand [TWh]	El. Consumption for desalination [TWh]	CEEP [% total el. demand]
2020	A	30.99	0	0%
	B	30.99	0	4%
	C	34.3	3.31	0%
	D	34.3	3.31	4%
	E	38.26	7.27	4%
	F	38.26	7.27	4%
2030	A	51.14	0	0%
	B	51.14	0	4%
	C	57.78	6.64	0%
	D	57.78	6.64	5%
	E	65.69	14.55	4%
	F	65.69	14.55	4%
2050	A	69.05	0	0%
	B	69.05	0	5%
	C	85.63	16.58	0%
	D	85.63	16.58	5%

E	105.41	36.36	4%
F	105.41	36.36	4%

Table 6 presents the CO_2 emissions, RES share in the production of electricity, total annual cost of the system and total annual fuel consumption of the created scenarios. As expected Scenario C has the highest CO_2 emissions as a result of the higher electricity demand because of the use of RO desalination and no RES utilization. It is also the scenario with the highest fuel consumption and total cost. The Scenario F is the one with the lowest CO_2 emissions and the highest share of RES reaching 76% in the year 2050. The remaining 24% should be satisfied with biomass or synthetic fuels. The issue of overusing biomass in high RES share energy systems has been discussed in [46]. The lowest overall total cost of the energy system is achieved in Scenario B in the years 2020 and 2030 and in Scenario F in 2050.

Table 6 Results of the scenarios

Year	**Scenario**	**CO2 emissions [Mt]**	**RES share in el. Production [%]**	**Total cost [M€]**	**Fuel consumption [TWh]**
2020	A	19.555	0.1	5054	78.47
	B	14.135	31.3	3974	56.72
	C	21.649	0.1	5686	86.87
	D	15.623	34.4	4486	62.69
	E	12.434	50.9	4212	49.89
	F	12.183	52.1	4203	48.89
2030	A	32.272	0.1	9867	129.49
	B	23.205	32.5	7506	93.11
	C	36.459	0.1	11329	146.29
	D	26.007	37.1	8614	104.36
	E	20.791	51.5	7932	83.43
	F	17.334	61.1	7120	69.55
2050	A	43.575	0.1	15795	174.85
	B	31.023	33.7	11816	124.48
	C	54.042	0.1	20043	216.85
	D	38.498	40.4	15134	154.48
	E	28.278	59.1	13814	113.47
	F	19.442	76	11674	78

Figure 6 presents the electricity production mix by source. This further illustrates the RES share in electricity production shown in Table 6. The most interesting comparison is between Scenarios D, E and F, the three scenarios utilizing RES and different configurations of the desalination system. The shares of RES in electricity production is 34%, 51% and 52% for the respective scenarios in 2020, 37%, 52% and 61% in 2030 and 40%, 59% and 76% in 2050.

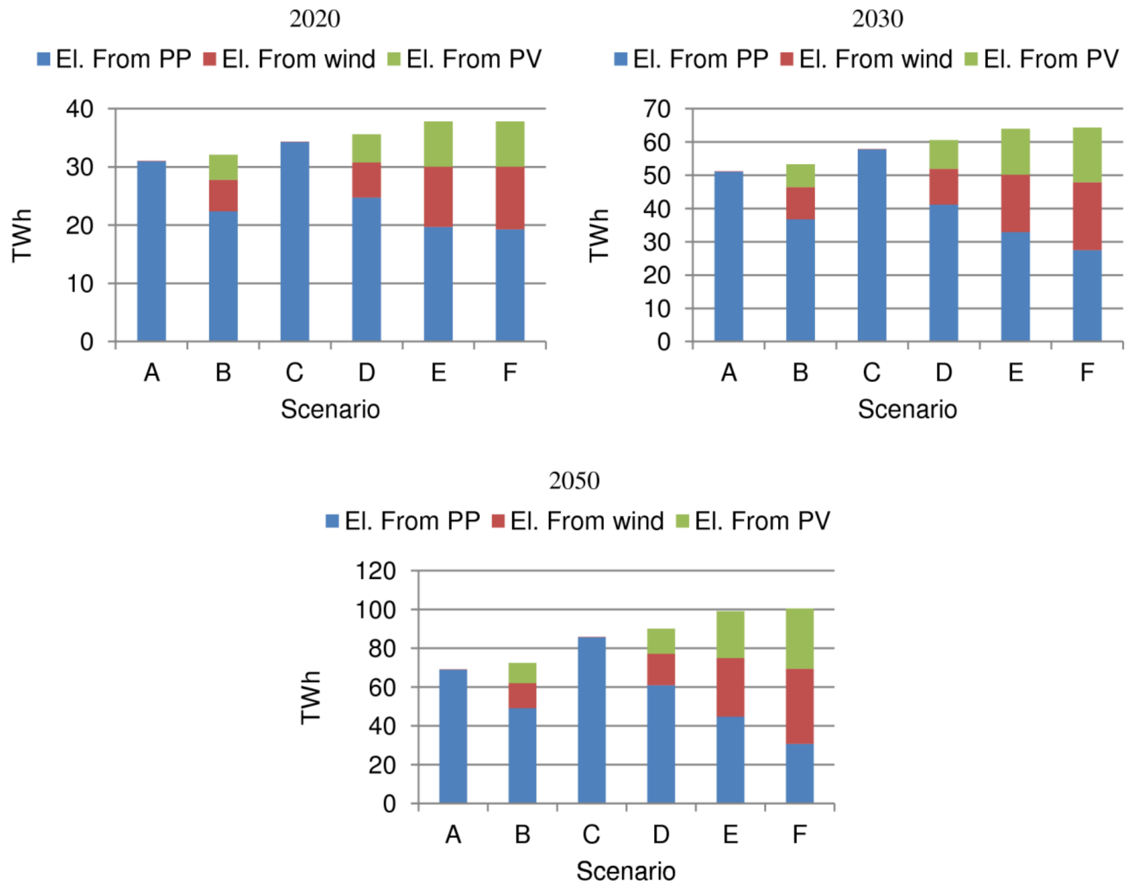

Figure 6 Electricity production by source

Figure 7 presents the annual CO_2 emissions and total costs of the six created scenarios (scenarios A-F). As it can been seen, the lowest level of CO_2 emissions is achieved in the Scenario F, followed by E, B and D. In 2050 the reduction of emissions in Scenario F compared to A (business as usual) is 55.38%. The increase in CO_2 emissions for Scenario A in comparison with the reference model in 2050 is 5.8 times. For Scenario F this increase is 2.1 times. The results are similar when it comes to the total cost. They are lowest for Scenario B followed by F, E and D. This changes in 2050 when Scenario F becomes the cheapest with a cost of 11,674 M€ which is 10.4 times more than the reference model.

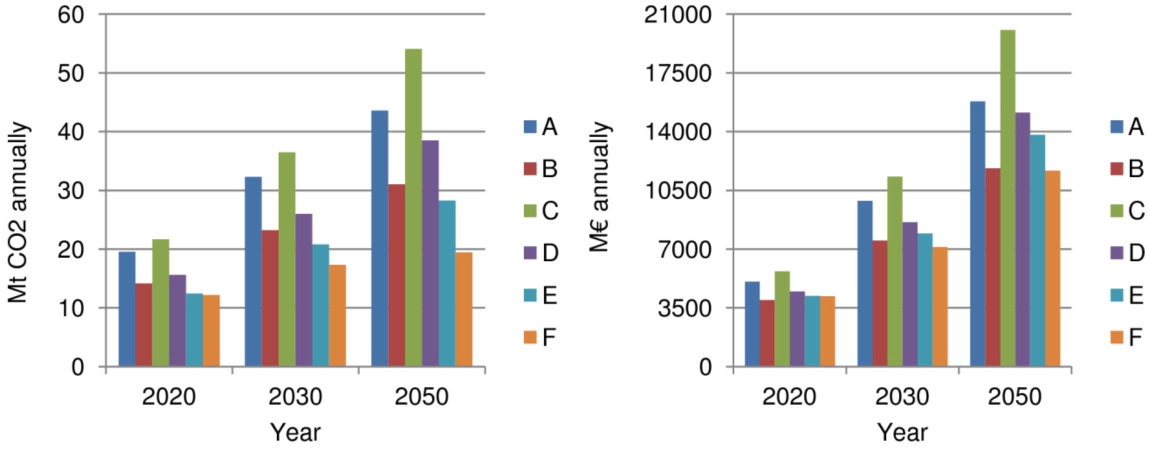

Figure 7 CO_2 emissions and total cost of the scenarios

5. Sensitivity analysis

In order to analyse the impact fuel and investment costs have on the total annual cost of the system, a sensitivity analysis has been conducted. The fuel prices, total investment costs in the desalination plant including the RO desalination unit, water storage, pumps and turbines and the investment cost of PV and wind power plants has been varied from -50% to +50% with an increment of 25% for Scenario F in the year 2050. For comparison, the sensitivity analysis has also been performed the same way for Scenario A in the year 2050 but only for the fuel prices. The results of the analysis are presented in Figure 8. The x axis labelled "Relative change" represents the variation of the base costs of the individual units performed in the analysis. Table 7 presents the base prices of the fuel, desalination, PV and wind power plants used in all the scenarios for the year 2050 and in the sensitivity analysis.

Table 7 Base prices used in the scenarios for the year 2050 and in the sensitivity analysis

Cost category		**Price**
Fuel cost	Fuel Oil	25.76 EUR/GJ
	Diesel	35.61 EUR/GJ
	Petrol	39.06 EUR/GJ
	Natural Gas	20.39 EUR/GJ
	Biomass	4.5 EUR/GJ
Desalination cost	Desalination plant	62.64 MEUR/1,000m^3 fresh water
	Water storage	370 EUR/m^3
	Pump	1.5 MEUR/MW
	Turbine	1.5 MEUR/MW
PV cost		0.86 MEUR/MW
Wind cost		0.5 MEUR/MW

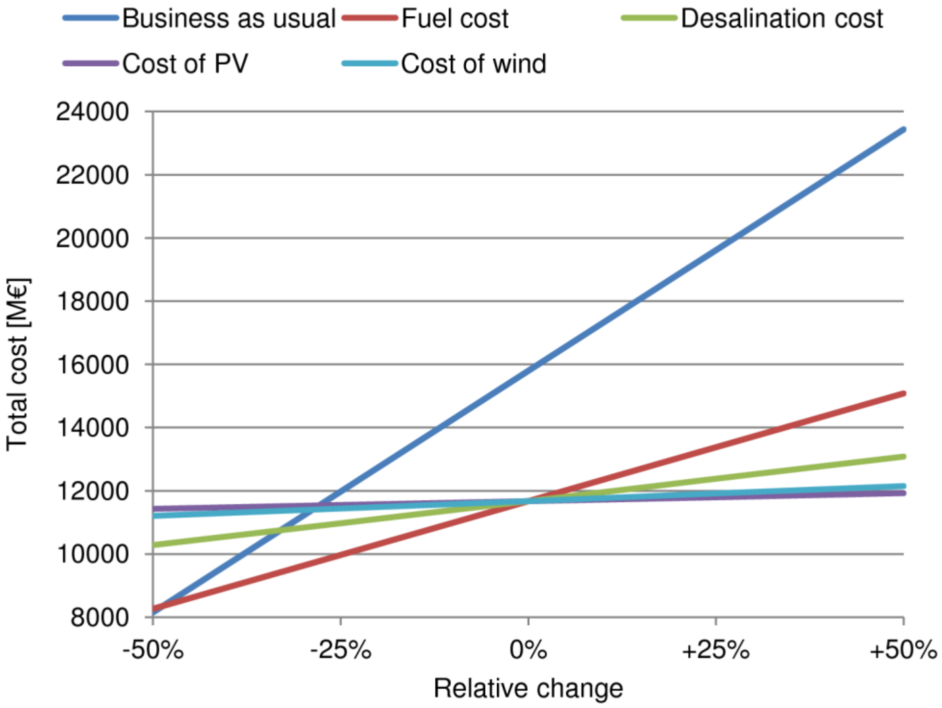

Figure 8 Sensitivity analysis

As the analysis presents, the change in the cost of the PV and wind power investments has a relatively small impact on the total annual cost of the system. The decrease of the investment prices of PV by 50% reduces the total cost by 2% while the reduction in the cost of wind power reduces the total cost by 4%. On the other hand the increase of PV investment cost by 50% increases the total cost by 2% and for wind by 4%. The cost of desalination has a significantly larger impact with its reduction by 50% reduces the total cost of the system by 12% and its increase by 50% increases the cost by 12%. The fuel prices have the strongest impact on the overall cost. Its reduction and increase by 50% varies the total costs by 29%. These results are even greater for the business as usual scenario where the increase and decrease of the fuel costs by 50% vary the total cost by 48%.

It should also be noted that the total annual cost of the system in the business as usual scenario, Scenario A, is higher than the cost of Scenario F in all cases except when the fuel prices are reduced by 50%.

6. Conclusion

The results of this work demonstrate the economic and environmental feasibility of the implementation of RES and RO desalination in the country of Jordan. It can be seen that the flexibility of the desalination system can greatly increase the potential for the penetration of intermittent RES and therefore decrease the total annual fuel consumption and with that, the total annual cost of the system and CO_2 emissions.

The calculated CO_2 emissions produced by the business as usual scenario, Scenario A, are 2.24 times higher than in the high RES penetration system with a highly flexible desalination system, Scenario F. The total costs are 1.3 times higher. The conducted sensitivity analysis has shown that the fuel cost has a very high impact on the total annual cost of the created systems. A reduction or increase of the fuel cost by 50% varied the total annual cost of the system by 29% in scenario F and 48% in scenario A.

The utilization of an integrated water and energy system utilizing a flexible RO desalination configuration with BOPS units and wind and PV power can provide both economic and ecological benefits to the Jordanian energy system. The scenarios utilizing RES have shown to be economically more feasible than the business as usual scenarios and the use of RO desalination can push the penetration of wind and PV to 76% by the year 2050.

ACKNOWLEDGEMENTS

Financial support from the European Union's Seventh Framework Programme managed by REA-Research Executive Agency htt p://ec.europa/rea (FP7/2007-2013) under Grant agreement PIRSES-GA-2011-294933 (DISKNET project) is gratefully acknowledged.

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