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The role that battery and water storage play in Saudi Arabia's transition to an integrated 100% renewable energy power system

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ABSTRACT

Saudi Arabia can transition to a 100% renewable energy system by 2040 including the integration of the power, desalination and non-energetic industrial gas sectors. Single-axis tracking PV and battery storage contribute the highest to the final LCOE of the system. By 2050, single-axis tracking PV accounts for 79% of the total electricity generation. Battery storage accounts for 30% of the total electricity demand. Battery storage and desalination plants provide additional flexibility to the energy system. Through sensitivity analysis, it is found that decreasing the capex of desalination plants results in lower full load hours (FLH) and a decrease in battery storage output. This results in lower energy system costs. However, the SWRO capex has to be reduced by 50% to achieve a reduction of 1% in SWRO FLH and a 2.1% in the annualised energy system costs. This is because it is preferable to run the expensive SWRO plants in baseload operation for total energy system cost reasons. Flexibility to the energy system can be provided at a lower cost by solar PV and battery storage than by SWRO plants and water storage. Decreasing battery capex reduces the flexibility of desalination plants further, increases single-axis tracking PV capacities, decreases wind and CCGT capacities, and ultimately results in lower LCOE. These insights enable to establish the least cost pathway for Saudi Arabia to achieve net zero emissions by mid-century.

1. Introduction

Energy storage is seen as a cornerstone of the green energy revolution [1,2]. The intermittent nature of solar and wind resources can be overcome with different types of flexibility (supply side management, demand side management, grids, sector coupling, storage), thereof energy storage is regarded as one of the most important, enabling a faster transition towards a 100% renewable energy system [3–5]. With the increase in global installed capacities of renewable energy power plants, there is a surge in demand for energy storage capacities. The Bloomberg New Energy Finances (BNEF) New Energy Outlook 2016 report forecasts the storage capacity to increase to 25 GW by 2028 from the 1 GW installed today [6].

Luo et al. [2] provides an overview of the current storage technologies and explains that pumped hydro storage (PHS) accounts for 99% of the global storage capacities. However, with improved power to energy ratios, Lithium-ion batteries are currently experiencing by far the fastest growth of all storage options and being used in small and utility-scale applications [2]. Consequently, there has been a sharp decline in the capex of batteries as presented by Liebreich from BNEF [7]. The price of the electric vehicle (EV) lithium ion battery price is estimated to have fallen from 770 €/kWh in 2010 to 243 €/kWh in 2015 [7]. The report forecasts the cost to plunge even more sharply to 162 €/kWh by 2018, a 77% fall in cost between 2010 and 2018. Based on the discussed learning curve rate of 14% - 19%, the capital cost of electric vehicles is expected to arrive at parity with internal combustion engine cars by 2022 [7]. Tesla is reported to project even steeper cost reductions with cost of electric vehicle battery packs dropping to 100 USD/kWh by 2020 [8]. These projections are further supported by Kittner et al. [9], who based on their model, expect electric vehicles to be cost competitive with combustion engine vehicles as early as 2017 and no later than 2020. The core technology of Li-ion batteries does not differ substantially between mobile and stationary applications. Thus, cost reductions in one type of battery storage also translates to cost reductions in other applications. Schmidt et al. [10] analyses future cost projections for electrical energy storage, based on learning curves. The learning rate for lithium ion battery storage in electric vehicles is estimated to be 16%. Meanwhile, lithium ion battery storage in electronics has the steepest learning rate with 30%. Utility and residential scale applications had a lower learning rate of 12% in the past. Breyer

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et al. [11] have assessed the impact of learning rates for lithium ion battery storage on battery system cost and base their analysis on a learning rate of 15–20%.

In a recent study, we investigated the least cost pathway for Saudi Arabia to transition from the current fossil-based power sector to a 100% renewable energy based system by 2050, whilst integrating the increasing desalination sector with the power sector [12]. This study was motivated by the Saudi government's new vision to embrace the country's renewable energy resources and build a future without reliance on oil. Salam and Khan [13] explain that in order to achieve energy security and minimise energy costs, Saudi Arabia has to adopt higher shares of renewable energy. In addition, Saudi Arabia has consented to achieving 'net zero emissions' by mid-21st century at the Conference of the Parties (COP21) in Paris [14]. A pathway towards achieving this vision, agreed upon by almost all nations on the planet, is what we present. The energy transition pathway discussed aims to fulfill three main criteria: i) only existing technology is used; (ii) no conflict to the Paris Agreement; (iii) low cost pathway.

In the study in [12] it was found that Saudi Arabia can achieve a 100% renewable energy power system by 2040 with a power sector dominated by PV single-axis tracking and battery storage. Single-axis tracking PV contributed 210 GW out of the total 403 GW by 2040. The contribution increased to 369 GW out of a total of 520 GW by 2050. Battery storage contributed up to 30% of the total electricity demand in 2040 and the contribution increases to 48% by 2050. The combination of PV and battery storage provided the least cost option to meet Saudi Arabia's power and desalination sector demands. This was mainly due to the sharp anticipated decrease in PV and battery storage.

In addition, the integration of the power and water desalination sector provided the least cost transition pathway as opposed to the independent transition of the two sectors. The desalination plants and water storage provide additional flexibility to the system, enabling better utilization of the renewable energy generated. This leads to a reduction in the demand for battery and power-to-gas (PtG) storage in the transition. The study [12] highlights the relationship between water and battery storage in the energy transition pathway for Saudi Arabia. Al-Nory and El-Beltagy [15] have modelled the role of water storage when high shares of renewable energy capacities are integrated into the Saudi Arabian electricity grid. The model was simulated for 7 days, on a daily resolution. A 12% reduction in total costs was determined, compared to the integration of renewable energy capacities without water storage. This study further contributes to the understanding of the role that seawater desalination and water storage can play in a 100% renewable energy power system. Similarly, Bognar et al. [16] found that the integration of SWRO plants in a hybrid wind and diesel energy system, for Cape Verde, resulted in the least electricity and water costs. These views are further supported by Lopes et al. [17]. Strang [18] discusses the benefits of storing excess electricity in water and presents an example of tidal power plant design in Australia utilising desalination plants and water storage.

Located between the Persian Gulf and the Red Sea, Saudi Arabia is one of the largest arid countries without any permanent rivers or lakes. Whilst the global average renewable water resource per capita per year is 6000 m^3, Saudi Arabia has only 84.8 $m^3/(capita \cdot a)$ [19]. In spite of the water scarcity, Saudi Arabia has the third highest water consumption per capita at 250 liters/(capita·d). This is only behind the United States and Canada. The country's water demand is expected to increase by 56% by 2035. Meanwhile, at the current rate of water withdrawal, ground water aquifers are expected to provide potable water only for the next 10–30 years [20].

To augment the fresh water resources, Saudi Arabia relies on seawater desalination, particularly to meet the municipal and industrial water demands. In 2010, 58% of the country's total water demand was met through non-renewable ground water resources, 33.5% by surface water and renewable ground water, 6% by desalinated water and 2.2% by waste water reuse [21]. In 2014, desalinated water is estimated to have met 60% of KSA's municipal water demand [22]. By the end of 2015, Saudi Arabia accounted for 15% of the global installed desalination capacity [21]. With the diminishing of fresh water resources, seawater desalination is expected to play a pivotal role in meeting Saudi Arabia's future water demands.

The Saudi Vision 2030 document, released in April 2016, illustrates the Saudi government's road map to ensure the country's development and security [23]. The document, together with the more detailed National Transformation Program 2020 document [23], highlights the government's urgency to secure the country's water resources. In addition to better management of existing renewable water resources and more water from desalination, one of the objectives is to increase the strategic water storage from 0.4 days at present to 3 days by 2020 [23]. However, this is much lower than the water storage capacities planned for by other countries in the Gulf region. The United Arab Emirates (UAE) have recently completed an underground water reservoir that can provide 180 liters of water per person per day for 90 days [24,25]. Similarly, the Water Security Mega Reservoirs Project in Qatar is expected to provide 7 days of water storage. After the final phase of construction, the reservoirs are expected to store 14,384,520 m^3 of water [26], as opposed to the current water storage capacity of 1,097,766 m^3. Research on food and water security in Saudi Arabia by Future Directions International highlight the importance of long term water storage in water-scarce Saudi Arabia [27].

Saudi Arabia's increasing demand for water storage, and the results in [12], which suggest an interplay between battery and water storage, provide the motivation for the current study: How do the technical and financial parameters of battery and water storage influence the least cost transition path to a 100% RE based power system? The research answers will demonstrate if it is cost-effective for Saudi Arabia to harness the increasing desalination and water storage demand to reduce the requirements for battery storage in the energy transition. Or, will battery storage remain the lower cost storage option for the Saudi energy transition? Existing literature discuss the potential role of desalination and water storage in hybrid energy systems on a smaller scale. In this manuscript, a more detailed study of the role of desalination plants and water storage in a full energy system is conducted.

In the sections that follow, a cost-optimised energy transition pathway for Saudi Arabia to achieve a 100% RE based power sector, seawater desalination and industrial gas sector, by 2050, is presented. A sensitivity analysis is then carried out on the pathway to understand the interplay between battery and water storage. This will enable to further optimise the energy transition pathway for Saudi Arabia.

2. Methodology

2.1. Overview

The objective of our work is to understand the features of battery and water storage that will allow for the optimal transition of Saudi Arabia's 2015 power, seawater desalination and industrial gas sector to a 100% renewable energy based system by 2050.

The approach taken to answer the research question is similar to that in [12] and additionally accounts for KSA's multiple effect distillation (MED) desalination plants and the industrial gas sector. In addition, the water storage plants are now located at the desalination site rather than at the demand site. The methodology maybe summarized as follows:

1. The energy transition from the current (as of the beginning of 2015) fossil based power system in KSA to a 100% renewable energy based power system by 2050, in 5-years time steps, is found. After 2015, there are no new fossil powered thermal plants allowed, except gas turbines, which can be shifted from firing fossil gas to RE-base synthetic natural gas (SNG), or biomethane. The existing fossil based power systems are phased out based on their lifetimes. The increase in total electricity demand and population over the years is accounted for. The optimal mix of renewable power systems to replace the phased out fossil power systems are found and the resulting system's levelised cost of electricity (LCOE) is found for every time step. The industrial gas and desalination sectors are integrated with the power sector.
2. The non-energetic industrial gas demand of Saudi Arabia, from 2015 to 2050 is found and integrated into the power system.
3. Fig. 2 presents the projected growth in the industrial gas demand in Saudi Arabia. To attain a 100% renewable energy future, our work assumes that over time the industrial gas demand is met from SNG. This can be achieved through power-to-gas plants (PtG) that comprise of two processes already used in industry: electrolysis and methanation [28,29]. PtG plants convert renewable electricity to renewable methane that can be stored in the existing gas infrastructure and used as per conventional natural gas or used for the industry.
4. Seawater desalination demand in KSA from 2015 to 2050 is determined and the corresponding desalination capacities integrated into the system. After 2015, seawater reverse osmosis plants are allowed to be installed due to the dominance of the technology in the Saudi Arabian desalination market. Multiple Effect Distillation (MED) plants are considered due to the low thermal consumption and lower electricity demand than seawater reverse osmosis (SWRO) [30,31]. The waste heat from the power system is used to meet the thermal demand of the MED plants.

   Multi stage flash (MSF) desalination capacities that were online up to 2015 are included and phased out based on the lifetimes. MSF stand alone plants are excluded due to the relatively higher thermal consumption compared to MED plants [30,31]. MED and MSF cogeneration plants are excluded due to the requirement for fossil powered thermal power plants [32].
5. Once the successful energy transition has been set up, the capex of the battery storage and SWRO desalination plant is varied, separately, to identify the impacts on the total system costs. Thus a sensitivity analysis is carried out to understand the relationship between battery and water storage.

The final results of the integration of the power, desalination and gas sectors is discussed in [26]. In this paper, we focus on the battery and water storage aspects of the energy transition.

2.2. Model overview

The LUT Energy System Transition model is utilised for the design and analysis of the energy transition as discussed in [12]. The energy model is based on the linear optimization method with interior point optimization and designed in an hourly temporal and 0.45° x 0.45° spatial resolution. The model optimises the installed RE capacities, cost of electricity generation and generation ramping such that the total annual cost of the energy system is minimised.

It is composed of all relevant power generation and storage technologies, respective installed capacities and different operation modes of these technologies. A key feature of the model is its flexibility and expandability besides the hourly resolution for a full real year. Detailed information on the construction and operation of the hourly linear optimisation model is presented in [33–36].

Fig. 1 illustrates the LUT model. For the energy transition, the model determines the optimal combination of the components that meets the electricity demand of every hour for the time period from 2015 to 2050, in 5-years time steps.

2.3. Input data – power, desalination and the industrial gas sector in KSA

The input data is similar to the data presented in [12] except for the adjusted PV capex assumptions, additional MED desalination capacities and the non-energetic industrial gas sector. Thus, this section provides an overview of the data with details of the additional input data. Table 1 presents the updated PV capex numbers used for this paper, based on recent PV capex projections from [37].

Table 2 illustrates the increase in electricity demand assumed for Saudi Arabia from 2015–2050 [38–40]. The electricity demand

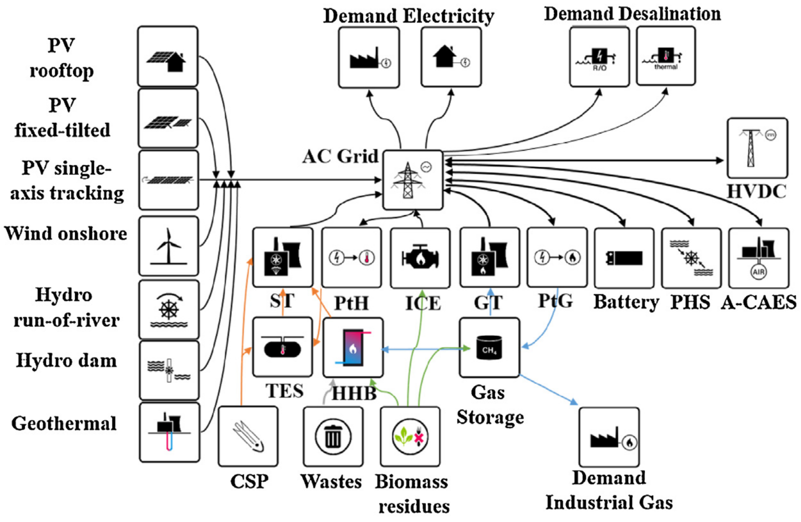

Fig. 1. Block diagram of the LUT Energy System Transition model used for Saudi Arabia.

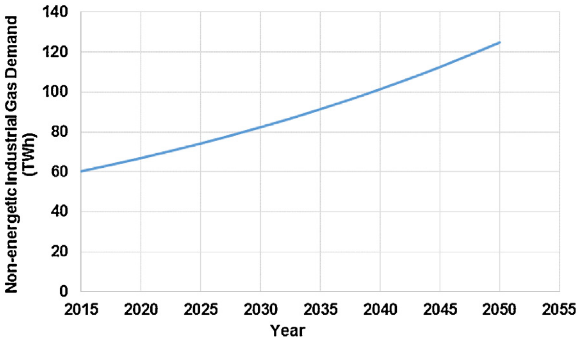

Fig. 2. Variation in non-energetic industrial gas demand for Saudi Arabia.

in 2015 was taken from [38,39]. The World Energy Outlook [39] projects a compound annual growth rate of 2.7% for the Middle East. This was then applied to the demand of 289 TWh in 2015 to project the Saudi electricity demand in the years to come. The LUT model optimises the renewable energy power plants necessary to meet the increasing electricity demand over time.

Table 3 presents an overview of the desalination demand from 2015 to 2050 and the installed capacities by 2015. The methodology used to determine the desalination demand is described in [12]. The table also accounts for the MED technologies online by 2015. After 2015, the model optimises the SWRO and MED stand alone desalination plants required to meet the desalination demand. The optimization is based on the availability of excess heat in the energy system and the cost effectiveness. The cost of the desalination technologies is presented in Appendix A (Table A1). Cost projections for SWRO is based on the model described by Loutatidou et al. [41]. The projections display a learning rate of 15%, as explained in the maiden paper on learning rates of SWRO [42] and an annual growth of desalination capacity slightly higher than 20%. The methodology used to project the technical and financial parameters of SWRO is presented in [12]. All the technical and financial parameters of the power plant technologies utilised by the model are also provided in [43]. Fig. 2 presents the expected growth in non-energetic industrial gas demand in Saudi Arabia [44]. In our model the aim is to ensure that by 2050, the non-energetic industrial gas demand is met from renewable energy. In 2015, the industrial gas demand is met with fossil natural gas. However, over time, PtG plants produce the SNG required. The increase in cost of fossil natural gas over time and the decrease in cost of PtG plants, makes it viable to produce SNG.

3. Results

The three scenarios modelled are described below. The objective of each simulation scenario is to determine the energy system with the least total annualised cost, based on section 2.2 and the technical and financial assumptions of all components presented in Fig. 1. Conducted as a sensitivity analysis, the difference between the simulation scenarios are the SWRO and battery capex values. Different capex values result in different optimised energy systems and system costs. By studying the resulting energy systems and costs, discussed in the following subsections, it is possible to understand the flexibility provided by SWRO and battery plants to the energy system.

Table 1
Updated PV capex assumed in this research [37].

		2020	2025	2030	2035	2040	2045	2050
PV fixed-tilted	€/kWp	580	466	390	337	300	270	246
PV single-axis	€/kWp	638	513	429	371	330	297	271

Table 2
Variation in the electrical energy consumption of Saudi Arabia from 2015 to 2050.

	Total Electricity Consumption (TWh)
2015	289
2020	330
2025	377
2030	431
2035	492
2040	563
2045	643
2050	734

1. Integrated scenario: This section presents an overview of the optimal transition pathway for the power, desalination and non-energetic industrial gas sectors in Saudi Arabia. The objective of each simulation scenario is to determine the energy system with the least total annualised cost, based on section 2.2. The water storage behavior and desalination plant operation is illustrated. Detailed discussions of the technologies and costs for the optimised transition pathway for Saudi Arabia is provided in [43].
2. Integrated scenario with decrease in SWRO capex: In this scenario, the same simulation as in point 1 is run, but for different SWRO capex values. This helps to understand the impact of SWRO plants on the optimal energy transition path.
3. Integrated scenario with decrease in battery capex: In this scenario, the same simulation as in point 1 is run, but for different battery capex values. This helps to understand the impact of battery storage on the optimal energy transition path.

3.1. Integrated scenario

Fig. 3 (left) presents the variation in the LCOE during the energy transition and the contribution of the different components to the LCOE. The LCOE decreases from 139.7 €/MWh in 2015 to 41.5 €/MWh in 2050. KSA achieves a 100% renewable energy system by 2040 with an LCOE of 48.9 €/MWh. Single-axis tracking PV and battery storage is the largest contributor to the LCOE by 2050, followed by wind power plants. As shown in Fig. 3 (right), by 2050, single-axis tracking PV accounts for 377.5 GW out of the total power plant capacity of 600 GW. Battery storage provides a total output of 329 TWh_{el} that accounts for 30.3% of the total system electricity demand.

Fig. 4 (left) illustrates the increase in water desalination and storage capacities to meet the desalination demand. SWRO desalination is the preferred technology due to the low electricity consumption. MED stand alone plants account for less than 1% of the desalination demand due to the low availability of excess heat in the system. By 2050, there is 58 880 614 m^3/day of SWRO plants and 1 531 649 m^3 of water storage. At times of excess electricity production, larger volumes of water can be desalinated and stored in water storage. When there is lower electricity production, the water in storage can be pumped to meet the water demand. In 2050, water storage capacity is 3% of the daily desalination demand. Fig. 4 (right) illustrates the variation in the water storage for 2030. The water storage fluctuates on a daily basis, although not a large variation. The water storage is used mostly in the evening hours. The full load hours of the SWRO desalination plants is estimated to be 8707 h, which is baseload operation. Water from storage is used to supplement the remaining 53 h.

Table 3
Desalination demand and capacities required to meet KSA's increasing total water demand. The desalination capacities after 2015 will be determined by the model.

		2015	2020	2025	2030	2035	2040	2045	2050
Population	mill	31.50	34.40	36.85	39.13	41.24	43.14	44.76	46.06
Total water demand	mill m^3/day	65.4	68.5	75.6	81.0	88.6	96.7	105.0	112.6
Desalination demand based on	mill m^3/day	19.1	21.8	27.5	32.0	38.4	45.2	53.8	58.7
Final non-renewable water resource used	mill m^3/day	8.9	7.9	5.8	3.9	6.2	8.5.	0	0
Actual desalination demand	mill m^3/day	10.2	13.9	21.7	28.2	32.3	36.7	53.8	58.7
Installed capacities									
SWRO	mill m^3/day	2.7							
MSF stand alone	mill m^3/day	1.52							
MSF cogeneration	mill m^3/day	2.73							
MED stand alone	mill m^3/day	1.57							
MED cogeneration	mill m^3/day	0.95							

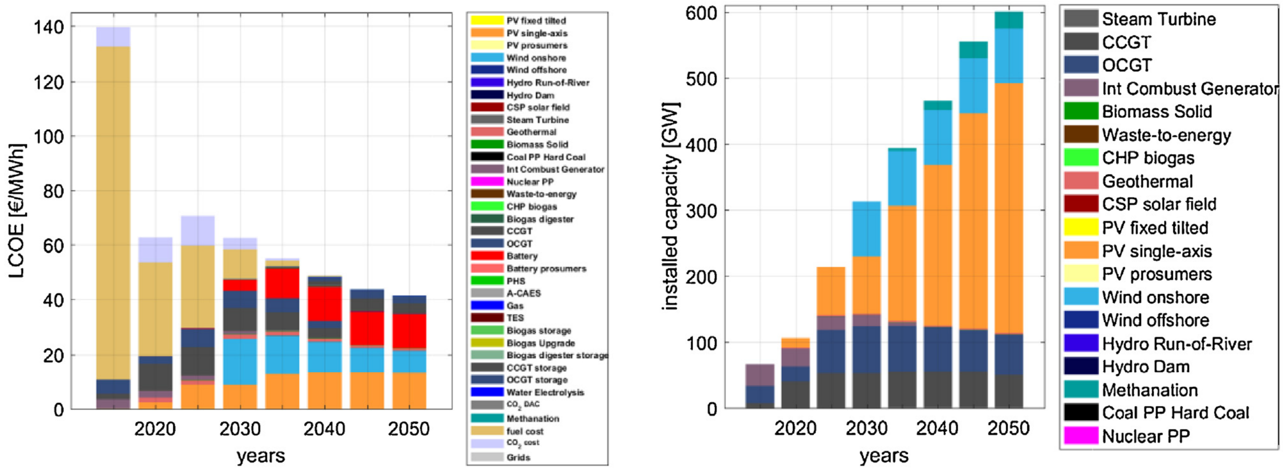

Fig. 3. Variation of LCOE (left) and installed capacities of the different power plants required (right) for the energy transition from 2015 to 2050.

Fig. 4 (bottom) illustrates the further reduced use of water storage in 2050. The SWRO plant full load hours increase to 8733, implying that the water storage is used only for 27 h. It was found that the integration of the desalination plants into the transition enabled a decrease between 1% and 6% in the annual levelised costs of the total energy system. This can be attributed to the additional flexibility offered by the SWRO plants and water storage.

3.2. Integrated scenario with decreasing SWRO capex

The SWRO capex was reduced to different percentages of the original capex in 2030 and the model re-run. Similar to section 3.1, the model establishes the least cost energy transition pathway. However, this time based on the reduced SWRO capex in 2030. All other parameters are the same as that utilised in section 3.1. The procedure was repeated for the year 2050 and the corresponding energy system analysed.

Tables 4 and 5 illustrates some of the key observations of the energy system for the year 2030 and 2050 respectively. The initial SWRO capex is estimated to be 725 €/(m^3·day) for 2030 and 415 €/(m^3·day) for 2050. In 2030, as the SWRO capex is reduced, the FLH of the desalination plants decrease and consequently water storage capacity increases. Concurrently, there is a reduction in the output of the battery storage. This is due to the increased flexibility provided by the reduced capex of SWRO and water storage plants. When the SWRO capex is reduced by 50%, the FLH of the desalination plants decreased from 8707 h to 8432 h – a reduction of 3%. The water storage capacity increased from 506 577 m^3 to 1 647 112 m^3 – accounting for 6% of the 2030 daily desalination demand. The flexibility of the water storage and desalination plants allow for a decrease in battery energy output of almost 6%. In 2050, at 50% of the SWRO capex, the SWRO FLH dropped to 8638 h from 8733 h – a reduction of 1%. The water storage capacity increased from 1 531 649 m^3 to 2 817 521 m^3 – accounting for 4.6% of the 2050 daily desalination demand. The relatively lower flexibility of SWRO plants and water storage in 2050 meant that battery storage output only reduced by 0.6%.

The reduced battery storage output and the desalination capex leads to a reduction in the total system costs. The total annualised system cost is the sum of the annualised cost of the power system and the desalination system. When the SWRO capex is halved, the annualised costs of the system decreases by about 2%. The results indicate that a large and unrealistic drop in SWRO capex is required to obtain concrete benefits for the energy system costs. It has to be noted that throughout this work a weighted average cost of capital (WACC) of 7% is assumed.

Fig. 5 (top) illustrates the variation in the SWRO FLH with the variation in capex. As can be seen for both years 2030 and 2050, there is a decrease in the FLH as the capex decreases. This is because at higher capex, the desalination plants have to be run at higher FLH to enable lower water production costs. There is a slightly steeper decrease in FLH in 2030. Fig. 5 (bottom) illustrates the variation in the battery output with the capex. The battery output decreases with the decrease in SWRO capex. This is attributed to the increasing flexibility of the SWRO plants with the decrease in SWRO capex.

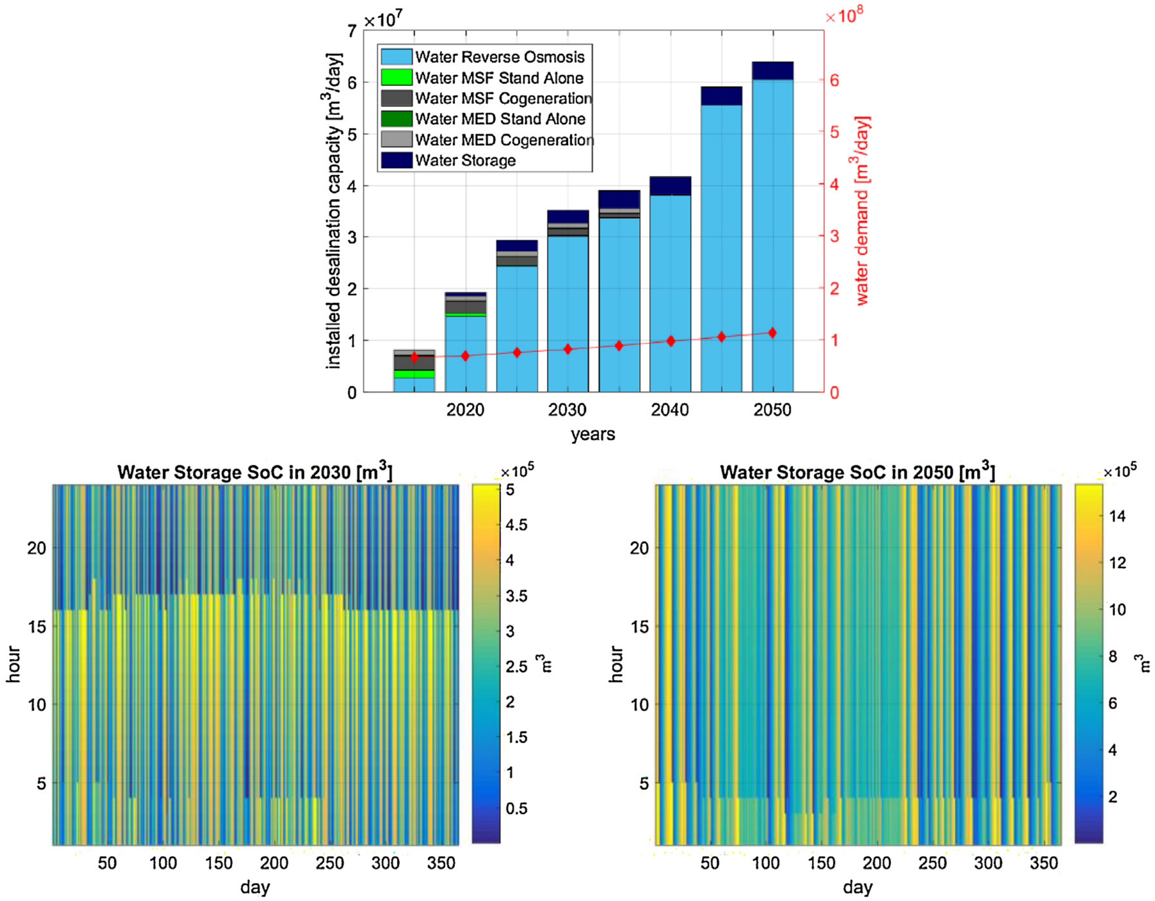

Fig. 4. Water desalination capacities required to meet the desalination demand from 2015 to2050 (top), water storage relative state of charge in 2030 (bottom left) and in 2050 (bottom right).

Table 4
Key observations for the transition year 2030 when SWRO capex is reduced (WACC assumed is 7%).

		100% SWRO Capex	80% SWRO Capex	75% SWRO Capex	50% SWRO Capex
Desalination Demand	m^3/day	28 200 000			
SWRO capacity	m^3/day	28 371 078	28 681 559	28 752 164	29 291 681
Water storage capacity	m^3	506 577	1 145 083	1 175 160	1 647 112
Relative increase in storage to 100% case			638 506	668 583	1 140 535
% of daily demand	%	2%	4%	4%	6%
SWRO FLH	hrs	8707	8612	8591	8432
Relative decrease in FLH to 100% case	%		1.1%	1.3%	3.0%
Battery output	TWh	34	33	33	32
SWRO capex	€/(m^3·day)	725	580	544	363
Battery capex	€/kWh	150	150	150	150
Desalination capex	b€	49	45	43	38
Gas storage output	TWh	0.57	0.57	0.57	0.57
Thermal energy storage output electricity	TWh	0.01	0.01	0.02	0.02
System capex	b€	280	275	274	267
Total capex	b€	329	320	317	305
Relative decrease in total capex to 100% case	%		2.7%	3.6%	7.0%
Total annualised system cost	b€	43.2	42.8	42.7	42.3
Relative decrease in annualised cost to 100% case	%		0.82%	1.03%	2.03%

The role played by gas storage and thermal energy storage is minimal compared to that of battery storage in the energy transition. As illustrated in Tables 4 and 5, the output of gas storage in 2030 is approximately 0.57 TWh_{th} and thermal energy storage is between 0.01–0.02 TWh_{th} for all SWRO capex values. Similarly in 2050, the output of gas storage is between 2.8–2.9 TWh_{th} and thermal output is between 14–16 TWh_{th}. The output of gas and thermal energy storage increase from 2030 to 2050, due to the increase in electricity demand. However, there is no influence from the decreasing SWRO capex.

3.3. Integrated scenario with decreasing battery capex

To determine the impacts of battery capex, the energy transition was modelled for 90% and 80% of the full battery capex. The SWRO capex was not modified. Table 6 illustrates some of the key observations for the 2030 energy system.

Table 5
Key observations for the transition year 2050 when SWRO capex is reduced (WACC assumed is 7%).

		100% SWRO Capex	80% SWRO Capex	75% SWRO Capex	50% SWRO Capex
Desalination Demand	m^3/day	58 699 992			
SWRO capacity	m^3/day	58 880 614	59 020 730	59 093 596	59 522 416
Water storage capacity	m^3	1 531 649	2 080 367	2 440 161	2 817 521
Relative increase in storage to 100% case			548 718	908 512	1 285 872
% of daily demand	%	3%	4%	4%	5%
SWRO FLH	hrs	8733	8712	8701	8638
Relative decrease in FLH to 100% case	%		0.2%	0.4%	1.0%
Battery output	TWh	329	328	327	327
SWRO capex	€/(m^3·day)	415	332	311	208
Battery capex	€/kWh	75	75	75	75
Desalination capex	b€	71	65	63	56
Gas storage output electricity	TWh	2.9	2.9	2.9	2.8
Thermal energy storage output electricity	TWh	16	16.1	16.2	16.1
System capex	b€	465.9	459.4	457.7	449.4
Total capex	b€	536.9	524.4	520.7	505.4
Relative decrease in system capex to 100% case	%		1.4%	1.8%	4.0%
Total annualised system cost	b€	58.9	58.4	58.2	57.6
Relative change in annualised cost to 100% case	%		0.88%	1.09%	2.13%

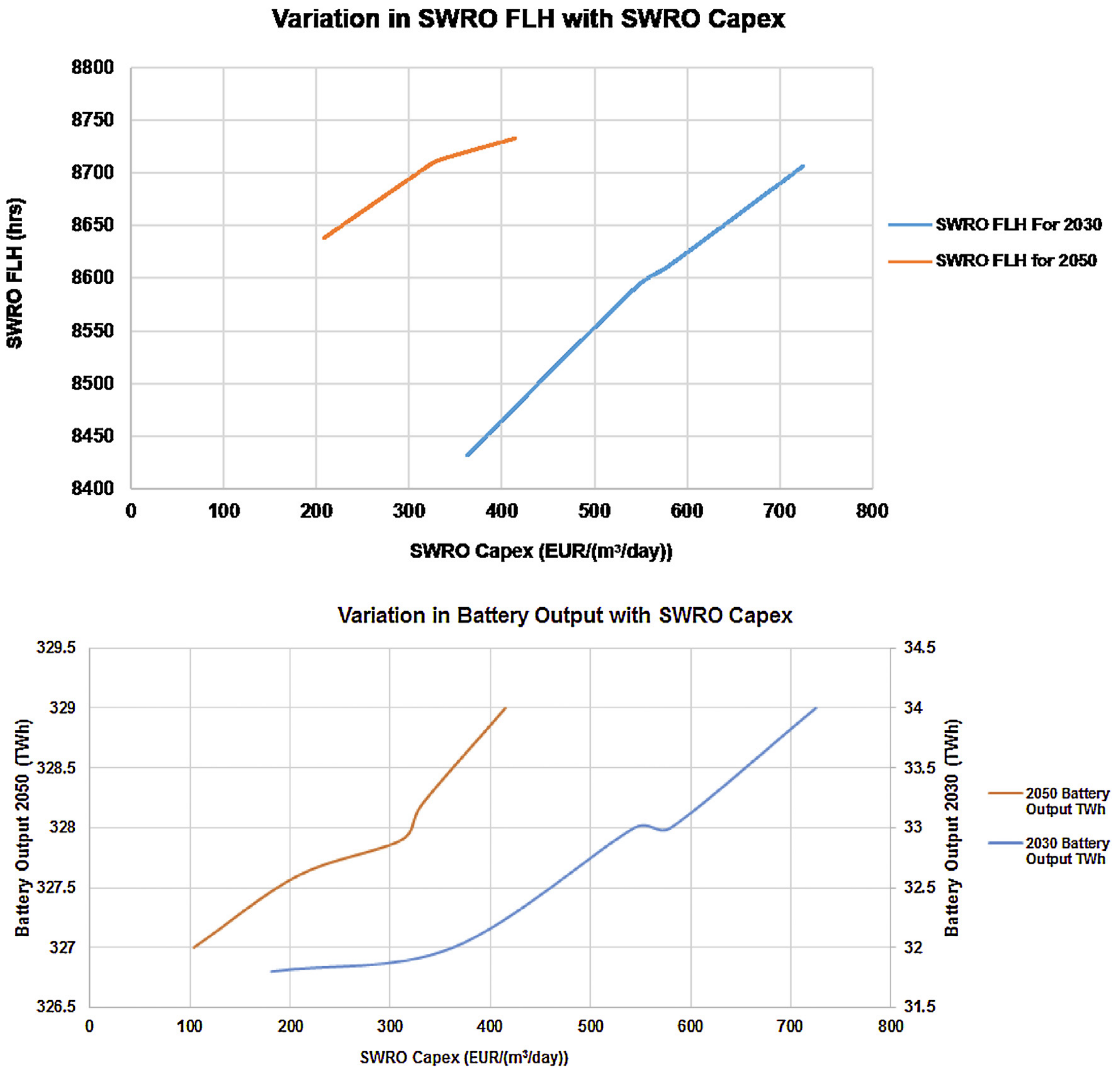

Fig. 5. Variation of SWRO FLH (top) and variation of battery output (bottom) with the SWRO Capex for the years 2030 and 2050. Expected SWRO capex are 725 and 415 €/(m^3·day) for 2030 and 2050 respectively.

Table 6
Key observations for the transition year 2030 when battery capex is reduced (WACC assumed is 7%).

		100% Battery Capex	90% Battery Capex	80% Battery Capex
Battery output	TWh	34	46	61.3
Relative change in Battery output	%		35%	80%
Battery capex	€/kWh	150	135	120
SWRO capacity	m^3/day	28 371 078	28 213 180	28 204 192
Relative change in SWRO capacity	%		−1%	−1%
Water storage capacity	m^3	506 577	53 629	36 343
SWRO FLH	hrs	8707	8756	8758
Relative change in SWRO FLh	%		0.6	0.6
Gas storage output	TWh	0.57	0.56	0.54
Relative change in gas storage output	%		−2%	−5%
Thermal energy storage output	TWh	0.01	0.009	0.008
Relative change in thermal energy output	%		−99%	−99%
Generation share – renewables	%	81.8%	83.0%	84.7%
Total Capex	b€	329	332	336
Relative change in total capex	%		1%	2%
Curtailment loss	%	3.9%	3.6%	3.4%
LCOE	€/MWh	62.5	62.4	62.1

As the battery capex is reduced, the electricity output from battery storage increases. At 80% of the battery capex, which is 120 €/kWh, the battery output increased by 80% to 61 TWh. This was accompanied by a slight increase of 1% in the full load hours of the SWRO plants. As the battery capex drops, it is beneficial to increase the output from battery storage and run the capex intensive SWRO plants on baseload. The latter approach enables lower water production costs for the SWRO plants of 0.6% in 2030. In addition, due to the increase in full load hours, the installed capacity of the SWRO plants reduced slightly. Water storage capacity dropped by 93%, due to the increase in full load hours of the SWRO plants.

For 80% of the battery capex, the gas storage output, utilised at the gas turbines, reduced by 5%. Thermal energy storage, although has the least output, decreased drastically by 99%. This can be attributed to the lower heat loss in the system due to the increase in battery storage output and consequent decrease in output from thermal power plants. The heat loss from thermal power plants is stored in thermal energy storage and used as required.

The total capex of the system accounts for the capex of the power and desalination sectors. Despite the decrease in battery capex, there is a slight increase in total capex of the system. At 80% of the capex, there is an increase of 2% in the total system capex. This slight increase can be attributed to the increase in battery storage. With the increase in battery storage, there is an increase in single-axis tracking PV power plants from 86.7 GW to 104.3 GW. This is illustrated in Fig. 6. However, the increase in capex is offset with a reduction in curtailment losses resulting in a slightly lower LCOE with the decrease in battery capex.

Fig. 6 illustrates the variation of installed capacities with the decrease in battery capex in 2030. Single-axis tracking PV experiences the largest increase in installed capacity while wind power plants decrease from 83.1 GW to 72.9 GW. Geothermal and fixed-tilted PV capacities remain the same. CCGT capacities and generation decrease from 53.1 GW to 51.9 GW and 99.9 TWh to 83.9 TWh respectively. OCGT capacities increase from 70.7 GW to 77.9 GW, but generation is zero GWh. This is attributed to the zero full load hours of the OCGT plants.

Table 7 illustrates the impacts of the decreasing battery capex on the energy system in 2050. Similar to 2030, the decrease in battery capex resulted in an increase in battery output. However, in 2050, the relative increase in battery storage output, for 80% of the battery capex was 8%. The relative increase in battery storage output, in 2030, for 80% for the battery capex, was 80%. Furthermore, the decreasing battery capex resulted in a decrease in the total system capex. This is in contrast to 2030 where the decrease in the battery capex resulted in an increase in the total system capex. The water production costs of the SWRO plants are lowered by 1.1% in 2050. This can be explained by the fact that by 2050, the Saudi Arabian energy system is run solely on 100% renewable energy. The decrease in battery capex increases the battery storage output and single-axis tracking PV capacities as shown in Fig. 7. However, the increase in single-axis tracking PV from 377.5 GW to 386.4 GW is 2% for a 20% decrease in battery

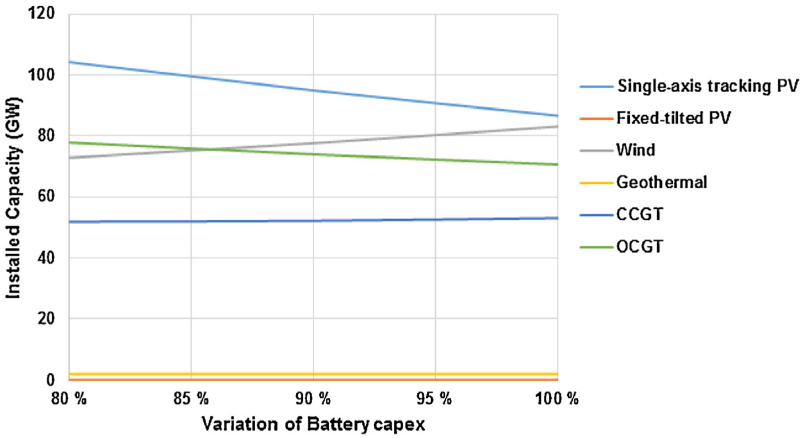

Fig. 6. Variation in installed capacities with decrease in battery capex for 2030.

Table 7
Key observations for the transition year 2050 when battery capex is reduced (WACC assumed is 7%).

		100% Battery Capex	90% Battery Capex	80% Battery Capex
Battery output	TWh	329	343	356.3
Relative change in Battery output	%		4%	8%
Battery capex	€/kWh	75	67.5	60
SWRO capacity	m^3/day	58 880 614	58 828 536	58 763 836
Relative change in SWRO capacity	%		−0.1%	−0.2%
Water storage capacity	m^3	1 531 649	1 275 466	894 929
SWRO FLH	hrs	8733	8741	8750
Relative change in SWRO FLh	%		0.1%	0.2%
Gas storage output	TWh	2.9	2.05	1.52
Relative change in gas storage output	%		−29%	−48%
Thermal energy storage output	TWh	16	5.79	0.09
Relative change in thermal energy output	%		−64%	−91%
Generation share - renewables	%	100%	100%	100%
Total Capex	b€	537	529	520
Relative change in total capex	%		−1%	−3%
Curtailment loss	%	3.9	4.3	4.5
LCOE	€/MWh	41.4	40.9	40.4

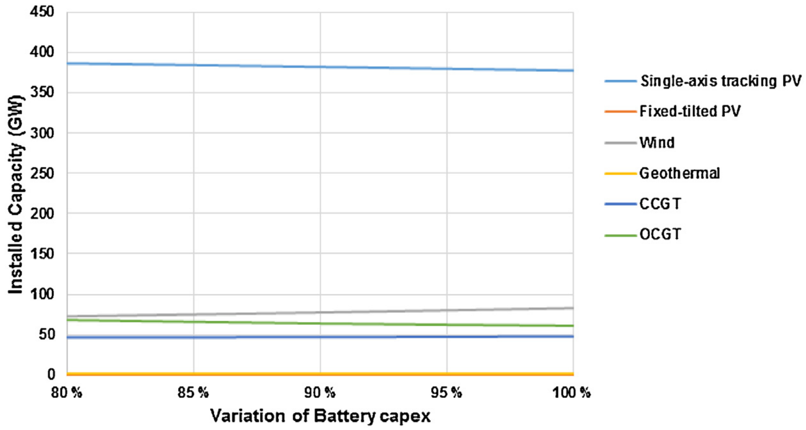

Fig. 7. Variation in installed capacities with decrease in battery capex for 2050.

capex. In contrast, the single-axis tracking PV capacities increased by 20% for the same decrease in battery capex in 2030. The capacity and generation of wind power plants reduced from 83.1 GW to 77.9 GW and 217.7 TWh to 191.1 TWh respectively. The capacity and generation of CCGT plants decreased from 48.1 GW to 46.9 GW and from 1697 GWh to 883 GWh respectively. The combination of lower capex of battery storage, single-axis tracking PV, increase in PV and battery storage capacity, decrease in wind and CCGT capacities, results in a lower total system capex. This translated to a further reduction in the LCOE from 41.4 €/MWh to 40.4 €/MWh. In addition, the low capex of battery and PV allowed for slightly higher curtailment losses. If the capex of single-axis tracking PV reduced further with the battery capex, then there may be a higher increase in installed capacity of PV and battery storage output. The scenario would then lead to steeper reduction in the LCOE (Table 7).

The flexibility of the SWRO plants reduced from 8733 FLH to 8750 FLH while water storage capacity reduced by 42%. Similarly, so did the output of the gas and thermal energy storage. The reasons for the behavior are similar to that in 2030.

4. Discussion

The reduction in the capex of the SWRO plants enables the desalination plants, together with water storage, to run on lower full load hours without increasing the water production costs. This adds another dimension of flexibility to an energy system where the desalination sector is integrated with the power sector.

At times when there is excess energy, it may be more economical to store the excess as water and utilize the water when there is not enough renewable energy in the system. This in turn leads to a decrease in the requirement for battery storage but also more installed desalination capacity.

It was found that when the SWRO capex is decreased by 50%, the relative decrease in total system capex is 7% in 2030 and 4% in 2050. This can be attributed to the reduction in desalination capex and the battery storage output. The battery storage output is reduced by 6% in 2030 and 0.6% in 2050.

In addition, Fig. 5 illustrates that the decrease in the SWRO capex affects the 2030 and 2050 transition in different ways. The decrease in capex causes the SWRO FLH to decrease more sharply in 2030 compared to 2050. In addition, the battery storage output decreases more sharply in 2030 than in 2050. This can be attributed to the fact that battery storage and single-axis tracking PV is increasingly cost competitive in 2050 as opposed to 2030. Therefore, as opposed to the 2030 system, it is more cost effective to run the SWRO plants at higher full load hours with higher battery storage output in 2050.

Meanwhile, the decrease in battery capex results in a reduction in the LCOE for 2030 and 2050, but the impact is more pronounced in 2050. In 2030, when the battery capex is reduced, there is an increase in battery storage output, installed capacity of single-axis tracking PV and a decrease in wind and CCGT capacities. The increase in capacity of single-axis tracking PV is due to the compatibility with battery storage. At 80% of the battery capex, the output from battery storage and installed capacity of single-axis tracking PV increased by 80% and 20% respectively. This resulted in an increase in total capex of the system although there was a decrease in wind and CCGT capacities. However, the increase in capex was offset by a decrease in curtailment losses, resulting in a decrease in LCOE from 62.5 €/MWh to 62.1 €/MWh. Simultaneously, there was an increase in renewable energy generation share from 81.8% to 84.7%. In addition, varying battery capex decreases the SWRO full load hours by less than 1%.

In 2050, the renewable energy generation share is 100%. The increase in battery output with the decrease in battery capex is not as significant as in 2030. At 80% of battery capex, the output increased by 8%. Meanwhile, the installed capacities of single-axis tracking PV increased by 2%. Coupled with the low PV, battery capex and the reduction in wind and CCGT capacities, the total capex of the system decreased. This results in an LCOE reduction from 41.4 €/MWh to 40.4 €/MWh. If the capex of single-axis tracking PV decreased together with the battery capex, the impacts on the final system cost and behavior will be more significant. For the given single-axis tracking PV capex of 271 €/kWp by 2050, it does not seem cost effective to increase battery storage output significantly. Decreasing battery capex results in a reduction in the total cost of the energy system and enables a faster growth of the renewable energy generation share. However, the results are more pronounced with decrease in cost of PV technologies which is very likely due to the compatibility of the two technologies.

The results demonstrate that, for Saudi Arabia, battery storage together with single-axis tracking PV provides the least cost flexibility option in the energy transition pathway. SWRO plants and water storage are not flexible because of the relatively higher capex and it is cost effective to operate these plants in baseload mode. In addition, steeper reduction in battery capex negates any flexibility provided by the SWRO plants as demonstrated in Tables 6 and 7. However, for more drastic reduction in energy system costs, the decrease in battery capex has to be accompanied by a similar drop in the capex of PV plants.

5. Conclusion

In this work we presented a study on the impacts of battery and water storage on the energy transition pathway for the Kingdom of Saudi Arabia.

The least cost pathway to achieve a 100% renewable energy system through the integration of the power, desalination and non-energetic industrial gas sectors is presented. A sensitivity analysis is carried out on the SWRO plant and battery capex values to understand the impacts on the energy transition costs.

The reduction in the SWRO capex leads to a decrease in the total system capex. However, the maximum decrease is 2.1%, observed in 2050, for a reduction of 50% of the SWRO capex. The lower SWRO capex enables desalination plants to run on lower full load hours, leading to an increase in water storage and consequently a decrease in battery storage output. The reduction in battery storage output results in a lower total system capex.

The results suggest that the relatively high capex of SWRO desalination plants does not allow this component to be operated in a more flexible way, but rather in a baseload mode. This can be explained by the fact that the energy system flexibility can be offered on a lower cost level by PV power plants and battery storage. A drastic decrease in capex, of about 50% - which is not foreseeable - by 2050, would lead to a reduction of 2.1% in the total annualised energy system cost. Therefore, SWRO plants and water storage cannot compete with the flexibility provided by the combination of PV and battery storage.

Similar to the analysis of the capex of SWRO plants, the battery capex were varied. The decrease in battery capex results in an increase in battery storage output, higher single-axis tracking PV capacities and reduced wind and CCGT capacities. The LCOE reduced by a maximum of 2.4% for a 20% reduction in the battery capex in 2050. The results suggest that the impact of decreasing battery capex alone does not lead to steep decrease in the LCOE. The reduction could be more significant if costs of single-axis tracking PV plants reduced accordingly. In addition, faster reduction in battery capex further renders the flexibility offered by SWRO plants and water storage minimal.

For a more comprehensive study the following aspects should be studied further:

1. The impacts of lower battery cost and PV cost on the energy system.
2. The impacts of having a minimum water storage capacity.
3. With the integration of the heat sector of Saudi Arabia, the thermal desalination technology, MED, may play a more prominent role. The use of free heat in the energy system for MED might result in more flexible MED desalination plants.

By understanding the interplay between battery and water storage better, it is possible to further optimise the energy transition pathway for Saudi Arabia. These insights enable to establish the least cost pathway for Saudi Arabia to achieve net zero emissions by mid-century. In addition, the study contributes to the understanding and development of battery and water storage, not only in Saudi Arabia's energy transition, but within the context of the much needed global energy transition.

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Appendix A.

Table A1
Technical and financial parameters of the seawater desalination technologies from 2015–2050.

			2015	2020	2025	2030	2035	2040	2045	2050
Seawater Reverse Osmosis	Capex	€/(m^3·day)	1150	960	835	725	630	550	480	415
	Opex fix	€/(m^3·day)	46	38	33	29	25	22	19	17
	Energy consumption	kWh/m^3	4.1	3.6	3.35	3.15	3	2.85	2.7	2.6
	Lifetime	years	25	25	30	30	30	30	30	30
Multi Effect Distillation – Thermal Vapor Compression for stand alone	Capex	€/(m^3·day)	1437	1200	1043	906	787	687	600	519
	Opex fix	€/(m^3·day)	10	13.2	15.6	18	21.6	24	24	24
	Thermal energy consumption	kWh$_{th}$/m^3	68	51	44	38	32	28	28	28

Table A1 (*Continued*)

			2015	2020	2025	2030	2035	2040	2045	2050
	Electrical energy consumption	kWh_{el}/m^3	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	Lifetime	years	25	25	25	25	25	25	25	25
Multi Effect Distillation – Thermal Vapor Compression for cogeneration	Capex	€/(m^3·day)	1437	1437	1437	1437	1437	1437	1437	1437
	Opex fix	€/(m^3·day)	47.43	47.4	47.4	47.4	47.4	47.4	47.4	47.4
	Thermal energy consumption (Total gas input required for water and electricity)	kWh_{th}/m^3	168	168	168	168	168	168	168	168
	Electrical energy consumption	kWh_{el}/m^3	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	Lifetime	years	25	25	25	25	25	25	25	25
Multi Stage Flash for cogeneration Gain Output Ratio: 8 Power-to-Water: 2.25 kW/(m^3·day)	Capex	€/(m^3·day)	2000	2000	2000	2000	2000	2000	2000	2000
	Opex fix	€/(m^3·day)	100	100	100	100	100	100	100	100
	Thermal energy consumption (Total gas input required for water and electricity)	kWh_{th}/m^3	202.5	202.5	202.5	202.5	202.5	202.5	202.5	202.5
	Electrical energy consumption	kWh_{el}/m^3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Lifetime	years	25	25	25	25	25	25	25	25
Multi Stage Flash for stand alone Gain Output Ratio: 8	Capex	€/(m^3·day)	2000	2000	2000	2000	2000	2000	2000	2000
	Opex fix	€/(m^3·day)	100	100	100	100	100	100	100	100
	Thermal energy consumption	kWh_{th}/m^3	85	85	85	85	85	85	85	85
	Electrical energy consumption	kWh_{el}/m^3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Lifetime	years	25	25	25	25	25	25	25	25
Water Transportation Piping	Capex	€/(m^3·a·km)	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053
	Fixed Opex	€/ (m^3·a·100 km)	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
	Lifetime	years	30	30	30	30	30	30	30	30
Vertical Pumping	Capex	€/(m^3·h·m)	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4
	Fixed Opex	€/(m^3·h·m)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Energy consumption	kWh/ (m^3·h·100 m)	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
	Lifetime	years	30	30	30	30	30	30	30	30
Horizontal Pumping	Capex	€/(m^3·h·km)	19.26	19.26	19.26	19.26	19.26	19.26	19.26	19.26
	Fixed Opex	€/(m^3·h·km)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	Energy consumption	kWh/ (m^3·h·100 km)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	Lifetime	years	30	30	30	30	30	30	30	30
Water Storage	Capex	€/m^3	65	65	65	65	65	65	65	65
	Fixed Opex	€/m^3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
	Lifetime	years	30	30	30	30	30	30	30	30

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