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Seawater reverse osmosis (SWRO) as deferrable load in micro grids

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ABSTRACT

Seawater desalination in the capacity range 100–1000 m^3/day is globally of increasing importance, especially when it comes to in remote costal regions. By meeting the energy demand of desalination plants by using renewable energy technologies, the environmental impact can be minimised. For water production of more than a few cubic meters per day, usually conventional constantly operating desalination systems are used requiring the implementation of expensive energy storage systems and/or a grid-connection. Variable operating SWRO plants could eventually increase the efficiency of an energy supply system by minimising the otherwise unavoidable dump load and the capacity of energy storage systems. To provide evidence for this thesis, data of the Cape Verdean Island Brava were used and three main scenarios compared. Simulations using hourly data-sets show that energy supply systems with a high wind share can benefit from deferrable loads like a variable desalination plant. Based on their flexibility, such processes are very attractive to implement as dynamic load in stochastically fluctuating renewable energy supply systems. Technological requirements for a variable operation of a SWRO plant are described, considering pressure changes and interruptions of the energy supply and water flow. For the simulation, a preliminary plant design configured by SYNLIFT Systems is used. A detailed analysis of levelised costs of water and electricity highlights options, how desalination could be applied as deferrable load in grid-connected systems in a technologically feasible and economically profitable way.

Keywords: Renewable energies; Desalination; Water cogeneration; Demand side management

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1. Background

The energy and water supply of remote and developing regions often depends on the import of fossil fuels and freshwater respectively. Nowadays energy supply systems including renewable energy sources are able to compete successfully with fossil fuel-powered systems, especially in remote regions [1,2]. The main drawbacks of implementing such systems are comparatively high initial investment costs and limitations when it comes to payback strategies.

Island grids with a high share of fluctuating energy sources implicate challenges in frequency stabilisation and require usually a high installed nominal power. To handle the intermittent character of wind energy, typical approaches for managing fluctuation on the supply side are the use of diesel generators for

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providing operational and capacity reserve, curtailment of intermittent generation, a distributed generation, complementarity between renewable sources and the integrations of energy storages [3].

A further approach is demand-side management [4]. One option of managing the demand is the application of demand–response concepts, considering a minimisation of electricity demand in periods of supply shortages by varying the price of electricity. Forecasts of solar radiation or wind conditions make such approaches possible. A second option of managing the demand is the introduction of a deferrable load. Potentially, a desalination plant can act as such a load. It cannot store electricity, but can use surplus electricity and minimise unused dump load increasing the overall efficiency.

Numerous remote regions with high solar irradiance and good wind conditions are dry and do not have access to natural freshwater reservoirs. But even if groundwater is available, excessive usage of it results in an inflow of seawater from nearby coastlines making freshwater unemployable for human consumption and other applications. Especially for coastal areas desalination is increasingly being used to reduce current or future water scarcity.

When looked at from an environmental perspective, desalinating seawater can be an ecological friendly solution if the usage of fossil fuels and the emission of chemicals in the brine can be minimised. Depending on the process applied, for desalination either thermal (distillation) or electrical (e.g. membrane-based filtration) energy is needed. Nowadays desalination plants operate continuously and require a constant energy supply. Such an inflexible operation though is not sufficient for an application as deferrable load. Constantly operated SWRO units can adapt to a variable power source in a discrete manner, cf. results of Subiela et al. [5]. The authors enunciate that a discrete, variable operation is possible, but a variable process adaption would be necessary for a technological and economically optimal implementation. Such a variable operation is addressed in this case and could enhance seawater desalination by means of renewables.

Powering desalination plants by renewable energy sources is a widespread objective, cf. [6,7]. Grid-connected as well as stand-alone, electrically and thermally driven desalination systems using wind energy are well documented and discussed in the literature [8–11]. This research study thus provides the basis for further questions.

The integration of desalination plants in the capacity range 100–1000 m^3/day into energy supply systems is not a well-established concept yet. Ecological and economic chances of combining power generation with the production of freshwater as deferrable load are addressed by Kaldellis et al. [12] and Bognar et al. [13].

Previously to the simulations presented in this paper, a model of self-sufficient energy and water supply systems was developed and implemented in general algebraic modelling system (GAMS) [14]. Based on this model energy systems considering various energy storages and desalination processes were calculated, compared and sensitivity analysis performed.

For a very specific case, a more detailed analysis is being provided in order to determine requirements of a desalination unit, if it is applied as deferrable load. As a case study, the Cape Verdean Island Brava has been selected. Due to high electricity costs and an expected increase of fuel prices in the upcoming decades, the utility ELECTRA and the government of Cape Verde are encouraged to seek for solutions in order to increase the share of renewables in their service. The government is the first in West Africa passing a renewable energy law and setting the goal to draw 50% of the country's supply from renewable energy sources [15].

The investigated island Brava is a volcanic island in Cape Verde, 450 km away from the west coast of Africa in the Atlantic Ocean. It is the smallest inhabited island of Cape Verde with a surface area of 67 km^2 and about 6000 inhabitants. The island's agricultural products serve primarily for domestic use and add value with fishing, farming, and tourism. Although the climate of Cape Verde is semi-arid, the weather on Brava in the very south of the islands is humid tropical with temperatures in the range 20–25°C. The precipitation on Brava is currently sufficient for meeting the water demand. Excessive usage of groundwater though is endangering the supply and thus alternative water supply concepts are discussed [15,16].

Previous research determined an optimal energy and water supply system out of a number of possible components: Two types of photovoltaic modules, three types of wind turbines, two diesel generators, 12 energy storage systems and four desalination processes. For desalination two thermal processes (humidification–dehumidification and multi-effect-distillation) and two electrically driven processes (mechanical vapour compression and reverse osmosis) were considered within the model [13].

The optimal system for the given island consists of wind converters, lead-acid batteries and a diesel generator set. As desalination process both the electrically driven processes were competitive. Since RO is assumed to be more adjustable to a flexible load than MVC, cf. [5], the behaviour of a variable operating SWRO unit is addressed in detail.

2. Objective

Implementing desalination as deferrable load is promising, because produced water can be stored easier and less expensive than electricity. The potentials of such a system is evaluated for the island Brava.

Goal of the research is to determine requirements and constraints of operating a desalination unit as flexible load, considering e.g. interruptions of the energy supply and part-load operation.

The research questions are whether

- the implementation of flexible operating desalination plants is beneficial in micro grids,
- a discontinuous and part-load operation is required for acting as deferrable load, and if yes,
- such an operational mode is technologically feasible and profitable.

3. Method and approach

3.1. Simulation and optimisation

Micro grids with special emphasis on the integration of renewable energy sources can be modelled and simulated by supporting tools like INSEL, TRNSYS, Ebsilon, RETscreen, HYBRID2, HOMER, and others. The simulation for the given case is done with HOMER, an energy simulation tool developed by the U.S. National Renewable Energy Laboratory [17].

Based on the previously optimised energy and water supply system using hourly data-sets of one year, the following scenarios will be compared:

ES 1: energy generation only, considering the excess electricity potential,
ES 2: energy generation and water production with a constantly operating desalination plant,
ES 3: energy generation and water production with a discontinuously operating desalination plant.

Analysing hourly data-sets of one year the required behaviour of such a flexible operation is being addressed in detail. Hoevenaars and Crawford investigated, whether or not a temporal resolution of one hour is sufficient for determining energy supply systems [18], focussing on the efficacy of temporal resolutions in the range of one second to one hour for a model that includes variable residential loads, wind converters, solar modules, diesel generators and batteries. Their findings show that optimal system configurations using diesel generators and batteries as backup are fairly close in all temporal resolutions, what justifies as hourly time-steps.

Technological requirements of a variable operating SWRO-plant are determined and discussed. For a detailed analysis using energy and water balances, as well as economic data such as discounted net present costs, levelised costs of electricity and water are calculated.

3.2. Energy supply

According to measured data from ELECTRA, energy supplier of Cape Verde, the peak-load on the island is 815 kW with an overall demand of 6.3 MWh/day. The load curve is available from log sheets in one-hour steps for typical weekdays and weekends every month for one year (2008). With a deviation of 15 s% from hour to hour and day to day a typical load curve of one year is used.

Currently power is supplied exclusively by diesel generators. The price of 1 kW h is 0.31 € (for >60 kW h/month) and 0.25 €/kW h respectively (for <60 kW h/month) on Cape Verde [19]. Although almost all villages are connected to the grid by now, many inhabitants cannot afford the usage of electricity.

The modelled diesel generator set is a Prime 800 ekW from Caterpillar. A starting fuel price of € 0.7 is set, considering an annual increase of 4% over the project period of 20 years. As wind energy converter technical data and prices of the 275 kW wind turbine from Vergnet were considered. Due to the small harbour and installation restrictions of heavy and big size equipment, larger wind turbines are not considered. Out of initially 15 energy storage systems most of them are not applicable on the island due to their minimum dimension, their market maturity or their high price. Redox-flow batteries could be competitive in near future, but within the simulation an established lead-acid battery, the Hoppecke 24 OPzS 3,000 with a capacity of 6 kW h per battery and a depth of discharge of 70% is chosen. Within the simulation the batteries are being replaced every five years and replacement costs are considered in the optimisation process.

3.3. Desalination unit

ELECTRA provides not only power but also water and sewerage services in Cape Verde. Water prices are about six to seven times higher than on the mainland [20] and about three times higher than in most European countries. Water prices vary between 2.35 €/m^3 (<6 m^3) and 4.36 €/m^3 (>10 m^3) with a maximum of up to 4.93 €/m^3 for tourists and tourism-related industry [19]. The water demand on Brava is assumed to be about 800 m^3/day, if existing sources would not be accessible. Considering a daily consumption of 600 m^3/day on the part of inhabitants, this capacity is able to supply up to 400 tourists additionally (calculating with a daily consumption of 0.5 m^3 per tourist).

The considered desalination plant consists of two separate SWRO-trains, each 400 m^3/day. The constantly operated SWRO-train would produce 400 m^3/day throughout the year. For the variable operating SWRO-trains referring to Käufler et al. [21] a maximum production of 600 m^3/day and a minimum production of 200 m^3/day are assumed. They could be operated separately or parallel. For modelling the constantly operated SWRO in HOMER, in ES 2 only the total power consumption (133.3 kW) of the two SWRO-trains is defined as a constant secondary load. The variable operating SWRO-plant in ES 3 is considered as deferrable load, with a peak load of 215.4 kW, a minimum load ratio of 17% and an average daily load of 3368 kW h/d.

Comparing a constantly operating reverse osmosis unit with a variable operating one in more detail, some technological approaches are to be underlined. The energy consumption of the variable operating desalination unit of 4.3 kW h/m^3 is based on a similar plant design configured by SYNLIFT Systems. Already Segura realised energy consumptions about 5 kW h/m^3 without energy recovery [22], approaching the calculated energy consumption of 4.3 kW h/m^3. The application consists out of standard spiral wound modules from Filmtec (SW30 HRLE400i) considering an additional energy consumption for intake and pre-treatment and safety margins for the operation of the membrane system by a flow factor of 0.85 and a salt passage of 1.5.

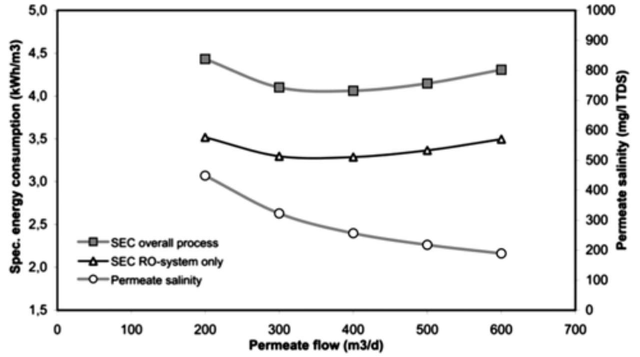

Fig. 1. Specific energy consumption (SEC) and permeate salinity vs. permeate flow of a single SWRO-train.

For a variable operating SWRO-plant with ultra-filtration as pre-treatment and energy recovery by hydraulic turbochargers a single SWRO-train delivers a nominal permeate flow of 400 m^3/d at a rate of 67.7 kW, with a specific energy consumption of 4.06 kWh/m^3. A single, variable operating SWRO-train has a maximum power consumption of 107.7 kW at a rate of 600 m^3/d and a minimum load of 36.9 kW at 200 m^3/d (Fig. 1). At nominal flow, the salt concentration of the permeate (multiplied by a safety factor) is 257 mg/l NaCl and increases to 449 mg/l at minimum flow. At a maximum flow the salinity would decrease to 189 mg/l (see Fig. 1). Since significantly more volume of freshwater is being produced at high flows and less at minimum flows and considering the safety margin on the salt passage, the average permeate salinity is certainly lower than 500 ppm.

The permeate production over the entire range of power consumption in ES 3 differs a bit from ES 2. Due to the variable operation, in ES 3 only 793 m^3/day can be produced in average instead of 800 m^3/day as in ES 2. An overview of all assumed data can be found in Table 1. The water storage has a capacity of two nominal daily productions and is modelled as energy storage equivalent (energy consumption times produced cubic meters of water).

Table 1
Input-data of SWRO unit

	ES 2: Constant operation	ES 3: Variable operation
Water consumption (m^3/d)	800	793 (closest result)
Energy demand (kWh/m^3)	4	4.3
Average load	133.3 kW h/h	3,368 kW h/d
Peak load (kW)	Constant	215.4
Minimum load ratio (%)	Constant	17
Energy storage equivalent to water storage (kWh)	(not required)	6,736
Investment costs (€)	1,344,000	1,344,000
O&M costs (€/year)	79,340	79,160

Investment and production-related costs are based on market prices. Operation and maintenance costs of 0.07 €/m^3 contain the costs for chemicals and pre-treatment, costs for the exchange of 10% of the installed membranes per year, 30,000 €/year for labour, and 2% of the investment costs for maintenance per year. The absolute data are shown in Table 1.

4. Results

4.1. Scenario results

4.1.1. ES 1: Energy supply only

In the first step, the optimal energy supply system is determined for Brava. Energy system 1 (ES 1) shows the optimal energy supply system if no desalination plant is considered for water production. In Table 2 the optimal combination of power generators can be found. ES 1 consists out of three 275 kW wind turbines from Vergnet and two diesel generator sets from Caterpillar with a nominal power of 600 kW each. Generally, only one generator set is in operation. In a worst case scenario, if no wind energy and no stored electricity is available but the load is maximal (around 815 kW), the second generator can operate simultaneously. As energy storage device lead-acid batteries with an overall capacity of 1.4 MW h are installed, which are connected to the grid through AC/DC-Converters. About 45% of the wind energy is unused dump load, as shown in the energy balance overview in Table 3.

4.1.2. ES 2: Energy supply with constantly operating SWRO

Including the additional energy demand of a constantly operating desalination plant the optimal energy supply system can change. But since the energy supply system of all scenarios should be comparable, no changes on the supply side are allowed and the energy generation units are fixed to the three 275 kW-wind turbines and the 600 kW diesel generator set. What changes instead is the size of the battery bank. The final system configuration of ES 2 is illustrated in the second row of Table 2. Additional to the daily average demand of 6.3 MW h/day the secondary load for the desalination plant is 3.2 MWh/day at a constant load of 133 kW. By integrating the desalination unit, the amount of unused electricity can already be minimised as shown in Table 3.

4.1.3. ES 3: Energy supply with variable operating SWRO

In scenario ES 3 the variable operating SWRO as deferrable load adds up to the primary load with an average energy demand of 3.4 MW h/day and a peak load of 215 kW. In ES 3 significantly less energy storage capacity is required than in ES 1 and ES 2, cf. Table 2. What is also demonstrative, is the low cost of electricity of 0.16 €/kWh compared to 0.19 and 0.20 €/kWh in ES 2 and ES 1. These costs include only costs of the energy supply system, where no investment or operation and maintenance costs of the desalination units are

Table 2
Energy supply systems in comparison, – with Conv. for AC/DC-Converter, O&M for operation and maintenance costs and *Renew. fraction* for share of renewable energies

	Wind (kW)	Gen (kW)	Battery (kWh)	Conv. (kW)	Initial capital (€)	O&M (€/year)	Total NPC (€)	CoE (€/kWh)	Renew. fraction	Diesel (L)	Operating hours (h)
ES 1	825	600	1,440	600	2,211,000	273,649	5,349,734	0.208	0.79	191,149	1,543
ES 2	825	600	1,728	600	2,273,400	470,646	7,671,674	0.194	0.72	377,683	2,901
ES 3	825	600	1,296	600	2,179,800	389,602	6,648,500	0.164	0.78	312,304	2,399

Table 3
Energy and water balances per year

	Energy by wind converters (MW h)	Energy by diesel generators (MW h)	Primary load (MW h)	Desalination load (MW h)	Dump load (MW h)	Desalinated water (10^3 m^3)
ES 1	3,627	468	2,283	–	1,681	–
ES 2	3,627	954	2,283	1,167	978	292
ES 3	3,627	789	2,283	1,249	797	289

included. The relative energy costs in ES 3 also shrink, because the overall costs are divided by a higher amount of used energy as in ES 1 and ES 2. Table 3 shows that in ES 2 and ES 3 the served load for desalination is adding up to the primary load. The unused dump load of ES 3 is the lowest of all three scenarios. In comparison to ES 2 the operating hours of the diesel generator set are reduced by 17.4% with the variable operation of the SWRO, resulting in an increasing renewable energy fraction.

4.2. Flexible operation of SWRO

The produced volume of permeate depends mainly on the available energy for the desalination plant. Due to the fact that within the simulation no load management is modelled, an unrealistic high amount of starting sequences of the diesel generator and the desalination unit are noticeable. The desalination unit in ES 3 would start 950 times, whereas 114 of these times the desalination plant would operate or pause only for one or two hours. Realistically, a load management should avoid such short operation periods by optimising the collaboration of diesel generator, battery bank and desalination unit.

In Fig. 2 the classified occurrence of absolute power variations of the variable operating desalination unit within one year is shown. The absolute power variations of 220 kW comprise activations and deactivations of the SWRO-plant already cleaned from the one- and two-hour activations. Despite the last bar in Fig. 2, representing the power variations related to activations and deactivations, the tendency is visible, that the larger the power variations are the less frequent they occur. More than 50% of the year the desalination unit operates constantly at the nominal and maximum power or is not in operation.

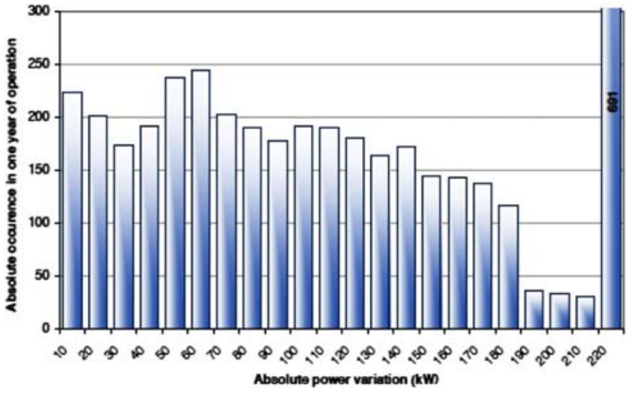

Fig. 2. Power variations of a variable operating SWRO.

Dealing with variable water flows within a RO plant, the flexibility of the SWRO system—especially the flexibility of the power consumption of the membrane system—needs to be addressed. The flexibility to adapt to the power is limited by the allowed pressure changes given by membrane manufacturers, e.g. 0.7 bar/s [23]. For a brief analysis, the period from the starting point to the nominal operation of a single RO train and to the maximum operation of two RO trains different constant pressure gradients were considered and compared, cf. Table 4.

Table 4 shows that theoretically, with a maximum gradient of 0.7 bar/s, the plant could reach maximum power within three minutes, if all delays of the plant control are neglected. One RO train could go into nominal operation within less than two minutes. With smaller pressure gradients, e.g. with 0.02 bar/s, it would not be possible anymore to go from zero to the maximum power within one hour. Assuming a high fluctuation of power supply within one hour, the applied pressure gradient should be higher than 0.05 bar/s in order to be able to activate one train in around 10 min. For a more accurate determination of required pressure alterations, simulations with a higher temporal resolution would be necessary.

4.3. Economic analysis

Following the illustrations of the technological challenges and benefits of a flexible operating SWRO plant, the economic meaning is addressed as well.

In Fig. 3 the levelised costs of water of ES 2 and ES 3 are shown, considering a constant fuel price of 0.7 €/l, a fuel price with a yearly increase of 4% and an increase of 8%, respectively, over the period of 20 years. The fuel costs influence the energy costs and therefore also the water costs.

Table 4
Power performance depending on pressure gradient

Pressure gradient (bar/s)	Period up to nominal operation of single RO-train at 67.7 kW and 50 bar (s)	Period up to max power of both RO-trains at 215.4 kW and 62.2 bar (s)
0.02	2,506	5,913
0.05	1,002	2,365
0.1	501	1,183
0.2	251	591
0.25	200	473
0.5	100	237
0.7	72	169

The fuel cost of a constantly operating desalination unit is responsible for 0.05–0.1 €/m^3 higher levelised costs of water, depending on the fuel price development. If, for any reason, a variable operating SWRO plant has higher investment or O&M costs than a constantly operating one, a financial benefit of ES 3 would hardly be noticeable. Still, desalination as deferrable load has significant advantages. For this reason another analyses focusing on the energy costs of all three scenarios is presented.

Looking at the levelised costs of electricity instead of water, the impact of an additional or a deferrable load appears more significant. Fig. 4 shows the levelised costs of electricity of ES 1, ES 2 and ES 3 depending on the fuel price for the entire investment period of 20 years. An annual increase of fuel costs of 0%, 4%, and 8% is considered again.

For the overall considered fuel costs, ES 3 is the most economic energy supply system. The main reason for this is the high fraction of energy being used and the minimised fraction of unused dump load, cf. Table 3. By increasing the share of sold kWhs the cost of each kWh shrinks. That is why ES 2 has lower electricity costs than ES 1 for 0% and 4% fuel price increase, and ES 3 the lowest costs for all scenarios of assumed fuel price development. By integrating desalination as deferrable load into the supply system, energy costs can be 20% lower than without a deferrable load, assuming a 4% increase of fuel costs.

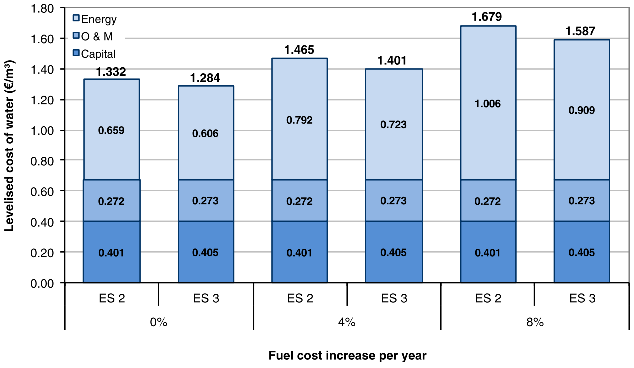

Fig. 3. Levelised costs of water depending on fuel costs.

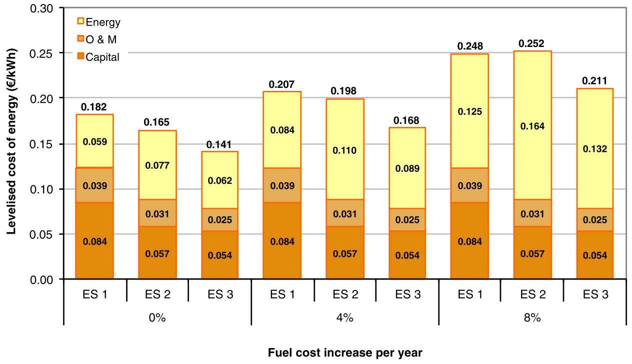

Fig. 4. Levelised costs of electricity depending on fuel costs.

It is evident, that an increasing fuel price increases the energy costs of each system. As mentioned before, for scenarios ES 2 and ES 3 no system adjustments are allowed on the supply side. This means that the generation is fixed to three 275 kW wind turbines and the 600 kW diesel generator set.

In comparison to an increasing fuel price of 8% ES 2 becomes more expensive than ES 1, since the renewable energy share of ES 2 is lower than of ES 1, cf. Table 2. The higher energy demand is met by excess electricity of the wind turbines but also by the diesel generator. Due to the lower wind penetration and therefore more operating hours of the diesel generator at a higher diesel price, in this case the levelised cost of electricity increases above the one of ES 1.

The cost structure can also be compared considering the main cost drivers. The investment costs of the batteries, the fuel costs for the diesel generators as well as the capital and the operation and maintenance costs of the SWRO plant are the main cost drivers independent from a flexible or constant operation. Fig. 5 shows the results of a sensitivity analysis considering these main cost drivers. Each cost value is being increased and decreased without changing any other input factor of the supply system. The influence of each variation of the base value on the overall levelised cost of water can be seen on the ordinate. The effects in both scenarios ES 2 and ES 3 are similar. The investment costs of the SWRO plant and the fuel costs are the main cost drivers of the supply system. Overall the constantly operating desalination plant (ES 2, left figure) is more sensitive for an increase of the SWRO-investment costs and fuel costs.

This result indicates that a variable operating SWRO is slightly more robust when it comes to increasing fuel prices, which is related to the higher wind penetration of ES 3. Overall investment costs of the SWRO plant and fuel costs are the most significant cost drivers within the supply systems. Changes of operation and maintenance costs of the reverse osmosis plant as well as the investment costs for batteries are less dominant than expected.

5. Discussion

Comparing all three energy supply scenarios a number of immediate results can be seen: For the

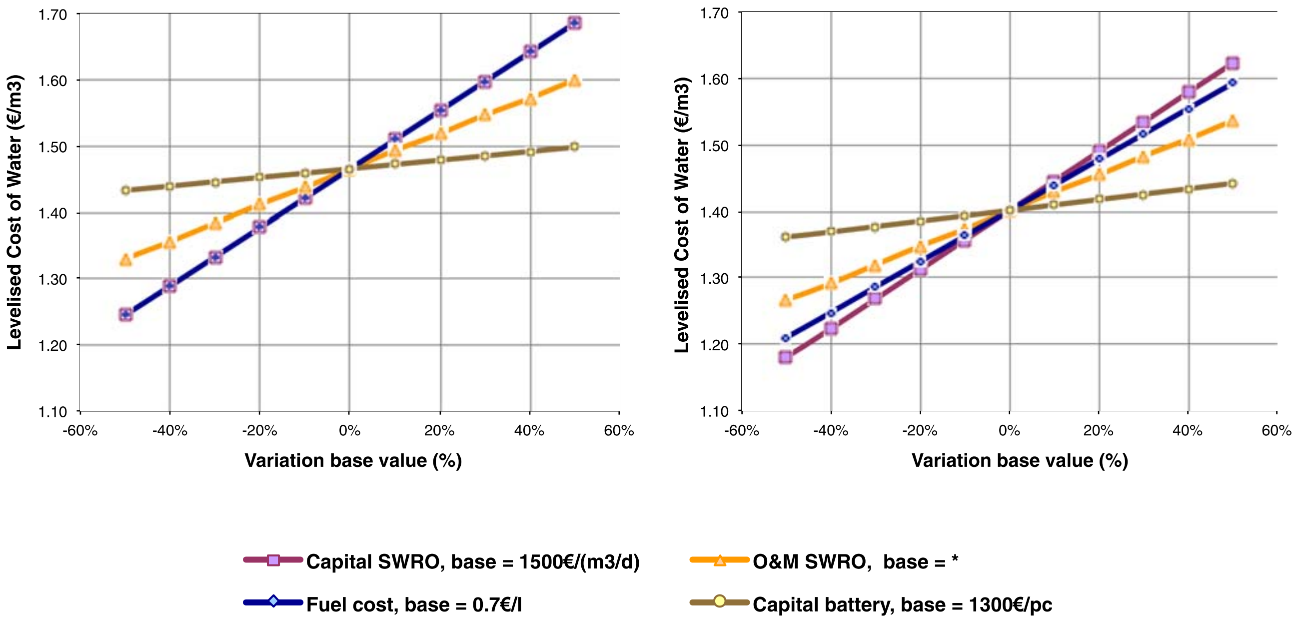

Fig. 5. LCoW depending on changing costs for ES 2 (left) and ES 3 (right), –*with O&M SWRO base = 0.07 €/m^3 for chemicals and pretreatment + 10%/y membrane exchange + 30,000 €/year labor + 2%/year Capital SWRO.

additional load of the constantly operating desalination unit (ES 2), the largest energy storage capacity is needed, cf. Table 2. Storing electricity is much more expensive than storing water. In ES 2 batteries with the overall capacity of 1,728 kWh and investments of 374,400 € are required (288 batteries, 1300 € each). A battery with this capacity can store sufficient energy for producing 432 m^3 freshwater (with an energy consumption of 4 kW h/m^3, neglecting significant energetic losses of the battery). If water imports or additional production is required, storing freshwater is much cheaper, considering storage costs of 90 €/m^3, which would mean in this sample calculation 38,880 € for water storage instead of 374,400 € for electricity storage. That is why energy supply systems with less energy storage capacities, as in ES 3, can be economically beneficial compared to ES 1 and especially to ES 2 due to the deferrable load, cf. Table 2. Depending on the size of the battery bank, the initial capital costs of the energy supply system are higher (ES 2) or lower (ES 3) than in ES 1. This result confirms conclusions by Käufler et al. [21].

Using desalination as deferrable load, not only electricity storage systems can be avoided, but also dump load and fuel consumption can be minimised.

Since a variable desalination unit is more adjustable to wind conditions, more excess electricity can be used and less fuel needs to be consumed, which is due to less operating hours of the diesel generator set. The performance of the diesel generator is almost equal in ES 2 and ES 3, cf. Table 4. The energetic performance shows that although the specific consumption in ES 2 and ES 3 is higher than in ES 1, the energetic performance is better and therefore more efficient than in ES 1 (Table 5).

Table 5
Performance of diesel generator set

	Energetic performance (kW h_{el}/L)	Power performance (kW h_{el}/h)
ES 1	2.29	284
ES 2	2.53	329
ES 3	2.53	329

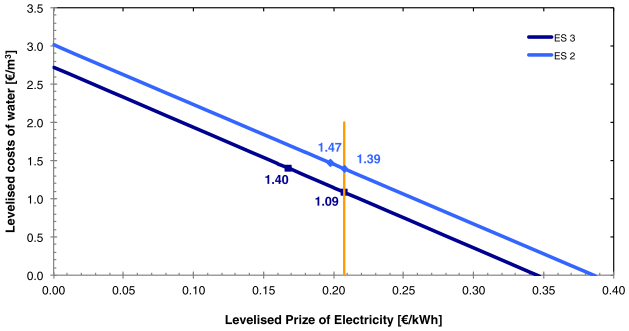

Fig. 6. Levelised costs of electricity and water.

As a further perspective on hybrid energy and water supply systems, the relation of water production costs to electricity prices are addressed. Fig. 6 illustrates the dependency of water prices on energy prices. At each point of the graph the entire costs of the energy supply system and the desalination plant are covered. The optimal solutions of the reference scenarios ES 2 and ES 3 with an assumed fuel price increase of 4% are marked on the graphs with the corresponding levelised costs of water and electricity, cf. Figs. 3 and 4.

The reference line symbolises the levelised costs of electricity of ES 1. Given the case that the energy price is constant at the level of ES 1, the water costs would be 1.39 €/m^3 using a conventional desalination plant (ES 2). Taking the same energy price of 0.209 €/kW h as reference, a flexible desalination unit (ES 3) could provide water for 24% less, i.e. 1.09 €/m^3. Since a fixed price of electricity is used as reference, the x-axis is denoted as levelised price of electricity instead of levelised cost. For each supply system, payback strategies can be developed by determining water and electricity costs by shifting the break even point on the graphs.

6. Conclusion

Options of including a desalination unit into an optimised wind-diesel energy supply system have been presented. Comparing the three scenarios ES 1 (energy supply only), ES 2 (energy and water supply with a constantly operating desalination plant) and ES 3 (energy and water supply with a variable operating desalination plant) it is depicted that ES 3 can provide the lowest and most stable electricity and water costs considering increasing oil prices. A huge benefit of ES 2 and ES 3 is that water supply can be guaranteed independent from expensive freshwater imports without major changes in the energy supply.

Simulations based on hourly time-steps and analysis of levelised costs of water and electricity have shown that energy supply systems with a high wind penetration as in the given case, can benefit from the integration of deferrable loads as a variable desalination plant. Based on their flexibility such processes are very attractive to be implemented as dynamic load complementing consumer induced load curves in stochastically fluctuating renewable energy supply systems.

The benefits of desalination as deferrable load in a micro grid are:

- better capacity utilisation of the fossil fuel-powered diesel generator set,
- less fuel consumption and therefore less dependency on fuel imports,
- less unused excess electricity generated by renewable energy technologies,
- saving of energy storages within the micro grid,
- lower levelised costs of electricity and water.

Requirements of a flexible operating desalination plant were determined based on analysing the time series of the island Brava. Interruptions of the energy supply as well as pressure changes up to 0.7 bar/s need to be tolerated by the SWRO unit without damaging the modules and increasing operational costs. The presented system setup is able to perform in such a manner. It could be shown, that such an operational mode is technologically feasible and profitable under given circumstances.

If, in general, a variable operation is beneficial compared to discrete adjustments to a fluctuating energy supply as discussed by Subiela et al. [5] cannot be evaluated conclusively. Since the presented results have been generated based on simulations, further research is required to provide further evidence by means of measured data. Especially the energy consumption and costs of operation and maintenance need additional verification. For this purpose it is envisaged to set up a variable operating reverse osmosis pilot plant.

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