# Energy and water supply systems in remote regions considering renewable energies and seawater desalination

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## Abstract


Islands and remote regions often depend on the import of fossil fuels for power generation. Due to the combined effect of high oil prices and transportation costs, energy supply systems based on renewable energies are already able to compete with fossil-fuel based supply systems successfully. A limiting factor for development in arid regions is the fresh water scarcity resulting from low natural water stocks and excessive groundwater usage.

How seawater desalination and remote island-grids with a high share of renewable energies can benefit each other, is still not sufficiently investigated. To answer this and related research questions, a model for optimizing self-sufficient energy and water supply systems has been developed, using the modeling language GAMS. Based on sets of hourly data various scenarios implementing energy conversion technologies, energy storage systems and desalination processes have been simulated and techno-economic optimizations accomplished. A global sensitivity and real option analysis addresses optimal system designs and finance strategies taking uncertain demand and price developments into consideration.

Key findings reflect that the integration of renewable energies is beneficial. On the Cape Verde island Brava, that has been chosen as a case study in the framework of this research, power is currently provided by diesel generators at prices of 0.25 to 0.31 €/kWh and water is sold for 2.35 and 4.93 €/$m^3$ depending on the quantity. With the recommended wind-battery-diesel and desalination supply system specific electricity costs ranging from 0.15 to 0.21 €/kWh and water costs of 1.53 €/$m^3$ are achievable.

Effects of integrating desalination as a dynamic load complementing consumer induced load curves in stochastically fluctuating energy systems are analyzed as well as the respective benefits highlighted: Excess wind energy, fuel consumption, and required energy storage capacities can be minimized resulting in lower specific electricity costs. From five thermally and electrically driven desalination processes a variable operating reverse osmosis unit is the most flexible process facing intermittent and part-load operation.

To determine the technological and economic robustness of such an energy and water supply system the most sensitive parameters are identified and various analyses performed. The approaches that have been introduced and respectively the results derived for the Cape Verde island Brava have been further underlined by investigating comparable island-grids and are transferable to a global perspective.

**Zusammenfassung**

Inseln und abgelegene Regionen sind für die Energieversorgung häufig auf den Import fossiler Energieträger angewiesen. Auf Grund hoher Diesel- und Transportkosten rechnen sich Versorgungssysteme basierend auf erneuerbaren Energien wirtschaftlich schon heute. Ein limitierender Faktor für die Entwicklung arider Regionen ist die Wasserknappheit, die in der Regel auf geringe natürliche Wasservorkommen und die Übernutzung des Grundwassers zurückzuführen ist.

In wie weit Meerwasserentsalzungsanlagen in Inselnetzen mit einem hohen Anteil erneuerbarer Energien energetische und ökonomische Vorteile bringen kann, ist noch ungenügend untersucht. Um diese und ähnliche Forschungsfragen beantworten zu können, wurde ein Modell zur Optimierung von autarken Energie- und Wasserversorgungskonzepten in der Modellierungsumgebung GAMS entwickelt. Basierend auf stündlich aufgelösten Nachfrage-, Windgeschwindigkeits- und Solareinstrahlungsdaten werden Szenarien techno-ökonomisch und ökologisch optimiert, in denen verschiedene Umwandlungstechniken regenerativer und fossiler Energien, thermische sowie elektrische Energiespeicher und Entsalzungsprozesse miteinander kombiniert werden. Eine globale Sensitivitäts- und auch Realoptions-Analyse beschäftigt sich mit Effekten von Nachfrageveränderungen, preislichen sowie technologischen Unsicherheiten und Ihren Auswirkungen auf ein langfristig robustes Versorgungskonzept.

Es wird gezeigt, dass die Integration von erneuerbaren Energien und der Meerwasserentsalzung in allen untersuchten Inselnetzen vorteilhaft sein kann. Gegenstand der Untersuchung ist die kapverdische Insel Brava, wo der von Dieselmotoren generierte Strom derzeit 0,25 bis 0,31 €/kWh kostet und Trinkwasserpreise bei 2,35 bis 4,93 €/m$^3$ liegen. Unabhänging von der Preispolitik können mit dem errechneten Konzept spezifische Stromkosten von 0,15 bis 0,21 €/kWh und Wasserkosten von 1,53 €/m$^3$ erreicht werden.

Weitere Ergebnisse sind u.a., dass eine Meerwasserentsalzungsanlage bei stark fluktuierenden Versorgungsstrukturen als dynamische Last Vorteile bringen kann: Überschüssige Windenergie, der Dieselverbrauch sowie die Kapazität von Stromspeichern können gesenkt werden und damit auch die spezifischen Stromkosten. Von den fünf betrachteten Entsalzungstechnologien ist trotz der sensiblen Membrane die variabel betriebene Umkehrosmose-Anlage die robusteste im Umgang mit unstetiger, anteiliger und abreißender Energieversorgung.

Um die technologische und ökonomische Verlässlichkeit und Optimalität des Versorgungskonzepts prüfen zu können, werden die sensibelsten Parameter bestimmt und deren Auswirkungen in weitreichenden Sensitivitätsanalysen untersucht. Vorgestellte Ansätze und Ergebnisse können durch die Betrachtung von ähnlichen Inselnetzen bestätigt und daher auch global auf weitere Regionen übertragen werden.

# Contents

# List of Figures

# List of Tables

# List of Acronyms

| | | |
|---|---|---|
| a-Si | Amorphous silicon thin-film solar cell | |
| AOSIS | Alliance of Small Island States | |
| BaU | Business as usual (scenario) | |
| bin | Binary variable to identify the interpolation range for diesel efficiency linearisation | |
| $c_{CO_2}$ | Specific carbon dioxide emission cost | [€/t$CO_2$] |
| $c_{E,O\&M}$ | O&M cost as a specific cost based on the electricity produced | [€/kWh y] |
| $c_{fuel}$ | Specific fuel oil cost based on the energy inside the fuel | [€/$kWh_{fuel}$] |
| $c_{land}$ | Specific mean land cost | [€/$m^2$] |
| $c_{P,O\&M}$ | O&M cost as a specific cost based on the installed power | [€/kW y] |
| $c_{plant}$ | Capacity specific cost of the type of desalination plant | [€/($m^3$/d)] |
| $c_{rep,E}$ | Specific energy replacement cost | $[\frac{e/kWh}{replacement}]$ |
| $c_{rep,P}$ | Specific power replacement cost | $[\frac{e/kW}{replacement}]$ |
| $c_{Res}$ | Specific cost of resource consumption and depletion | [€/t] |
| $c_{w,O\&M}$ | O&M cost as a specific cost based on the water produced | [€/kWh y] |
| $c_{wss}$ | Specific capacity investment cost | [€/$m^3$] |
| $c_E$ | Specific energy investment cost | [€/kWh] |
| $c_P$ | Specific power investment cost | [€/kW] |
| c-Si | multi crystalline solar cells | |
| CAES | Compressed air energy storage | |
| $Capacity_{Desal}$ | Installed production capacity of desalination plant technology | [$m^3$/d] |
| CdTe | cadmium-telluride thin-film photovoltaic module | |
| CIS | copper-indium-selenium thin-film photovoltaic module | |
| CSP | Label of the concentrated solar power subsystem | |
| d | Set of all days in the time-frame of the model | |
| DSM | Demand Side Management | |
| $Deration_i$ | Losses coefficient of subsystem "i" other then conversion | [-] |

| | | |
|---|---|---|
| Desal | Label of the desalination subsystem | |
| diesel | Label of the diesel generators subsystem | |
| DP | Diesel price | |
| $Dump_{el}$ | Flux of electric energy being dumped out of the system | [kWh/h] |
| $Dump_{th}$ | Flux of thermal energy being dumped out of the system | [kWh/h] |
| $E_{cons,el}$ | Electricity consumption of the desalination system to produce desalted water | [kWh/m$^3$] |
| $E_{i,in}$ | Flux of electric energy entering the technology of subsystem "i" | [kWh/h] |
| $E_{i,out}$ | Flux of electric energy leaving the technology of subsystem "i" | [kWh/h] |
| $E_i$ | Installed energy capacity of the technology of subsystem "i" | [kWh/h] |
| ESS | Label of the electric energy storage subsystem | |
| $\eta$ | Efficiency of conversion or round-trip efficiency | [-] |
| $\eta_{el}$ | Electrical efficiency of conversion, produced electricity - spent energy ratio | [-] |
| $\eta_{th}$ | Thermal efficiency of conversion, produced thermal energy - spent energy ratio | [-] |
| $Exist_i$ | Binary variable that allow the size of the system to be either inside the range or zero | |
| $f_{O\&M}$ | O&M cost factor as a percentage of the investment cost | [y$^{-1}$] |
| FLH | Full load hours | [h/y] |
| i | Interest rate | [–] |
| $H2_{PEMFC}$ | Hydrogen energy storage system with proton exchange membrane (fuel cell) | |
| $H2_{Engine}$ | Hydrogen energy storage system coupled with combustion engine | |
| HDH | Humidification-Dehumidification (desalination technology) | |
| $k_{CO_2}$ | Energy specific $CO_2$ emission from the fuel | [$\frac{tCO_2}{kWh_{fuel}}$] |
| $k_{LU}$ | Area coefficient for auxiliary space needed | [-] |
| LA | Lead-acid battery | |
| $\lambda$ | Weighting factor of interpolation for diesel efficiency linearisation | [-] |
| LCoE | Levelized costs of electricity | [€/kWh] |
| LCoW | Levelized costs of water | [€/m$^3$] |
| Li-ion | Lithium-ion battery | |
| Load | The hourly electric load of the island under exam | [kWh/h] |
| Losses | The hourly parasitic losses in terms of fraction of the energy stored | [h$^{-1}$] |
| $LU_i$ | Specific land use of the technology of subsystem "i" | [m$^2$/kW] |

| | | |
|---|---|---|
| $\mathrm{MaxP_i}$ | Maximum size bound for the technology of subsystem “i” | [kW] |
| MD | Membrane Distillation (desalination technology) | |
| MED | Multi-Effect Distillation (desalination technology) | |
| MVC | Mechanical Vapour Compression (desalination technology) | |
| $\mathrm{MinP_i}$ | Minimum size bound for the technology of subsystem “i” | [kW] |
| NaS | Sodium-sulphur battery | |
| NiCd | Nickel-cadmium battery | |
| NPC | Net present costs | |
| ORC | Organic rankine cycle | |
| p | risk-neutral probability | |
| $\mathrm{P_i}$ | Installed rated (or peak) power of the technology of subsystem “i” | [kW] |
| $\mathrm{P_{W,nom}}$ | Rated power of the standard wind turbine | [kW] |
| PCM | Phase change materials | |
| PHS | pumped hydroelectric energy storage system | |
| pts | Set of all points used in diesel efficiency linearization | |
| PV | Photovoltaics and label of the photovoltaic subsystem | |
| r | risk-free rate of return | |
| RES | Renewable energy sources | |
| RO | Reverse osmosis (desalination technology) | |
| ROA | Real option analysis | |
| SIDS | Small Island Developing States | |
| $\sigma^2$ | standard deviation (in ROA) | |
| SolarRadiation | Specific incoming solar radiation based on meteorological data | [kW/m²] |
| SOS | Special order sets (Modeling) | |
| SpecificOutput | Specific electrical energy output of the standard wind turbine | [kWh/h] |
| $\mathrm{Stored_{el}}$ | Amount of electrical energy stored in ess’ (that can be totally released) | [kWh] |
| $\mathrm{Stored_{th}}$ | Amount of thermal energy stored in tss’ (that can be totally released) | [kWh] |
| t | Set of all hours in the time-frame of the model | |
| $\mathrm{TC_i}$ | Total cost of the technology of subsystem “i” | [€] |
| $\mathrm{Th_{i,in}}$ | Flux of thermal energy entering the technology of subsystem “i” | [kWh/h] |
| $\mathrm{Th_{i,out}}$ | Flux of thermal energy leaving the technology of subsystem “i” | [kWh/h] |
| TSS | Label of the thermal energy storage subsystem | |
| $\mathrm{V_{wss}}$ | Installed storage capacity of the water storage | [m³] |
| $\mathrm{V_{cut-in}}$ | wind velocities, here cut-in | [m/s] |
| V-redox | Vanadium-redox-flow battery | |

| | | |
|---|---|---|
| var-RO | variable reverse osmosis (desalination technology) | |
| W | Label of the wind turbine subsystem | |
| $Water_{reserve}$ | The amount of water stored in the water storage system | $[m^3]$ |
| WaterDemand | The daily water demand of the island under exam | $[m^3/d]$ |
| $WaterGen_{Desal}$ | hourly water output of the desalination system | $[m^3/d]$ |
| WEC | Wind energy converter | |
| Wind1 | scenario with small wind capacity | |
| Wind2 | scenario with large wind capacity | |
| Wind1+PV | scenario with small wind capacity und PV systems | |
| WSS | Label of the water storage subsystem | |
| y | year | |
| ZnBr | zinc-bromine flow battery | |
| $\xi$ | Binary variable used to trigger the mutual exclusivity of some model variables | |