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.

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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	[€/tCO_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	
η	Efficiency of conversion or round-trip efficiency	[-]
η_{el}	Electrical efficiency of conversion, produced electricity - spent energy ratio	[-]
η_{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	
λ	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]

$MaxP_i$	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)	
$MinP_i$	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	
P_i	Installed rated (or peak) power of the technology of subsystem "i"	[kW]
$P_{W,nom}$	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	
σ^2	standard deviation (in ROA)	
SolarRadiation	Specific incoming solar radiation based on meteorological data	[kW/m^2]
SOS	Special order sets (Modeling)	
SpecificOutput	Specific electrical energy output of the standard wind turbine	[kWh/h]
$Stored_{el}$	Amount of electrical energy stored in ess' (that can be totally released)	[kWh]
$Stored_{th}$	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	
TC_i	Total cost of the technology of subsystem "i"	[€]
$Th_{i,in}$	Flux of thermal energy entering the technology of subsystem "i"	[kWh/h]
$Th_{i,out}$	Flux of thermal energy leaving the technology of subsystem "i"	[kWh/h]
TSS	Label of the thermal energy storage subsystem	
V_{wss}	Installed storage capacity of the water storage	[m^3]
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	
$\text{Water}_{\text{reserve}}$	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]
$\text{WaterGen}_{\text{Desal}}$	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	
ξ	Binary variable used to trigger the mutual exclusivity of some model variables	

Chapter 1

Introduction

1.1 Motivation

Globally, many developing regions face insufficient power supply and the lack of clean freshwater. Especially remote regions depend highly on stand-alone infrastructure systems and therefore often on the import of fossil fuels. As a preliminary work for remote regions in general, the focus is set on islands, investigating the challenges and chances of island-grids approaching a high share of renewable energies. Due to the combined effect of high transportation costs and increasing oil prices, which often range two or three times above onshore market price, energy supply systems based on renewable energies are already able to compete successfully with fossil-fuel based supply systems.

In remote and arid regions, there is not only a need to guarantee power generation, but also supplying freshwater is a common challenge. Global desertification and excessive usage of natural freshwater reservoirs diminish accessible water stocks. On islands, the unlimited usage of groundwater results in an inflow of seawater from nearby coastlines, leading to increased salt levels and making the previous freshwater unfit for human consumption and other applications. Many islands, therefore, depend also highly on freshwater imports. Ecologically friendly seawater desalination could provide a promising alternative that offers a reliable and, in many cases, less expensive water supply than the import by ships [1]. Combining renewable energy grids and desalination can have promising advantages: It needs to be proven whether implementing desalination as deferrable load, as a shiftable energy sink, can minimize unused dump-load, minimize the demand of electricity storage systems and minimize energy costs for desalination. Generally, the main question to be answered in this work is, **how seawater desalination and island-grids with**

a high share of renewable energies can benefit each other. Related research approaches deal mainly either with large-scale or small-scale applications. They usually try to answer following questions:

- how frequency stabilization can be reached in large grids, e.g in the UCTE in Europe, by energy storage systems or demand side management,
- how energy can be provided efficiently and/or renewable for large desalination plants of 500,000-1,000,000 m^3/day,
- how renewable energy technologies as thermal solar, photovoltaics or wind turbines can provide energy for stand-alone (without any grid connection), small-scale desalination plants producing only a few cubic meters fresh water per day.

Still insufficiently addressed are mid-scale grid-systems with electricity demands of 1 to 10 MWh/day and water demands of 100 to 1000 m^3/day, although the market demand is significantly increasing. Such medium-size energy and water supply systems are required for villages and small cities. Urban developments indicate, that population will be less focused in metropolitan areas and scattered in rural regions in future, but much more collected in smaller cities close to river and ocean coastlines. Already today about 70 % of the global population lives within 70 km from an ocean coastline [2].

Simulation tools for modeling micro-grids are usually developed for energy supply only. The question, if the integration of a desalination plant as energy sink is beneficial and which energy generation technology or desalination process should be used, cannot be answered. Detailed optimizations for each single energy and desalination technology combination can be calculated by commercial programs. But hardly any one considers and optimizes more than one technology constellation in comparison. In the developed model various energy and desalination technologies are considered and electrical, thermal and water flow balances simulated in an hourly resolution of one typical year. The goal of the model is to determine an optimal supply system based on technological, economic, and ecological criteria. This techno-economic optimization model is supposed to serve as a support tool for decision processes.

1.2 Research objective

The goal of this work is to analyze effects of integrating desalination into an island-grid with a high share of renewable energies. Some research questions to be answered in this work are:

- Can desalination enhance a micro-energy grid with a high share of fluctuating energy sources and contribute to the grid-stability?
- What effects does desalination have on the amount of dump-load, the required capacity of batteries and on the total costs?
- What solutions exist to integrate the energy demand of a desalination plant to the grid?
- How flexible do desalination plants need to operate in order to be applicable as a dynamic load?
- What is the techno-economic optimal energy supply scenario for a specific case study?
- How does the choice of electricity storage technologies influence the optimal energy and water supply system?
- How do changes of the diesel price, the energy demand and prices of main components affect the system design?
- Are local and global sensitivity analysis or a real option analysis applicable approaches to determine the robustness of a system facing the uncertainty of oil prices and demand structures?
- How adaptive is the model to other case studies and varying input data?

These and other related questions will be answered in the following chapters.

1.3 Structure of thesis

The thesis is structured in seven main parts: After giving a short introduction, the background of the research work is presented in chapter 2. The focus is set on technological characteristics of decentralized energy generation and water supply. In chapter 3 initially available simulation tools for energy grids, energy generation components as well as simulation tools for desalination processes are presented. GAMS (General Algebraic Modeling System), the Cplex solver and the simulation environment SimEnv are presented as modeling and optimization tool. How ecological perspectives and indicators are included in the model as well as the theory and goal of real options as economic decision tool is described within the methodology chapter. The model itself is presented in chapter 4. First the main functions and constraints are derived. Each technological component is modeled individually. The energy and water flows, the costs and the input data used for each component are described separately section per section and appear therefore very detailed. The chapter is rounded up with remarks on limitations of the model. In chapter 5 the investigated case-study is introduced. The results in chapter 6 are structured in sections, beginning with the recommended supply system and the consideration of various scenarios, determining the optimal technologies and components. After addressing the interferences of energy storage systems and desalination processes, some local and global sensitivity analysis give answers about the robustness of the supply system and each component. The approach and results of the real option analysis, taking into account the uncertainty of fuel prices, are also presented and discussed. Results of comparable islands allow a grading of the analytical approach and the results. The work ends with the conclusion of relevant findings and the recommendation fur future research in chapter 7.

All technologies, approaches and projects introduced, are based on comprehensive literature review, on interviews with companies and developers and on collaborations with other researchers in a time frame of four years. Specific research fields were also examined by students within their Bachelor or Master thesis and are cited in the relevant sections.

Chapter 2

Background

2.1 Energy supply structures

Energy engineering in general deals with technical solutions for supplying energy in various forms, from primary energy sources to effective energy for end users. Amongst others it comprises aspects of chemical, mechanical and electrical engineering and works on energy efficiency improvements. It analysis the demand and the supply of electrical or thermal energy and designs supply options by energy conversion processes. Energy systems consist of a number of stages. A very simple energy system consisting of only a single chain is illustrated in Fig. 2.1.

Between others, the goal of energy engineering is to design reliable power supply systems to match an existing or forecasted electricity demand. Since the 1970s, after the OPEC oil embargo 1973, the field of energy engineering expanded including new technologies and interdisciplinary knowledge developed referred to as energy analysis in a wider perspective. Renewable energy harvesting and first demand side management approaches were looked at to increase the independence from oil.

Energy engineering for remote regions, such as islands or remote villages, faces its own challenges and constraints. Depending on the location of the remote regions, the common method of rural power supply is either grid-extension, where applicable, or the utilization of diesel generators. Since grid-extensions are rarely possible and,

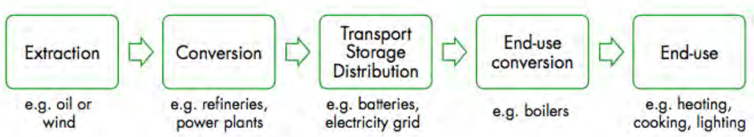

Fig. 2.1: *Simple chain from extraction to end-use within an energy supply system*

depending on the distance to the next grid, go usually hand in hand with disproportionately high infrastructure investments, the decentral use of diesel generator sets is widespread practice. However, the consumption of expensive fuel makes them not only for ecological but also for economic reasons increasingly unattractive [3].

Nowadays in remote regions, energy supply systems including renewable energy sources are already able to compete successfully with fossil fuel-powered systems [4, 5]. 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 stabilization 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 providing operational and capacity reserve, curtailment of intermittent generation, a distributed generation, complementarity between renewable sources and the integration of energy storages [6]. Therefore such a system has to fulfill following characteristics: It should consist out of relatively small-scale components, some of them have to be flexible in terms of following the load and starting quickly within ten minutes and act as frequency regulator in combination with an adapted managing system, and black-start-ability has to be guaranteed.

Although electricity grids play an essential role in energy system analysis, they are not addressed within this work. Grid-connection is no possible solution, because complete remoteness is assumed. Electricity grids within considered island systems are not modeled. Usually all systems require a grid-extension or enhancement and the required investments are comparable.

2.1.1 Demand Side Management

As mentioned before, first energy engineering approaches under the term *Demand Side Management* (DSM) came up in the late 1970s. In a number of countries the main approach was and still is to encourage consumers to use less energy during peak hours by introducing graded electricity prices [7]. Off-peak times are usually at night time and on weekends, that's why even in some European countries power is cheaper at night than during the day. DSM though has been argued to be ineffective due to additional management costs and less effects - measured in insufficient savings for utilities.

However, in times of an increasing share of renewable energies especially in remote regions DSM gains in importance. Generally, four different DSM strategies can be identified [8]:
Peak shaving: Utilities manage the customer's consumption, e.g., by installing demand-response systems like timers for water heaters in order to reduce peak hour demand.
Valley filling: Off peak loads will be build up to fill times with low demand, for instance charging electric cars during night time. The goal is to improve the economic efficiency of a plant or system.
Load shifting: This can be accomplished by energy storage systems or deferrable loads. Electrical and thermal storages enable a separation of generation and consumption, what can be used excellent for cooling purposes.
Conservation The most efficient and obvious way of saving energy, is to reduce the entire energy load by individual savings of every single consumer.

In island grids demand can be managed in various ways, cf. the literature concerning the integration of renewables e.g. [6, 9]. Within this work, next to electrical and thermal energy storages, the focus is set on the load shifting method of seawater desalination as deferrable load. Such a load cannot store electricity, but uses surplus electricity and minimizes unused dump load increasing the overall efficiency in island grids.

2.1.2 Renewable power generation in island grids

Renewable energy conversion technologies could already be integrated successful in various island grids. Some realized examples in particular are, e.g. Porto Santo, Bonaire or El Hierro.

On Porto Santo, a Portuguese island in the North Atlantic Ocean and part of the Madeira Archipelago, a hybrid wind-diesel utility was installed in 2004. The economic mainstay on the island is tourism, which comes with high energy demands, in particular for air conditioning. The island has a size of 42 km^2 and a population between 5,000 in off-season and 20,000 during tourist season. The hybrid energy system consists of diesel engine blocks with a total capacity of 10 MW and about 900 kW installed wind capacity by Vestas wind turbines. The modular constellation of the system allows a total load coverage of the fluctuating demand on the island. The maximum wind penetration of the system though is limited to 30 % [10].

On the island of Bonaire, Netherlands Antilles, in the Caribbean Sea the world wide biggest wind-diesel-installation was implemented in 2009. About 14,000 people live on the 288 km^2 large island and consume about 205 MWh/day power with a peak load of 11 MW. The planners' target was to become the first CO_2 neutral islands with twelve wind turbines, each 900 kW, five diesel engines, each 2.5 MW to be operated on bio-fuel (first imported certified vegetable oil, later locally produced algae-oil). Based on information by the constructors and planners Enercon, MAN and Ecofys, the system operates successfully with a higher share of wind energy than expected (about 60 %). On the dry island even a desalination plant is powered by the hybrid energy supply system.

The Canary islands are also an archipelago with a high ambition to supply power and water by renewable energy sources and to become independent from fossil fuel imports. El Hierro, one of the Canary islands, supplies electricity for the population of 10,500 by diesel engines (10.5 MW), a wind farm (11.5 MW) and a pumped-storage hydropower plant (11.3 MW). However, size restrictions on the island are a limiting factor for the feasibility of additional renewable energy projects. The power is also needed for seawater desalination plants, which consume up to 40 % of the generated electricity in peak times. The supply system operates successfully since 2011.

A number of further projects to integrate renewable energies into island grids were developed and also realized as reported in the literature, e.g. in [11, 12, 13]. Therefore the implementation of renewable energy technologies in island grids can be considered as state-of-the-art.

2.2 Renewable energy technologies

All renewable energy sources are based on solar energy (solar and wind energy, biomass), the interaction of planet gravitation and planet motion (partly wind, ocean and tidal powers) and the heat stored in the earth. The state-of-the-art of the modeled technologies are presented in the following sections, the ones not modeled but still relevant in Appendix B.

2.2.1 Photovoltaics

Photovoltaic modules use the photo effect to convert solar radiation immediately to electricity (DC). Various cells and modules have been developed and are in use. They can roughly be classified into monocrystalline, polycrystalline and thin film modules. Transfer technologies do also exist but have not come out on top until now.

Crystalline silicon modules
About 90 % of commercially available photovoltaic modules (PV) are manufactured out of crystalline silicon slices, so called wafers. Neglecting the introduction of production steps from quartz sand to wafers, from wafers to solar cells and from solar cells to modules, the state-of-the-art of PV modules is presented briefly.

The silicon solar-cell production uses the comprehensive experience of the electronics industry. Silicon is a so-called indirect semiconductor, whose absorption coefficient for solar radiation shows relatively low values. Therefore solar cells made of such semiconductor material must be relatively thick (at least 50 µm). High layer thickness implies high material consumption and thus high costs. They can reach a theoretical maximum efficiency of 30 %. The losses occur due to incomplete use of the solar spectrum and because a part of the absorbed energy is converted to heat instead of electricity. Nevertheless, crystalline silicon is commonly used for photovoltaic cells, because it is still the best understood material [14].

Common commercial multi-crystalline solar cells (c-Si) reach efficiencies of about 16 %, comparable mono-crystalline solar cells 17 to 20 %. The highest efficiency reached by specifically prepared laboratory cells was 25 %, pretty close to the theoretical maximum of 30 %. Higher efficiencies can be reached by stacked solar cells or by concentrating the solar radiation. The efficiency world record for stacked solar cells is short above 40 % but can reach theoretically above 60 % [15]. For reaching higher voltage and higher currents the solar cells are connected serially and parallelly to modules and are then hermetically enclosed.

Thin-film modules

Already in the 1960s, a multitude of research and development activities have been conducted to develop cost-efficient thin film solar cells. For this purpose "direct" semiconductors are required. Compared to the wafer-based industry the thin-film PV industry is about five to seven years behind. Numerous studies show, that the cost reduction potential of thin-film modules is higher than the ones for wafer-based modules ever was and due to the flexible material the modules can also be developed to further products. Amorphous silicon (a-Si), for example, discovered in the 1970's, is such a direct semiconductor. Due to the fact that amorphous silicon forms a direct semiconductor, very thin active layers in the range of 1 µm are required and very little material is needed. Additionally this process is characterized by very low deposition temperatures and thus small energy consumption. As a consequence the costs of solar cell manufacturing are reduced tremendously compared with crystalline silicon solar cells. Further commonly used thin-film solar cells are based on cadmium-telluride (CdTe) and copper-indium-selenium (CIS). However, compared to crystalline silicon, thin-film modules do not reach that high efficiencies. Amorphous solar cells reach up to 13 % in the laboratory (8 to 10 % in mass production), polycrystalline thin films as CdTe and CIS reach up to 16 and 18 % in the laboratory, commercial solar cells around 11 %. Large thin-film PV power plants, e.g. in Germany, are the plants in Lieberoser Heide with 53 MW (CdTe) installed capacity and Solarpark Buttenwiesen with 1 MW (a-Si) [16]. Despite the low efficiencies, the lower price has a significant impact on investors and decision makers. Inverters and further components that would usually be required, are not addressed in detail.

2.2.2 Concentrated Solar Power

Although Concentrated Solar Power (CSP) concepts like DESERTEC (electricity grids between northern Africa and southern Europe using thermal solar power plants) are discussed contrary, the technology itself is still a very promising approach using solar radiation for heat production and power generation. Most CSP-technologies are applicable only for large-scale power generation above 10 MW_{el}, but some have a potential to be used even in island-grids with power demands of under 1 MW. In contrast to photovoltaics, CSP can use only the direct, not the diffused

Fig. 2.2: *Parabolic Trough (upper left), Linear Fresnel (bottom left), Solar tower (upper right) and Solar Dish (bottom right) [17]*

radiation. Therefore it can only operate at daytime under clear, sunny weather conditions.

Four main CSP technologies are commercially available or in advanced research phases. They can be divided into two main groups: linearly focusing and punctually focussing plants. The two linearly focussing CSP technologies are Parabolic Trough and Linear Fresnel, the two punctually focusing ones the Solar Tower and the Solar Dish, cf. Fig. 2.2 [17]. The high-temperature heat is provided for electricity generation with conventional power cycles using steam turbines, gas turbines or Stirling engines. Most systems use glass mirrors for concentration, which continuously track the position of the sun. The solar receiver's coating has usually a high radiation absorption coefficient and a low reflectivity. It contains a heat transfer fluid, e.g. water, oil or molten salt that takes the heat towards a thermal power cycle, where high pressure or high temperature steam is generated to drive a turbine.

In a standard electricity generation system of **parabolic troughs** the solar collector assembly has a total length of around 150 meters. It consists of several solar collectors connected to a single axis sun tracking system. Parabolic troughs are the most mature CSP technologies. The common heat transfer fluid is thermal oil, the common steam parameters are 370°C at 100 bar. For periods when the sun is not shining thermal energy storages can be used as backup system [18]. The parabolic dish, or **dish Stirling** technology is combined with a Stirling engine. The surface of the dish is covered by mirrors, which reflect light into the receiver. This receiver

can be an engine, vessel or box located at the focal point of the parabola. The fluid is heated up to 750°C and electricity is generated. Solar dishes offer the highest solar-to-electric conversion performance of all CSP systems. Other features of this design are the compact size, the option of small capacity installations, a system design without cooling water, but the same time a low compatibility with thermal energy storages [19, 20].
In a central tower installation, also called **solar tower**, an array of heliostats (sun tracking mirrors) acts as the solar collector, concentrating solar radiation onto a central receiver located at the top of a tower. Like in the other methods air or a transfer fluid is being heated, which in turn is used for electricity generation [21].
Compared to parabolic troughs, **linear Fresnel** reflectors have the advantage of a simple and less expensive design, due to linear instead of bended mirrors. Direct steam generation can also be achieved easier than at parabolic through systems, where usually heat transfer fluids and heat exchangers are needed. On the other hand, Fresnel plants are less efficient and it is more difficult to combine their design with thermal energy storages.

An option to use CSP in smaller dimensions is to apply an organic working fluid with a low boiling point in a Clausius Rankine Cycle, also called **Organic Rankine Cycle** (ORC). Due to the low boiling point of the fluid, lower temperatures and smaller plant dimensions are sufficient for electricity generation. Such a plant can operate in a power range from a few kW up to 10 MW. Low temperature levels though also mean, that by relaxing the steam the gainable enthalpy difference and therefore the overall efficiency is relatively low. Up to now ORC processes are mainly used for geothermal energy conversion, combustion of biomass and waste heat recovery. First research approaches investigate chances of combining ORC processes with CSP [22, 23].

High investment costs are the bottleneck of concentrating solar power plants. Although current developments do not prove this tendency, some studies predict a significant decrease of investment costs, due to learning curves, economies of scale and technical innovation [24, 25, 26]. A clear advantage of the thermal solar power technology is the possibility to store high temperature ($>$ 120°C for power generation) as well as low temperature thermal energy, which is significantly easier and cheaper than to store electrical energy. This way power can be supplied also after sunset for three to eight hours. An overview of applicable thermal energy storage systems is given in section 2.3. Detailed technological data concerning the efficiencies, capacities etc., are presented in Tab. 5.2 in section 5.4, where all input parameter are introduced.

2.2.3 Wind energy converters

Wind energy utilization is one the most established renewable energy conversion technologies. Humans have used windmills since at least 200 B.C. for grinding grain and pumping water. The theoretical maximum overall efficiency of wind energy converters (WECs) is capped with the Betz power coefficient of 59.3 %. Commercially available wind energy converters transform 30 to 45 % of the energy contained in undisturbed wind into electric power. A wind turbine can differ in a number of characteristics. Today the most common turbine configuration is using a horizontal axis. It consists of a tall tower, a fan-like rotor on the top that faces into or away from the wind, a generator, a controller, and other components. Most horizontal axis turbines built today are three-bladed. WECs have different dimensions and rated powers depending on the requirements from 10 kW up to 5 MW per wind turbine and differ mainly in the manufacture process and the used materials. The most important features of various state-of-the-art technologies include:

- rotor axis position (horizontal, vertical),
- number of rotor blades (one, two, three or multiple blade rotors),
- speed (high and low speed energy converters),
- number of rotor revolutions (constant or variable),
- upwind or downwind rotors,
- power control (stall or pitch control),
- wind resisting strength (wind shielding or blade adjustment),
- gearbox (converters equipped with gearbox or gearless converters),
- generator type (synchronous, asynchronous or direct current generator),
- grid connection for power generation plants (direct connection or connection via an intermediate direct current circuit) [27].

For remote regions with a peak power demand of only a few megawatt or even under one megawatt, only small wind energy converters are applicable. Whereas at the megawatt level only horizontal axis installations can be installed, for small-scale applications occasionally also vertical ones can be employed. Independently from load profiles, sometimes the installation of small wind turbines is required because of shipping difficulties in small harbours or installation restrictions for heavy and large-sized equipment. Small to medium scale wind turbines under 300 kW though are not available that common due to the upscaling process at more and more manufacturers.

What also needs to be considered is the meteorological background. In hurricane regions, e.g. the Caribbean, only hurricane-proofed wind turbines can be erected. Some manufacturers (like Enercon) do not deliver in hurricane regions, others endure wind speeds of about 70 m/s and can be folded and lowered to the ground in case of hurricane or cyclone warnings. All detailed information of modeled wind turbines are presented in section 5.4.

2.3 Energy storage systems

2.3.1 Thermal energy storage systems

Thermal energy storage systems (TSS) are mostly used in combination with solar thermal panels, heat pumps, solar power plants, biomass plants, combined heat and power plants and district heating. In the developed model up to now only heat from CSP plants and waste heat from diesel generators can be stored. No other considered power generator produces storable heat. Thermal energy storage technologies can be classified as shown in Fig. 2.3.

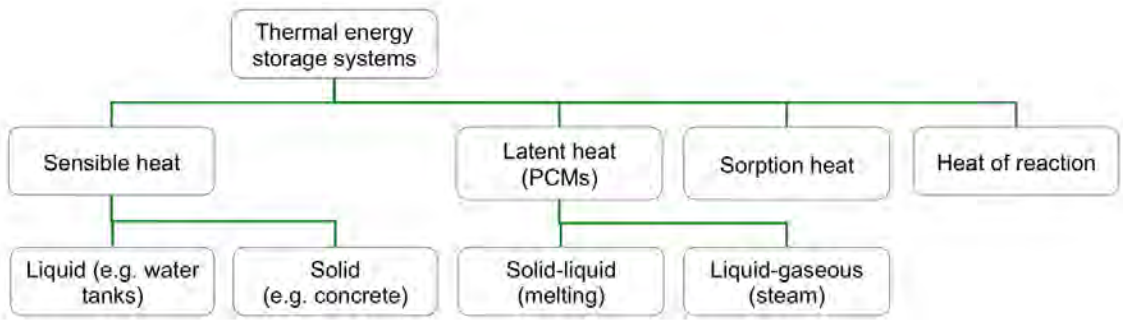

Fig. 2.3: *Types of thermal energy storage systems*

For larger power plants as CSP plants most commonly sensible heat is stored. The current status of commercial *molten salt* storage systems is based on indirect two-tank concepts. The common molten salt composition consists of 50 % KNO_3, 40 % $NaNO_2$ and 7 % $NaNO_3$. High temperature heat will be directed in one of the tanks filled with the liquid salt compound and heats it up from 290 to 390 °C. From the "cold" tank the molten salt compound will be pumped into the "hot" tank and absorbs further heat. Such molten salt tanks are usually designed to store sufficient heat for electricity generation for six to eight hours. Heat losses are assumed to be 1 °C per day and tank [17]. The molten salt storage test facility of DLR in Carboneras, Spain, e.g., has a storage capacity of 1 MWh, is kept under a steam pressure of 100 bar and can bear a maximum temperature of 500 °C. Temperatures in molten salt tanks need be be kept above 250 °C. As soon as the salt compound crystallizes, its storage capability freezes and the storage cannot be used anymore. Therefore when a molten-salt storage is not needed anymore, it can be cooled down and removed in a crystalline form. Molten salt storage systems show a limited potential for further cost reductions [28].

A further sensible heat storage is *concrete*: The basic module of a pilot plant in ANDASOL 1 in Granada, Spain, can store 5 MWh and has a temperature stability of up to 500 °C. From the solar collectors heated oil of 400 °C flows in parallel pipes through the concrete and heats it up. In case of discharge the oil disperses again through further pipes with a temperature of around 350 °C and produces through a heat exchanger steam for driving the generator. Concrete storages are usually also designed to store thermal energy for six to eight hours. Solid media storage systems represent a cost effective approach for medium and high temperature applications. Current investment costs are less than the ones for molten salt with around 35 €/kWh [17].

Latent heat storage units are usually low temperature storages used for smaller energy capacities than the ones discussed before. Steam cycles and phase change materials (PCMs) are the most common latent heat storage approaches. The basic principle of steam accumulators is, that sensible heat is stored in pressurized liquid water. Water is stored in an isolated pressure vessel in liquid and steam phase. Charging and discharging can generally occur in the liquid and in the steam phase. Latent heat storage by PCMs can principally be achieved through solid-liquid, solid-gas or liquid-gas phase changes. However, the only phase change used for PCMs is the solid-liquid one, because changes to the gas phase would require high pressures or large volumes. Commonly used organic PCMs are paraffins and fatty acids or inorganic salt hydrates. The feasibility of latent heat storage systems though has been demonstrated also for high temperatures up to 300 °C in the MW-range [28]. Aquifers and other heat storages are also possible solutions but not addressed in the framework of this study.

2.3.2 Electricity storage systems

Numerous electricity storage technologies (ESS) are in use. For micro-grids with a high share of renewable energy sources other storages are needed than for small-scale stand-alone systems or large interconnection grids. In isolated distribution networks, like the ones discussed here, the fluctuating character of most renewable energy technologies makes the usage of electricity storages indispensable.

Electrical energy storages can be structured into chemical, electrical and mechanical storages. Fossil and green fuels, hydrogen, thermochemical and electrochemical electricity storages (e.g. accumulators) are *chemical storages*, electrochemical condensators and superconductive magnetic energy storages are *electrical storages* and compressed-air, pumped hydropower, flywheels and stationary or mobile fuel storages belong to the group of *mechanical electricity storage systems*. Focussing on the typical power of some electricity storages and their energy-to-power ratio measured in time, storage technologies can be classified as shown in Tab. 2.1.

Tab. 2.1: *Electricity storage classification by duration*

	1 kW - 1 MW	1 MW - 100 MW	100 MW - 1 GW
Seconds	Capacitors, flywheels	flywheels	
Minutes	LA, Li-ion, redox-flow, ZnBr	Li-ion, NiCd/MiMH, capacitors	
Hours	LA, Li-ion, redox-flow, ZnBr	LA, Li-ion, NaS, redox-flow, ZnBr	pumped hydro, CAES
Days to weeks		redox-flow	pumped hydro, hydrogen

Within a hybrid energy supply system various energy storage technologies can be implemented. Only long-time electricity storage technologies are considered here, none for frequency stabilization. Therefore no electrical storages as capacitors and superconducting magnetic energy storages are addressed. In the model a wide range of possible technologies has been taken into consideration: Conventional batteries, high-temperature batteries, flow-batteries, hydrogen based systems, compressed air and pumped hydro storages as well as flywheels. Most common technologies will be introduced in the following; detailed input data used in the model though will be shown first in chapter 4.8.

Electro-chemical batteries

Electro-chemical batteries can be divided into external and internal storages. In contrast to internal ones, for external storages (e.g. flow batteries) the power unit can be dimensioned separately from the storage capacity. Internal electro-chemical storages can be further divided into low-temperature and high-temperature ones. Low-temperature storages for example are the lead-acid, nickel-cadmium and lithium-ion batteries requiring an ambient temperature of about 20 °C, high-temperature storages, like the sodium-sulphur battery for example, require a nominal temperature of above 250 °C.

Lead-acid batteries:
Conventional lead-acid batteries (LA) used for over a century are usually used for small but also several large applications. Low investment costs and relatively high efficiencies make this battery attractive. However, its low cycle lifetime and poor performance at extreme temperatures makes these batteries vulnerable. There are closed low-maintenance and open high-maintenance LA batteries. During charging processes and excessive charge hydrogen frees up. In open LA batteries water refilling (every three to six months) compensates the losses, in closed LA batteries the hydrogen recombines within the battery and pressure control valves are integrated, so called Valve-Regulated Lead-Acid (VRLA) batteries. VRLA batteries are almost maintenance-free but are more expensive.

Nickel batteries:
The Nickel-electrode batteries, and in particular the nickel-cadmium devices (NiCd) have a high specific energy and require little maintenance, but have high costs and a relatively low cycle life. Compared to lead-acid, these batteries are robust against extreme conditions and can be fully discharged without capacity and efficiency losses and without minimizing its cycle life. Since cadmium though is toxic, NiCd-batteries are not further considered (e.g. in Germany, their usage is prohibited.) Nickel-metal hydride batteries (NiMH) are the advanced batteries [29].

Lithium-ion batteries:
Li-ion battery installations have a significantly higher power density and energy density than lead-acid batteries and have a high application range. However, for stationary applications the cost per kilowatt hour stored is comparatively high and depending on the required capacity, it is not first choice for stationary applications [30].

Sodium-sulphur batteries:
Sodium-sulphur systems (NaS) are categorized as high-temperature batteries operating at temperatures around 300 °C. Since their electrodes are both molten, sometimes they are also called "molten salt" devices. Their specific energy is three

to four times higher than the one of lead-acid batteries, they have a strong life cycle performance, decent energy efficiencies and are able to provide high power bursts which make them applicable also for frequency stabilization purposes. Maintenance is required every three years. Further details can be seen in Tab. 5.5 in section 5.4.

Redox-flow batteries:
Redox-flow batteries differ from the previously presented batteries by the fact that the electro-chemical conversion is separated from the storage unit. The power capacity and energy capacity can be scaled independently. The electrolyte (storage medium) is stored in external tanks and will be pumped into the power unit according to requirements. There the electrolyte will be charged or discharged. The power performance depends on the power unit, the storage capacity on the size of the tanks. The efficiency of the system is quite low due to the pumping requirements. Redox-flow batteries are optimal for long-term energy storage as it can be designed to achieve very low self-discharge rates when the system is in standby. A further benefit of this system design is that complete discharges of the battery (100 % depth-of-discharge) are not damaging the battery, but even improve its performance. These systems have a long lifetime and typically only individual components need to be replaced, such as the stacks, while the electrolyte can be used indefinitely [31]. Typical redox-flow battery designs are the Vanadium redox battery (V-redox), the Polysulfide-bromide battery, and the zinc-bromine battery (ZnBr). The Polysulfide-bromide battery was commercially produced under the name Regenesys and performed best. The technology was bought though by RWE, the licenses were sold and the project abandoned. The most common flow battery is the Vanadium-Redox-Flow battery and its most present producer is Cellstrom. Zinc-bromine batteries are relatively new on the market and are only partly a flow battery. They are suited in applications that require deep cycle and long cycle life energy storage. There are still difficulties at the charging process, because zinc forms dendrites on the electrode that can form short circuiting pathways [29].

Hydrogen:
Hydrogen-based systems can only be considered as energy storage technologies if the production and storage of hydrogen is part of the overall system. Hydrogen can be generated by electrolysis of water and stored either cooled down to 20.28 K (-253 °C) as liquid or as pressurized gas in a tank. For power generation two main approaches are used: fuel cells or combustion engines. Fuel cells, as the proton exchange membrane (PEM) cells, have the advantage to operate with hydrogen and air at ambient temperatures with good time response and relatively high efficiencies.

Also common is to burn the hydrogen in a combustion engine. Diesel engines have already been modified for this task and produce electricity at a quite high efficiency with the advantage of a relatively inexpensive power generation section [30]. Further developments are solar fuel systems as the methane battery, commercialized by Solar Fuel Technology GmbH and Co KG. Here hydrogen is further converted into methane.

The Ragone plot shows some of the mentioned electrochemical storage devices characterized by their energy density over their power density. Capacitors as shown here for frequency stabilization are not addressed in detail, but the properties of commonly used lead-acid and lithium-ion batteries are demonstrative for stationary energy storage systems. The not depicted NaS high-temperature battery is maybe the most flexible battery, being able to operate as flexible load control but also as long-term storage system.

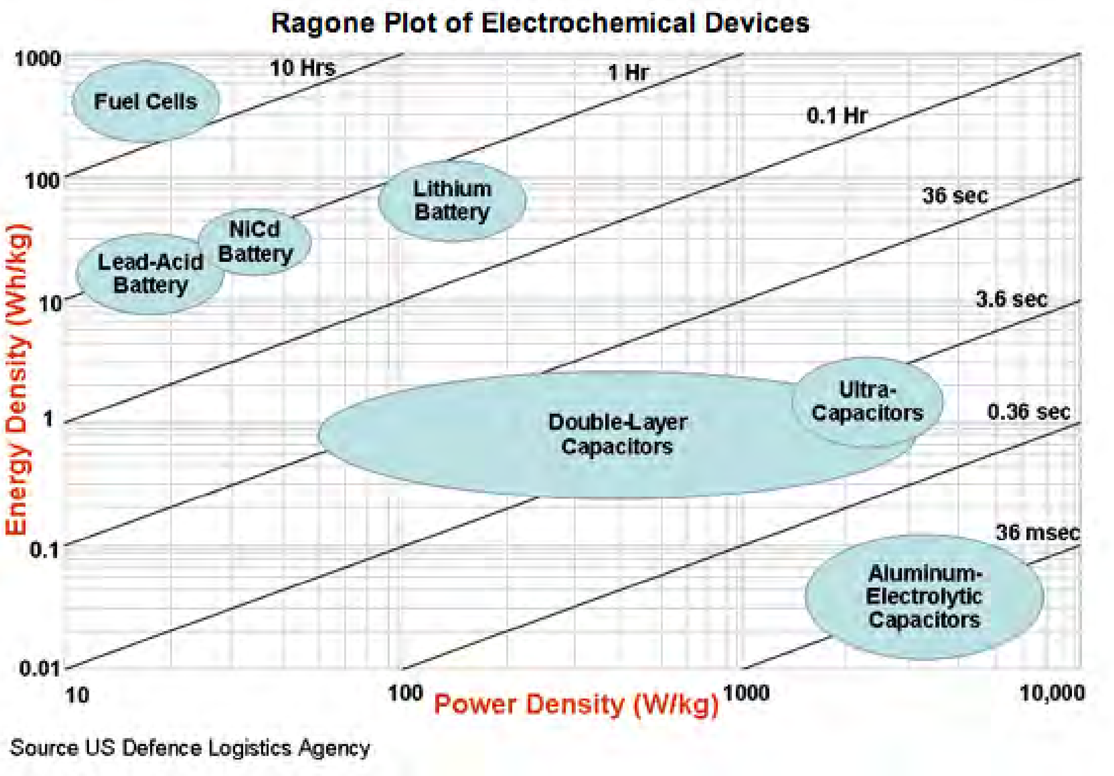

Fig. 2.4: Ragone Diagram of electrochemical storages

Mechanical ESS

Compressed-air energy storage:
The traditional compressed-air energy storage (CAES) uses geologic formations in the underground for storing air under high pressured. CAES systems have efficiencies of 50-55 % and can perform in part-load until minimum 20 %. They are essentially gas turbine plants where the air is already compressed and therefore less fuel is consumed [32]. Because of their similarity to standard gas turbine systems, they are easily to integrate into existing power networks. With a ramp rate similar and slightly faster than traditional gas turbine plants, these systems are ideal for meeting peak loads. For island systems as the ones discussed in this work, such big installations are not applicable. There are some small compressed air energy storage systems available, where the compressed air is stored in steel pipes that are typically used for natural gas transmission. These pipes are relatively inexpensive and are generally available [31]. Since no specific geological formations are required, such systems allow a higher flexibility in siting than conventional CAES. If the compression heat is not cooled down but stored in an additional heat energy storage (adiabatic CAES), the efficiency can increase up to 70 %.

Pumped hydroelectric storage:
Pumped hydroelectric storages (PHS) are based on conventional hydropower technology. Hydropower requires a considerable volume of water to generate electricity, approximately $\mathrm{V[m^3]} = 400 \cdot \frac{\mathrm{E[kWh]}}{\mathrm{h[m]}}$. A PHS consists of a pumping turbine, a motor-generator-unit, a lower and a higher reservoir. The simple design and the experience with hydropower plants has made PHS the standard energy storage design for a century. These systems can ramp up to full load in a few seconds. Plants have a power range from a few megawatt up to one gigawatt and a durability from usually 50 years [33]. However, they require very specific geographic features that limit the siting of such plants. PHS require relatively low maintenance but high initial investments. PHS projects also face criticism due to their significant impact on local wildlife, ecosystems, and landscape.

Flywheel:
Flywheels have been in existence for centuries, however, only over the past few decades they have been considered as forms of bulk energy storage. They store kinetic energy. These systems are extremely rapid in their response time and, with recent developments in bearing design, have been able to achieve high efficiencies for short durations of storage. Their main disadvantages are a high rate of self discharge

due to frictional losses and their relatively high initial costs. Flywheels are durable without significant replacement needs [34]. Although flywheels are occasionally also discussed as stationary storages, they are not considered in this study. High self discharge rates are not acceptable for long-term stationary storages.

2.4 Backup system

For the case that renewable energy sources cannot serve the load and the energy storage is empty, a backup system is required for guaranteeing a reliable energy supply. As backup system usually diesel generator sets are applied, since in many cases such a power station has provided the remote region with electricity previously. Stationary generator sets use usually diesel oil as fuel. As far as local conditions allow, diesel oil can be complemented with biodiesel. In case of the goal of renewable energy maximization, a 100 % share of renewables energy sources is not achievable another way. Depending on the utilization of a existent diesel generator or a new one and the share of renewables, the nominal capacity of such a backup system can operate far outside of the optimum. If the diesel generator used to meet the whole power demand, it will probably not operate that efficient in part-load and two diesel generators with lower nominal capacities could be beneficial. In system designs though commonly the peak demand is taken as nominal capacity of the backup diesel generator, not taking into account periods of part-load operation. This depends though on the dispatch strategy, if the diesel generator is operating load following or cycle charging. If it runs cycle charging, it operates at full load at the technical optimum and charges the batteries with the surplus electricity. In the given model a load following dispatch strategy is assumed. The cold-start-up time of a generator is usually about ten minutes and therefore flexible enough to be activated in case of low wind speeds or low solar radiation predictions. Part-load operation is usually limited to minimal 30 or 50 % of the nominal capacity. Commonly up to 1000 activations per year can be carried out by a diesel generator engine. The minimal duty-cycles have been set to three hours in the model. Specific load curves are presented in section 5.4, when the used input data will be introduced.

2.5 Seawater desalination in remote regions

2.5.1 Basics of water

Clean freshwater is globally a precious commodity. The World Health Organisation reports that 1 billion people do not have access to clean drinking water. Unclean drinking water is responsible for millions of water related illnesses and billions of dollars in health care costs. As a result of population growth, the sinking quality of existing water resources, the increasing industrial and agricultural demands, climate change, and the dissipation of clean water, resources are overused. Global desertification and excessive usage of natural freshwater reservoirs diminish accessible water stocks. Within the next two decades it is assumed that about one-third of the world's population will suffer serious water scarcity problems [35].

Since water usage is hard to describe, the water footprint and virtual water content of agricultural and industrial products was introduced in the late 1990s. For example, to harvest 1 kg rice up to 3000 liters of water are needed, for 1 sheet A4 paper 10 liters, for 1 pair of shoes (bovine leather) 8000 liters [36]. The daily per capita use of water in average in different residential areas are, e.g. 150 liters in the the European Union, 300-350 liters in the USA and Japan, 800 liters in the United Arabian Emirates, but only 10-20 liters in sub-Saharan Africa [35].

Worldwide, agriculture accounts for 70 % of all water consumption, compared to 20 % for industry and 10 % for domestic use. In industrialized nations, however, industry consumes more than half of the water available for human use. Belgium, for example, uses 80 % of the water for industry [37]. A basic reason for water scarcity is the fact, that only a small fraction of all water on earth is freshwater, the main part is salty seawater. Figure 2.5 shows that only 2.5 % (35 million m^3) of the world's water resources is freshwater, the rest (13 million m^3) is salty and therefore not usable for human consumption or industrial purposes [38].

The water quality and type can be differentiated depending on the salt content. Even in ocean basins the salt concentration differs due to regional freshwater losses (evaporation) and gains (runoff and precipitation). Table 2.2 gives an overview of various waters and their denotation.

Typically, seawater has a salinity of 35,000 mg/l. The Arabian Gulf though, for example, has an average salt content of 48,000 mg/l and the salinity of the Dead Sea reaches even 250,000 mg/l. The same time the salinity of the Arctic Ocean, i.e.

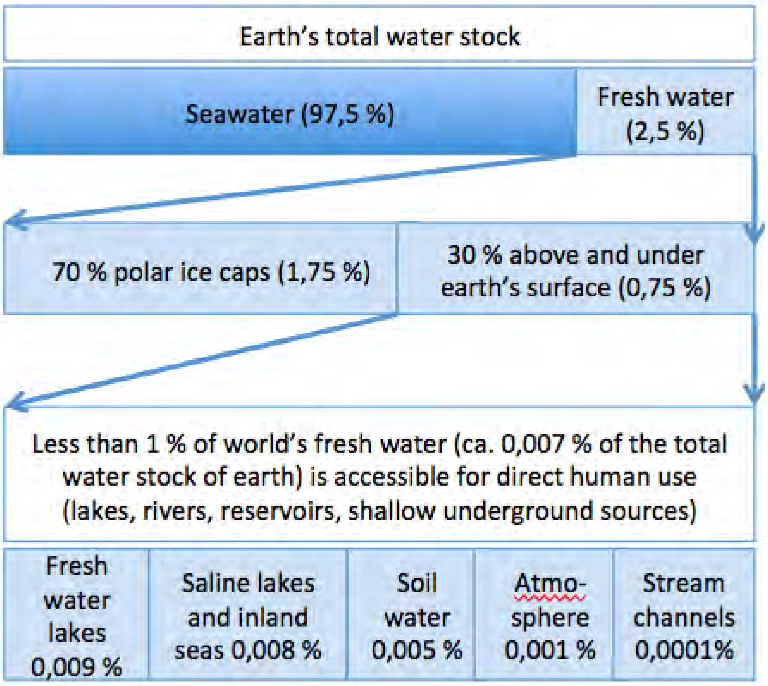

Fig. 2.5: *Global stock of water [38]*

Tab. 2.2: *Total dissolved solids in waters*

Type of water	TDS in mg/l
Sweet waters	1 – 1000
Excellent drinking water/potable water	less than 300
Brackish waters	1000 - 5000
Moderately brackish/saline waters	5,000 – 10,000
Severely saline waters	10,000 – 30,000
Seawater	more than 30,000

the top 50 meters, can be as low as 20,000 mg/l. About 99 % of sea salts consist out of six elements and compounds: chlorine (Cl^-), sodium (Na^+), sulfate (${SO_4}^{2-}$), magnesium (Mg^{2+}), calcium (Ca^{2+}), and potassium (K^+). The chlorine ion makes up 55 % of the salt in seawater. Drinking water contains also salts and minerals. These substances make water healthy and tasty. The concentration of dissolved solids refers to total dissolved solids (TDS).

The driving question is, how the availability of clean freshwater can be increased. Unitary water consumptions need to be reduced, wastewater recycled and eventually groundwater recharged. But in arid regions without any access to freshwater stocks, meeting the water demand is a huge challenge. Especially in coastal regions the unlimited usage of groundwater results in an inflow of seawater leading to increased salt levels making the freshwater unfit for human consumption and other applications. Globally desalination is increasingly used for reducing current or future water scarcity, especially in coastal areas [37].

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 is minimized. The combination with highly developed renewable energy technologies can be a chance to minimize at least the emission of greenhouse gases. Numerous remote regions with no access to natural freshwater reservoirs are characterized by high solar irradiance and good wind conditions. To understand better the options of combining renewable energy systems with desalination technologies, in the following an overview of the main desalination processes is given.

2.5.2 Desalination processes

Depending on the process applied, for desalination either thermal (distillation) or electrical (e.g. membrane-based filtration) energy is needed. Globally about 50 % thermal processes (MED and MSF) and 50 % membrane processes (RO) are implemented. However, there are much more processes in use and development. Table 2.6 is an own illustration and gives an overview of desalination processes. The processes considered in the model are shaded grey.

Separation	**Energy Use**	**Process**	**Desalination Method**
Water from Salts	Thermal	Evaporation	Multi-Stage Flash (MSF)
			Multi-Effect Distillation (MED)
			Vapour Compression (VC)
			Humidification-Dehumidification (HDH)
		Crystallisation	Freezing (FR)
			Gas Hydrate Processes (GH)
		Filtration/Evaporation	Membrane Distillation (MD)
	Mechanical	Evaporation	Mechanical Vapour Compression (MVC)
		Filtration	Reverse Osmosis (RO)
Salts from Water	Electrical	Selective Filtration	Electrodialysis (ED)
	Chemical	Exchange	Ion Exchange (IE)

Fig. 2.6: *Overview of desalination methods*

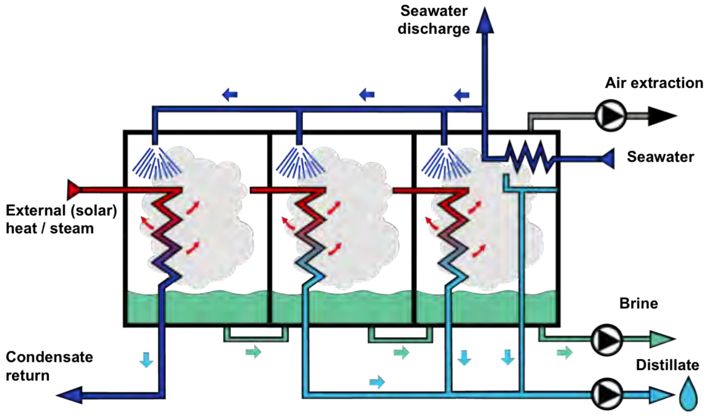

Fig. 2.7: *Multi-effect distillation process [126]*

Multi-Effect Distillation (MED)

For distillation, seawater is first evaporated by heat and subsequently recondensed in order to obtain a desalinated distillate. The remaining condensed seawater is discarded. Most processes use the available condensation heat to preheat seawater or for evaporation at a low pressure level. Thermal energy consumption amounts to 80 to 100 kWh/m^3 of distillate. Additionally, about 1 to 3 kWh/m^3 are required for pumping. Usually thermal desalination plants are cogeneration plants coupled to a power plant. Multi-Effect Distillation was used primarily by the industry to evaporate juice to get sugar and to evaporate water to get salt as commodities. Later there has also been use of this distillation method for drinking water desalination. Some of the early desalination plants used the MED process, but due to the high temperatures involved scaling problems occurred, and MED has been largely replaced by Multi-Stage Flash units, which were implemented large-scale in the Middle East in the early 1970s. In the 1980s though scaling problems could be minimized and Multi-Effect Distillation got established in the last decades. The main difference between both processes is, that MED processes require less energy, because permeate is evaporated instead of water (drops). Multi-effect distillation is a thin-film evaporative technology that utilizes low grade input steam to produce the distillate through repetitive steps of evaporation and condensation, each at a lower temperature and pressure. It operates at low temperatures (the maximum can be as low as 70°C). Figure 2.7 illustrates a simplified diagram of the multi-effect distillation.

The amount of produced fresh water per unit of steam increases almost proportionally with the number of stages, increasing also the investment costs. Since MED plants are usually large scale, they can benefit from economy of scale. It is a very reliable process with minimal requirements for operational staff. Due to distillation the product water has a higher quality than most membrane processes. Drawbacks of the technology are the high thermal energy demand, cf. Tab. 5.7 later on) and high capital costs, since due to corrosion high quality materials are required [39]. Corrosion is also avoided by adding appropriate chemicals. These though are harmful for the environment and are usually flushed into the sea. Extensive research is undertaken for realizing zero-liquid-discharge. Distillation processes like MSF and MED usually are robust and need only a crude filtration, other than membrane technologies, which depend on the incoming feed water quality and require more chemical pre-treatment.

Most of the almost 900 MED-plants worldwide, mainly located in the Middle East, the Caribbean, India and Southern Europe use a number of 8 to 16 effects and produce usually 50,000 to 800,000 m^3 of freshwater per day. Down-scaling is not beneficial from an economic perspective. The demand of mid-scale desalination plants in the range of 500 to 10,000 m^3/day is increasing though, e.g. for industrial purposes and smaller urban regions, and even one, two and three effect technologies are tried to be commercialized, e.g in El Gouna, Egypt.

Humidification-Dehumidification (HDH)
A further thermal desalination process is the humidification-dehumidification method. HDH is more a small-scale application, producing 50 to 500 m^3/day. The process requires also mainly thermal energy, e.g. waste heat from combustion processes or solar thermal heat, in the range of 50 to 95 °C and 1 to 3 kWh_{el}/m^3 for the pumps. Figure 2.8 illustrates a simplified process scheme. The heat source in this case is a solar collector, heating the incoming seawater, which is previously pumped through the condenser and acts as the coolant in the heat-exchange process of the system. The heated seawater is sprayed into the evaporation chamber, where it enriches dry air with vapour. The air circulates by natural or forced convection. The humidification of the dry air is based on the principle of mass diffusion. The vapour carrying capability of air increases with the temperature, e.g. 1 kg of dry air saturated with vapour can carry additional 0.26 kg of water vapour (about 208 kJ/kg) when its temperature increases from 30 to 80°C. When the enriched air reaches the condenser with the circulating cold seawater as coolant, it dehumidifies. The delivered distillate is collected at the condenser, while the brine is separated in the evaporator. The brine can be concentrated so high, that zero-liquid-discharge is a reachable goal for this process [40].

A further advantage of HDH is the simple, robust and relatively cheap construction. Some manufacturers use no steel at all, only plastics as polyvinyl chloride, which guarantees a corrosion-free process and low maintenance. Since no filters

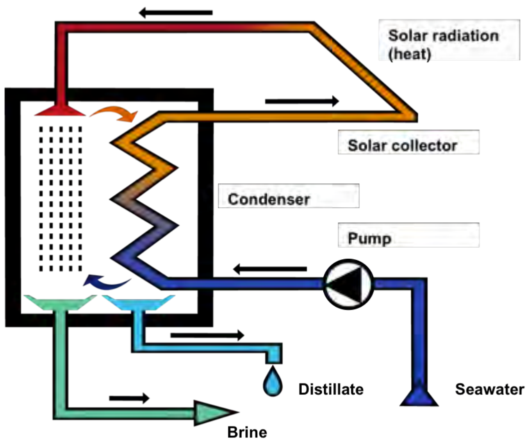

Fig. 2.8: *Humidification-dehumidification process [126]*

are required, only the pumps need to be changed every three to five years. Main drawback is the large area of land required (for 55 m^3/day one 40' container; 300 m^3/day one 40' container with a hight of 8,5 m) due to the relatively low efficiency [40, 41]. Multi-effect design can recover and reuse the heat of condensation but the performance is still relatively low and in case of space limitations this process can occasionally not provide the required water quantity [42].

Membrane Distillation (MD)

Membrane distillation combines both the membrane and evaporation technology. It is a technology designed initially for small scale and stand-alone applications. Various research institutes are developing this technology for about three decades with first commercialization approaches (e.g. SolarSpring GmbH in Freiburg, Germany). The MD technique is mainly developed for solar driven stand-alone desalination systems and waste heat utilization, where applicable. Although current MD applications produce only up to 10 m^3/day, it can be a promising desalination option for the near future and is therefore also modeled.

Membrane distillation is an evaporative process in which water vapour, driven by a difference in vapour pressure and temperature difference across the membrane, permeates through a hydrophobic membrane, separating it from the salt-water phase. Once the vapour has passed through the membrane, it can be extracted or directly condensed on the other side of the membrane. There are different air-water channel-constructions, but the main principle is the same. MD offers the attractiveness of operation at atmosphere pressure and low temperatures (30 to 90 °C, optimal operation in the range of 60 to 80 °C), with the theoretical ability to achieve 100 % salt rejection [43]. The membranes used in MD are tested against biofouling and scaling.

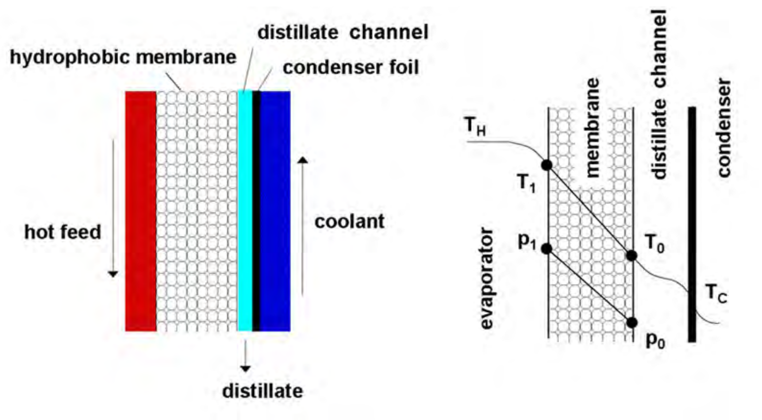

Fig. 2.9: *Membrane distillation process [44]*

In small-scale pilot plants chemical feed water pre-treatment is not necessary. The corrosion- and fouling-free operation though still needs to be proven in large-scale and long-term operation. A significant advantage is the possibility of intermittent operation. Like in most thermal processes the water quality is depended from the salinity of the feed water. Compared to HDH though, less space and equipment is required [44, 45].

Mechanical Vapour Compression (MVC)

Contrary to the previously presented thermal desalination processes, the Mechanical Vapour Compression desalination process (MVC) requires exclusively electrical energy. Vapour compression itself is a thermal process and can be operated as thermal plant as well (VC), but since a mechanical compressor generates the steam in this process, it is an electrical driven process as illustrated in Fig. 2.10. The thermal part of the process works similar to MED, in this illustration visualized by three chambers. Produced steam is guided into the first and coldest chamber. Since compression of vapour increases both the pressure and temperature of the vapour, it is possible to use the latent heat rejected during condensation to generate additional vapour. Instead of heating the steam via an external heat source its temperature is increased by pressure. The energy consumption of this process is 10 to 12 $\mathrm{kWh_{el}/m^3}$ [46, 47].

MVC processes require very short reaction times and can adjust rapidly to flux changes, which enables the use of fluctuating renewable energies as power source. A further advantage of this technology is that not much pre-treatment is required (comparable with other distillation processes). Due to relatively low temperatures, corrosion can be kept low. Disadvantages are, that the technology is limited to smaller sized plants, that the compressor needs higher levels of maintenance and that for the start-up an auxiliary heating source is required [39].

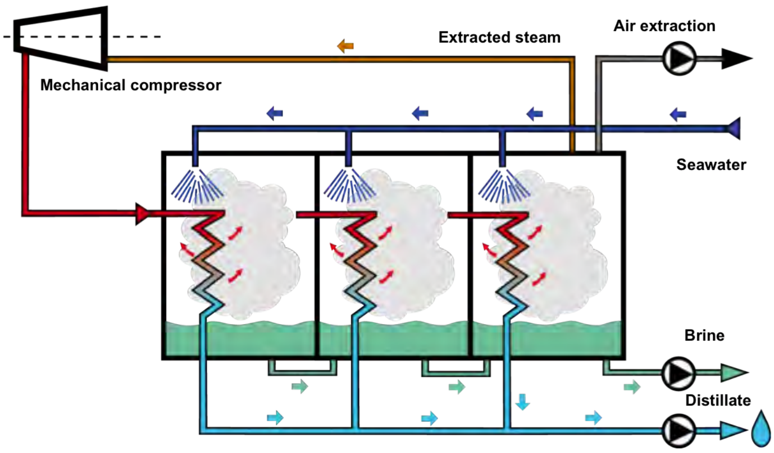

Fig. 2.10: *Mechanical vapour compression process [127]*

Reverse Osmosis (RO)

In reverse osmosis desalination processes seawater is pressed through a semi-permeable membrane at high pressure (between 50 and 80 bar). RO is a pressure-driven process, which counteracts the osmotic force. It uses pressure for separation by allowing fresh water to move through a membrane (30 to 50 % of the water), leaving the salts behind in the brine. No heating or change of the phase is necessary; the major energy is required for pressurizing the feed water. A reverse osmosis plant consists of four major systems: A pre-treatment system, high-pressure pumps, a membrane system and a post-treatment system. Figure 2.11 illustrates a simplified process diagram. Pre-treatment mostly consists out of sand-filtering and the addition of anti-scalants, anti-foaming, anti-fouling and other chemicals. Like in all desalination processes, in the post-treatment (not visualized in Fig. 2.11) residual chemicals are removed and the water is blended with minerals for making the filtered water applicable and tasteful for human consumption.

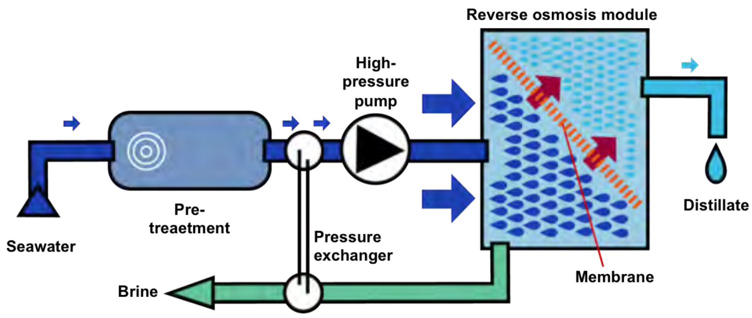

Fig. 2.11: *Reverse osmosis process [127]*

The energy consumption of reverse osmosis amounts to 6 to 8 kWh_{el}/m^3 excluding energy recuperation, and to 3 to 4 kWh_{el}/m^3 including energy recovery. However, the energy consumption depends almost linearly on the salt content of the feed water. Since reverse osmosis plants have considerably lower energy consumption compared to distillation processes most recently built desalination plants are RO plants. They can not operate as cogeneration plants though and require exclusively electrical energy. Further advantages of RO-units are the very flexible dimensioning and modular structure, the relatively low investment costs, and the simple operation and start-up phase. Furthermore no cooling is required. The main disadvantages are the high costs for chemical and membrane replacements (which cause high maintenance costs), the vulnerability to biofouling, the possible mechanical failure due to high pressure operations and the requirement of appropriately trained personnel. The sensible membranes need to be kept wet and usually under pressure. Due to the requirement of various chemicals, zero-liquid-discharge is a high-priority goal for all brines of desalination processes. Further information concerning chemical applied, environmental impacts and recommendations concerning impact minimization and assessments can be found in *Lattemann* [48].

2.5.3 Variable operating desalination

As previously mentioned, desalination plants operate usually continuously and require a constant energy flow. However, in order to adjust to fluctuating energy sources and to operate eventually as deferrable load a flexible operation needs to be possible. In thermal desalination processes the main obstacle is the inertial preheating phase, in membrane processes the high-pressure change. Up to now only small scale applications up to 10 m^3 water production per day were developed for off-grid and intermittent operation (e.g. solar stills or membrane distillation).

In the literature reverse osmosis processes are discussed as the most applicable for a flexible operation, cf. *Subiela et al.* [49, 50] In some cases Vapour Compression processes could also be identified as applicable but the most promising technology is reverse osmosis with specifically durable membranes.

The German research institution Fraunhofer is also seeking to solve this challenge. Even though the results have not been tested in real technical applications, in the laboratory and pilot plants they developed a technology with three membranes to achieve flexible loads. These can even be shut down for more than one day without destroying the membranes [51]. Enercon also developed an own approach to desalinate seawater in times of excess wind energy [52]. First variable control systems for reverse osmosis were considered by *Alatiqi et al.* in 1989 [53].

In the developed model, described later on in section cf. 4.7, a variable operating desalination plant is represented as well. A variable RO unit is selected and modeled based on data and research results derived from *Pohl et al.* [54, 55]. It consists of two separate seawater reverse-osmosis units, so-called trains, with 400 m^3/day each. The constantly operated RO-train would produce 400 m^3/day throughout the year. For the variable operating RO-trains configured by SYNLIFT Systems a production range of 50 to 150 % can be handled with an energy consumption of 4.3 kWh/m^3 (for the specific plant dimension in the considered case study) [55]. The literature confirms such relatively low energy consumptions even for variable operating RO-plants, cf. [56]. *Segura et al.* realized energy consumptions of about 5 kWh/m^3 without energy recovery. Without going into detail concerning the power performance depending on pressure gradients, it can be concluded, that membranes can withstand pressure changes as required for an intermittent operation. With a maximum pressure gradient of 0.7 bar/s, the plant could reach maximum power within three minutes. The derivation of these conclusions and chances and challenges of implementing desalination (RO) as deferrable load in micro-grids is discussed in detail by *Bognar et al.* [57] and will not be addressed in the framework of this thesis.

2.5.4 Desalination powered by renewable energies

Powering desalination plants by renewable energy sources is a widespread objective and discussed extensively in the literature, cf. e.g. [46, 58, 59, 60, 61, 62, 63, 64, 65, 66]. Depending on the technical process used, either thermal (distillation) or electrical (e.g. membrane-based filtration) energy is needed for desalinating seawater.

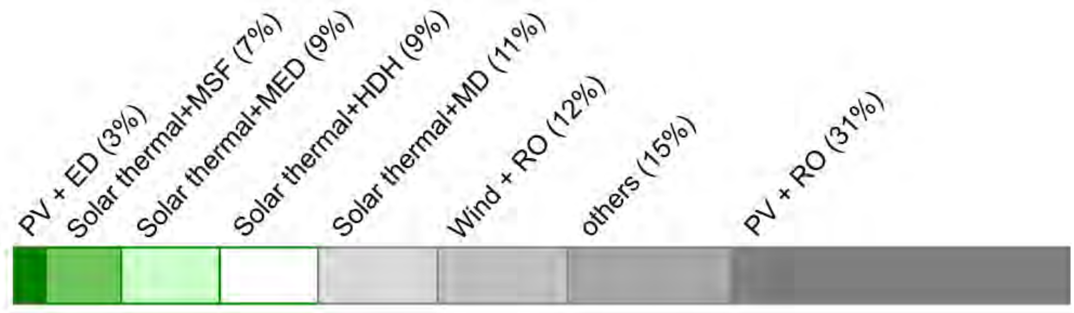

Fig. 2.12: *Technology combinations RE-powered desalination plants*

Currently only less than 1 % of the global desalination capacity is powered by renewable energies; the goal of the community is to reach a market share of 3 to 5 % in the next decade [41]. The projected growth will mainly come from large scale desalination plants, producing 30,000 to 300,000 m^3 freshwater per day. Some are planned in the Mediterranean and Middle East, Asia and Australia. An illustration of such a large-scale application is the Perth Seawater Reverse Osmosis Plant in Western Australia, with a capacity of 140,000 m^3/day, supplying about 1.5 million people. 48 wind turbines with an installed capacity of 80 MW produce the electricity needed. The plant is designed to operate continuously, drawing electricity from the grid when wind production is not sufficient [67]. Such large scale desalination plants though are not addressed in the framework of this work. The global current share of 131 renewable energy powered desalination plants (in 2009) is structured as shown in Fig. 2.12. Looking at desalination combined with renewable energy sources, it is helpful to categorize by plant dimensions:

- small scale: < 10 m^3/day
- medium scale: 10–1,000 m^3/day
- large scale: $> 1{,}000$ m^3/day

The focus of this work is set on medium scale desalination plants (10 – 1,000 m^3/day). Plants with this capacity can be used for water supply of villages or other large users like hotels. Even towns like in the Middle East region, islands, golf resorts etc. with a permanent or seasonal population from 500 up to 20,000 people could be served by such plant capacities, depending on their water consumption pattern. An attractive solution can be to power desalination directly by renewable energies, like in the case of wind-RO or wind-MVC, which are the most common technologies in that range. Exemplary plants have been built on the Canary Islands as well as in the Aegean Sea.

One successful medium-scale flexible operating wind powered desalination unit was developed by Enercon. The reverse osmosis plant could operate grid-connected as wind-diesel or also as stand-alone system powered by wind energy converters. Figure 2.13 shows the general concept of the system. One wind-RO plant with a capacity of 500 m^3/day was implemented on a Greek island in 1998 and a further demonstration plant of 1,200 m^3/day in Aurich, Germany in 2004 [41, 52]. In 2011 though Enercon decided to refocus to its core competence and abandoned the efforts in the desalination market.

RE powered desalination can be clustered as shown in Fig. 2.14 [46]. In addition further detailed information can be derived from Tab. C.1 in Appendix C.

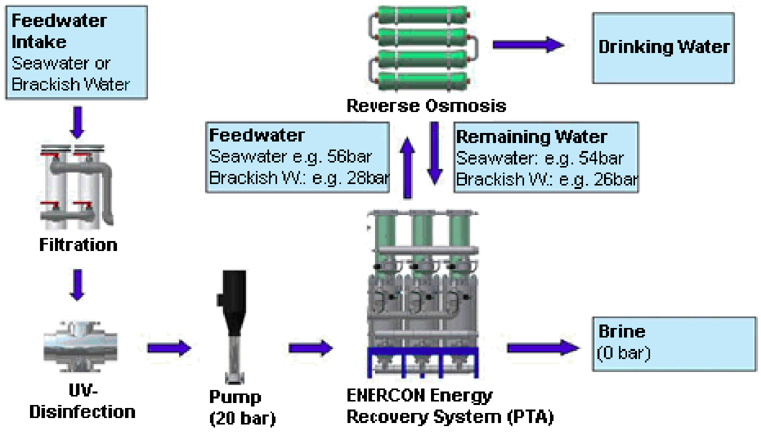

Fig. 2.13: *Concept of Enercon wind-RO system [41]*

Ecological and economic chances of combining power generation with the production of freshwater as deferrable load were investigated by *Kaldellis et al.* [68] and *Bognar et al.* [69]. *Kaldellis et al.* propose for small and medium size Greek islands the installation and collaboration of a wind park, a small hydro-electric power plant, a water pump station with two water reservoirs, a properly sized desalination plant and the usually existent thermal diesel engines as back-up system. System benefits due to the integration of pumped hydro-energy and desalination are shown. *Bognar et al.* [69] address options of integrating desalination into a hybrid renewable energy grid using the example of the small Caribbean island Petite Martinique and show theoretical advantages of desalination as deferrable load.

2.6 Small Island Developing States

Investigating isolated micro-grid systems it is very attractive to look at grids on real islands. Globally almost 55,000 islands are known, about 26,000 are populated. An overview is given in Tab. 2.3 [70].

From all these islands a large number of island states is represented in the Alliance of Small Island States (AOSIS). AOSIS is a coalition of small islands and low-lying coastal countries that share similar development challenges and concerns about the environment, especially their vulnerability to the adverse effects of global climate change. It was established in 1990, founding the group of small island developing States (SIDS) within the Barbados Programme of Action in 1994 and negotiating in the same year within the United Nations constituting the Kyoto Protocol [71]. Actually there are 52 member states within the SIDS from all oceans and regions of the world: Africa, Caribbean, Indian Ocean, Mediterranean, Pacific and South

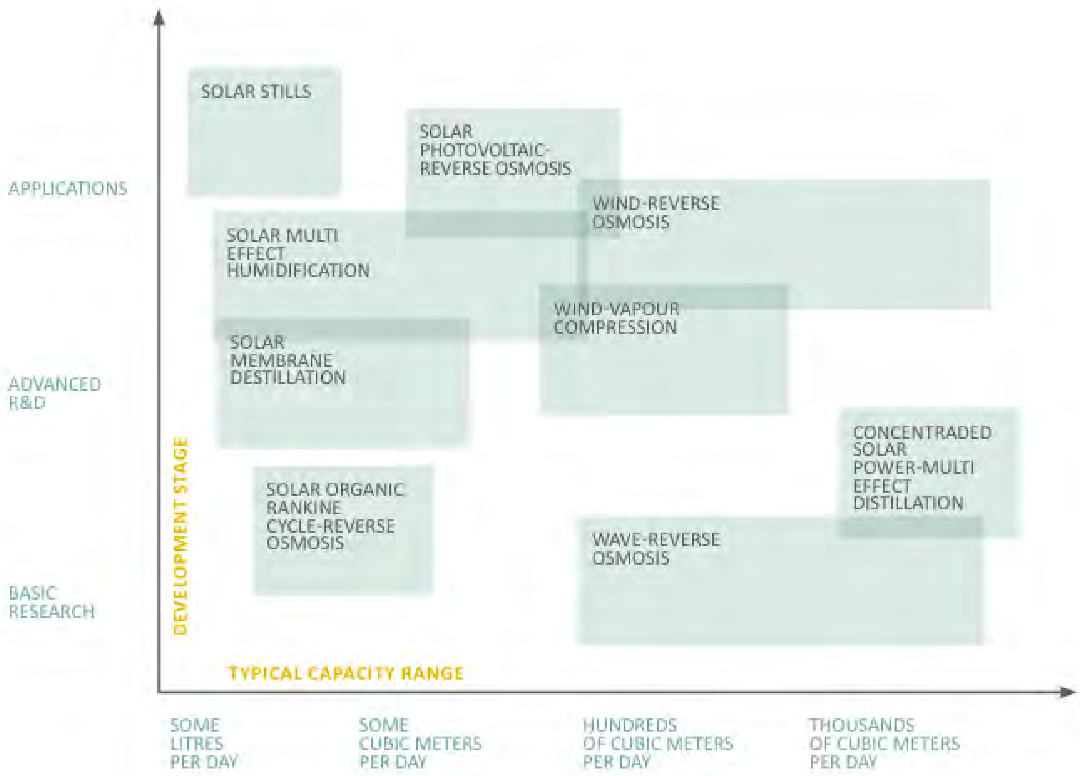

Fig. 2.14: *Development stage and capacity range of the main RE-desalination technologies [46]*

China Sea. Thirty-seven of them are members of the United Nations. Together, SIDS communities constitute some five percent of the global population. Figure 2.15 shows the current SIDS in an overview.

Most SIDS provide electricity by operating diesel generator sets and are exposed to rising fuel prices on the world market, facing often even higher fuel prices than on the mainland. A small Gross Domestic Product puts SIDS in a difficult situation concerning investments in energy efficiency or renewable energy technologies. However, institutions around the world, like the World Bank, the Asian, African, Inter-American or Caribbean Development Bank, the Council of European Development Bank or even the national banks of France, the Netherlands, Great Britain, Germany etc., offer special loans for renewable energy systems in developing countries.

Tab. 2.3: *Islands globally [70]*

Population	Number of islands	Inhabitants total	Inhabitants average	Area [km^2] total	Area [km^2] average
$<$ 1	54,614	0	0	323,034	6
1-100	18,154	352,866	19.4	441,266	24
101-1,000	4,944	1,716,699	347	492,121	99.5
1001-10,000	2,233	7,326,098	3,281	1,105,779	495
10,001-100,000	696	21,130,544	30,360	358,266	515
100,001-1,000,000	140	39,899,243	284,995	3,020,497	21,575
1,000,001-10,000,000	32	95,787,982	2,993,374	1,326,221	40,720
$>$ 10,000,000	14	499,424,286	35,673,163	3,005,447	214,675
all inhabited ($>$1)	26,213	665,637,719	25,393	9,749,598	371

Fig. 2.15: *SIDS worldwide*

Chapter 3

Methodology

There are various options of simulating and optimizing energy systems and concepts. Approaches can be time-step simulations, statistical analysis, mixed-integer programs for representing inter-temporal restrictions etc. Models principally differ in their complexity and level of detail, in the data requirements for generating useful outputs, in the availability and reliability of program and their costs. For answering the formulated research questions models or one model is required that represents energy systems as well as desalination concepts and the possibility of integrating desalination into the simulation and optimization. Before presenting the chosen approach, the most common programs are presented for modeling energy systems as well as desalination processes.

3.1 Simulation of energy systems

Energy modeling software ranges from only technical models over urban planning to economic planning models or combinations of those. From linear to dynamic models a wide spectrum of programming is available. Renewable energy concepts are mainly planned, developed, and dispatched by supporting tools like INSEL, RETscreen, HYBRID2, HOMER, and other programs. Before presenting the applied modeling approach, an overview of some available programs is given in Tab. 3.1. Since most models presented in the overview are in continuous development, this list is not exhaustive.

Programs like **MARKAL** (Market Allocation) are the first linear-programming models for energy-system-analysis minimizing total system costs. MARKAL is lodged with GAMS (General Algebraic Modeling System) and was developed within

	MARKAL	DEECO	EBSILON	TRNSYS/SAM	INSEL	RETScreen	HYBRID2	HOMER	VIPOR
Original purpose	Energy system analysis	Sustainability improvements in power cycle engineering	Engineering of conventional power cycles	Evaluation of solar systems for heating and cooling	System analysis of RE systems	Sustainability evaluation of energy technologies	Hybrid power systems in island grids and single households	Analysis of micro-power systems	Village power optimization
Fields of application	national, regional, local, 40-50 years, policy	detailed plant optimization	detailed plant optimization	transients simulation	system analysis / annual simulations	energy components and system analysis	power supply optimization in island grids	energy system analysis	economic grid and off-grid optimization
Initial publication	ca. 1981	ca. 1995	ca. 1990		ca. 1991	ca. 1998	ca.1993	ca. 1993	ca. 1993
Updated up to now	no	no	yes	yes	yes	no	no	yes	no
Developed by	International Energy Agency (ETSAP programme)	Technical University of Berlin, Department of Energy Engineering	STEAG Energy Services GmbH	Thermal Energy System Specialists, LLC, Madison, WI, USA / National Renewable Energy Laboratory	doppelintegral GmbH, Juergen Schumacher	Natural Resources an Research Canada, Quebec, Canada	Center for Energy Efficiency & Renewable Energy, University of Massachusetts / National Renewable Energy Laboratory	National Renewable Energy Laboratory, USA / HOMER Energy, Boulder, CO, USA	National Renewable Energy Laboratory, USA
Annual simulations / resolution	individually possible	yes, hourly	yes	(no)	yes	(no)	yes, hours and minutes	yes, hours (and minutes)	no
Required language	GAMS	flexible	EbsScript	Fortran	Fortran, C	not required (Windows only)	Fortran	not required (Windows only)	Fortran (not required)
Price (single academic licence)	ca. 4600 €	no	free for PhD students	ca. 5000 € / free as Beta-version	ca. 850 €	free	free	ca. 80 € for 6 months	not available, integrated in HOMER
AVAILABLE MODULES/LIBRARIES									
PV	no	no	no	yes	y (various types)	yes	yes	yes (various types)	no
Wind	no	no	no	no	y (various types)	yes	yes	yes (various types)	no
CSP	no	yes	yes	yes	yes	no, but solar heating	no	no	no
other RE systems	no	no	no	biomass, geothermal	no	hydropower, biomass	no	hydropower, biomass	no
Energy storages	no	thermal and electrical	thermal (molten salt)	thermal (concrete)	thermal (molten salt, concrete)	no	yes	electrical (various types)	no
Desalination	no	no	no	no	recently MED / RO	no	no	no	no

Fig. 3.1: *Modeling programs for energy systems in comparison*

the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency, documented by *Fishbone and Abilock* in 1981 [72]. The main reason, why this model is not used as base was the high price of 6000 USD even for academic purposes as listed on the MARKAL website. Since significant developments would have been needed anyways, a model development from the scratch was preferred.

Deeco (dynamic energy, emissions, and cost optimization), was developed by *Bruckner et al.* at the Technical University of Berlin. Deeco is an energy system modeling environment, which is used to define and evaluate sustainability improvements including CO_2-savings mainly for fossil but also for renewable power plants. The software requires a high resolution of accurate technical details. The program is normally used to compute sustainability gains versus costs relative to some assessment of business-as-usual by using recursive dynamic optimization techniques, cf. [73]. Since Deeco is optimizing single power plants in a much more detailed approach than available for most energy systems in remote and developing regions, it is not applicable for answering the formulated questions.

HOMER is an initially open-source program developed in 1993 by the National Renewable Energy Laboratory (NREL) which has been further developed and commercialized since then. It is a program which simplifies the task to evaluate different grid options no matter whether a grid-connected or off-grid power system is sought. HOMER is capable of modeling a wide range of energy systems including renewable energy sources (RES) like photovoltaics, wind turbines, hydro power, biogas and conventional systems fired with diesel or gasoline. Furthermore, storage systems like batteries and hydrogen are supported and can partly be integrated individually. Compared to other simulation tools, HOMER has a very user-friendly interface and has undergone continuous developments, especially since becoming a commercial product (since 2009). In HOMER, the best possible system configuration is the one that satisfies the user-specified constraints at the lowest total net present cost. Finding the optimal system configuration may involve deciding on the mix of components that the system should contain, the size or quantity of each component, and the dispatch strategy the system should use [74].

Main disadvantages of each optimization tool are that not all energy conversion technologies can be compared and that desalination cannot be integrated the way it would be required for an overall optimization approach. The best fitting software for answering the research questions is HOMER, although it is commercial in the meantime. The license costs are reasonable. A great advantage of HOMER compared to most other simulation environments is that a deferrable load can be introduced.

It can only be inserted with characteristics for one day in a month, what is not sufficient for the approached analysis, but still the best for comparing technologies with each other while considering a shiftable and flexible load within the demand structure. Initial and some scenario analysis were calculated with HOMER. For further developments, the integration of desalination processes, and global sensitivity analysis another model is required though. Applicable models are either too complex, working with not accessible algorithms or are too expensive. Developing an own model beginning from scratch seemed to be the best solution.

3.2 Simulation of desalination units

Searching for existent simulation and optimization tools for desalination powered by renewable energies, one can find around fifteen research programs launched between 1998 and 2004, mostly financed by the European Union. Unfortunately only a few of them were finalized and published. The most relevant ones are listed in Tab. 3.1.

Tab. 3.1: *Overview of modeling programs for desalination*

Software name	Responsible organization and year of development	Thematic area
SOLDES	Abu Dhabi Water and Electricity Authority, Saudi Arabia (2000)	solar thermal + MED
REDDES	Regional Energy Agency of Dodecanese S.A., Greece, Gerling Sustainable Development Project Gmbh, Germany (2003)	MultiCriteriaAnalysis (MCA) combined with GIS-system, RES+DES-potentional
DesalSolar	Institut für Verfahrenstechnik, RWTH Aachen, Germany (2002)	solar + desal, small scale < 100 m^3/day
RESYSproDESAL	Center for Solar Energy and Hydrogen Research, Gerrmany (2006)	stand alone systems, thermal and membrane processes
ROSA DOW	FILMTEC (2011 last version)	design software for RO systems (for manufacturers)

SOLDES is a program developed 1998 to 2002 simulating the operation of solar desalination plants, that utilize evacuated tube collectors, heat accumulators and multi-effect distillation systems. The model is developed and described by *El Nashar* [75]. Since it focuses on only one specific technology-combination, the model cannot be used for technology comparisons. The model itself is too detailed for integrating it into the techno-economic model approach, especially because thermal energy and desalination processes are not the focus of the research approach.

DesalSolar is a computer-based decision support system, useful for selecting the best desalination and renewable energy technology combination, from the literature reported combinations, based on site parameters of desalination plant and renewable energy supply system. Only off-grid stand-alone water and power supply systems are considered and their technical and economic performance predicted. The software is supervised by the Middle East Desalination Research Center (MEDRC) and can be accessed from their website.

RESYSproDESAL stands for Renewable Energy SYStems for DESALination. It is also a software tool for the prediction of the technical and economic performance of integrated water and power supply systems using renewable energy and fossil sources. RESYSproDESAL is the most applicable system for selecting feasible renewable energy desalination systems. Small and medium size projects can be designed with specifically prepared modules for brackish water and seawater. Considered desalination technologies are reverse osmosis, electrodialysis, solar still and humidification dehumidification. The part of energy conversion is not modeled in detail, only the desalination part. The license costs for accessing the library and using the full program would have been too high though. Still, the collaboration with the co-developer J. Rheinländer, was very helpful.

The modeling approach needed to be adjusted. A new desalination model has been developed in a simplified way, taking into account design layouts, calculated and recommended by manufacturers. For each desalination technology a cooperation partner from the industry has been found. Input data and the developed model are based on information by the manufacturers Terrawater GmbH for HDH [40], Fischer eco solutions GmbH for MED [76], Medesa Technology GmbH for MVC [47], and Synlift Systems GmbH for conventional and variable operating RO [55], supplemented with further interview partners and data from the technical report of the ProDes research program [46]. For determining the optimal conventional and variable operating RO-system, the RO design program **ROSA** has been used. ROSA is provided by the manufacturer DOW FILMTEC and allows system calculations with its own elements [77]. Based on the expertise of Synlift Systems GmbH, optimal module parameters have been defined to guarantee a realistic and available membrane system. Detailed information concerning the data used within the model can be found in section 4.7.

3.3 Optimization approach

Looking in more detail at the first and main task, the optimization approach of the energy and water supply can be broken down in some steps, illustrated in Fig. 3.2. The quality of a supply system model depends highly on the availability of data. For the considered island energy demand data (load) are available in an hourly resolution for one year. Hourly wind velocities measured by an anemometer and solar radiation data from satellites are available for the island as well. Data sets for all 8760 hours in a year can be generated. Knowing the typical water demand on the island per day suffices to calculate a representative energy supply system with integrated water production. These data are mentioned in Fig. 3.2 in the first row. In the following steps the energy generation technologies, storage systems and desalination processes are introduced and defined. The optimization model surrounds the technological and economical models of each sub-system. The model setup is presented in chapter 4.

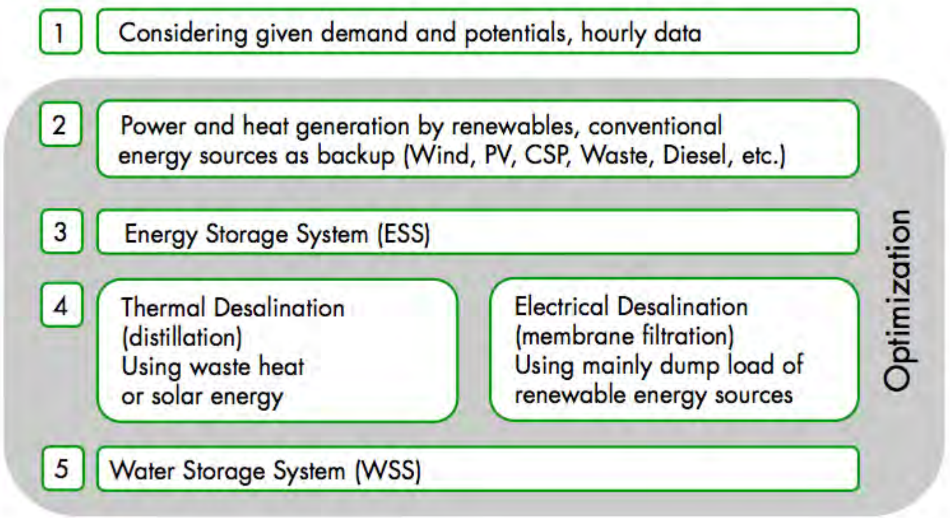

Fig. 3.2: *Overview of the optimization approach*

Within the simulation, hourly data sets over one year are considered. Based on Hoevenaars and Crawford [78], the temporal resolution is assumed as sufficient. The authors examined the efficacy of the temporal resolution in the range of one second to one hour for a model including variable residential loads, wind, solar, diesel generator, and batteries. They found that system configurations using only a diesel generator as backup consume more fuel than determined by a model with hourly resolution. Configurations with only a battery backup were hardly affected by the time step. For systems with both diesel and battery backup, the optimal system costs were fairly close in all temporal resolutions but differed in the optimal component sizes. Since in the given case a diesel generator and batteries are used within all solutions, a resolution of one hour time steps is assumed to suffice without deforming the economical optimal results. For exact information about the behaviour of the battery bank, the fossil and renewable conversion technologies within in each time step, an analysis with higher temporal resolution would be required. However, before implementing a supply system, an accurate dispatching strategy and frequency stabilization within each hour should be determined. Short-term energy storages as well as energy control and/or management systems would have to be integrated but are beyond the scope of this study.

3.3.1 GAMS/OSICplex

In order to map al relevant sub-systems in an appropriate model, including available fractions of other modeling approaches and to solve the large scale mathematical optimization problem, the programming language GAMS (General Algebraic Modeling System) was selected. GAMS does not solve optimization problems directly, but calls appropriate external algorithms. The one used in this work is the IBM's Cplex solver through the GAMS/OSICplex interface. OSICplex is available for free for six months for academic purposes and is a solver link, that uses the COIN-OR Open Solver Interface (OSI) to communicate with solvers. The OSI links support linear equations and continuous, binary, and integer variables. While semi-continuous and semi-integer variables, special ordered sets, branching priorities, and indicator constraints are currently not supported [79], the model presented in this work was created taking the mentioned programming limitations into account. Cplex is supposed to be the most robust and fastest solver for mixed integer programs using a number of binary variables. Alternative Solvers with comparable functions are Gurobi, distributed by Gurobi Optimization Inc., and ZIMPL, developed by the Zuse Institute Berlin.

Through the GAMS/OSICplex interface, a number of parameters were passed to the solver in order to optimize the use of computational resources and prevent the computer form running out of memory. The algorithm used is the primal simplex with best estimate strategy for node selection and strong branching. As for the computer resources management: the time and memory limits are extended from default values; the solver is asked to conserve memory when possible, and it is given the possibility to store and compress node files on the disk; advanced basis are used

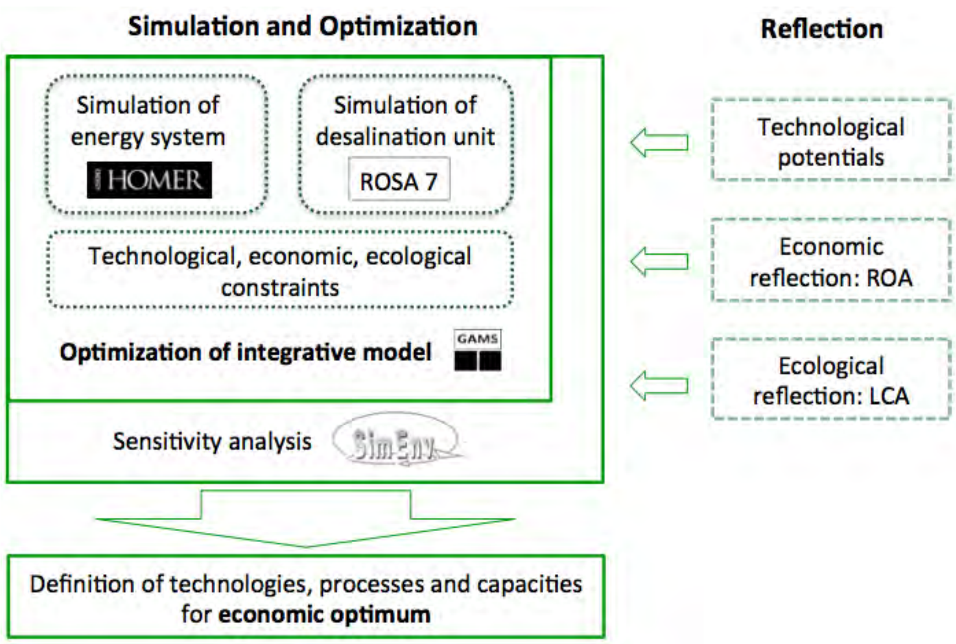

Fig. 3.3: *Methodology overview*

in order to quicken the solving. As the solver gets closer to the optimal solution, the solving speed becomes slower and slower. A 5 % gap tolerance to optimality needed to be set, to make the model solvable; that means, the objective function can be 5 % away from the bound for the optimal solution, also called the best estimate. All options have been chosen based on suggestions in the solver manual [80] and the GAMS support [79].

3.3.2 Characteristics of developed program

The strategic analysis approach used is illustrated in Fig. 3.3. Each topic visualized in a box is addressed in various chapters and sections. The simulation and optimization is approached in an integrative and iterative process. This model is developed in the GAMS (General Algebraic Modeling Systems) environment and is combined with an optional sensitivity analysis based on the simulation environment SimEnv. For a better understanding and defining detailed information of energy grids, conversion technologies and desalination processes, available simulation and optimization tools as HOMER and ROSA were screened and applied for preliminary calculations.

The model development followed common proceedings: The goal was formulated, the supply system with its components observed, the mathematical model of the problem with extensive rework formulated, the model and the use of the model for prediction verified, suitable alternatives selected if necessary, and recommendations implemented, evaluated and reflected. Standard literature used for determining the basic approach are e.g. [81] and [82]. Typical challenges in modeling and optimizing are minimizing time consumption. Adjustments of the model for minimizing time consumption are addressed in each section and at the end of the modeling chapter 4.

The model itself is *dynamic*, because decision variables do involve sequences of decisions over multiple periods. During the construction of the model a particular attention was paid to keep the *model linear*. While non-linear models enable the implementation to have more sophisticated dependencies between variables, thus allowing more complicated sub-models, this model was kept intentionally linear to enhance its speed and its convergence in respect to initial values. A non-linear program with the dimension of 8760 time steps, various energy generation technologies and storage systems, would not be solvable. Sub-models that may have required non-linear structures were linearized through reasonable assumptions or turned into models with piecewise linear dependencies. Because most energy generation, storage and desalination units need to be switched on an off during the operation within one year, the integration of binary variables, responsible for switching technologies on and off, is essential. Linear programs turn into *mixed integer programs*. A further characteristic of a model is the question, whether it is deterministic or stochastic. Although there are a number of uncertain values, as the oil price, wind and solar potentials or demand developments, the model is designed as *deterministic* model.

The Mixed Integer Programming (MIP) algorithm used is an implementation of a branch-and-bound search with specific algorithmic features such as cuts and heuristics. The branch-and-bound algorithm discards a significant part of unused subsystems by using upper and lower estimated bounds. The method was first proposed in 1960 for discrete programming [83]. Lagrange-multiplier can also be introduced if required. The MIP optimizer within OSICplex solves large and numerically difficult MIP models [80]. Integer variables, different branchings and nodes have been defined. As mentioned before, OSICplex faces limitations compared to Cplex. One, for example, is the fact, that in comparison to Cplex OSICplex does not support special order sets (SOS) of order 1 and 2. That means, parameters with one or two positive variables are provided with a set of specific conditions and boundaries, in case of two positive variables (SOS2), the variables need to be adjacent and the adjacency conditions are enforced by the solution algorithm. Most commercial solvers allow to specify SOS1 and SOS2, OSICplex not. Therefore alternatives need to be formulated as for the diesel generators or desalination units, cf. section 4.6 and 4.7, where binary variables are used for modeling a piecewise linear function. Implementing SOS2 enables to solve the model three times as fast [79]. A simplified flow chart of the optimization approach is shown in Fig. 3.4.

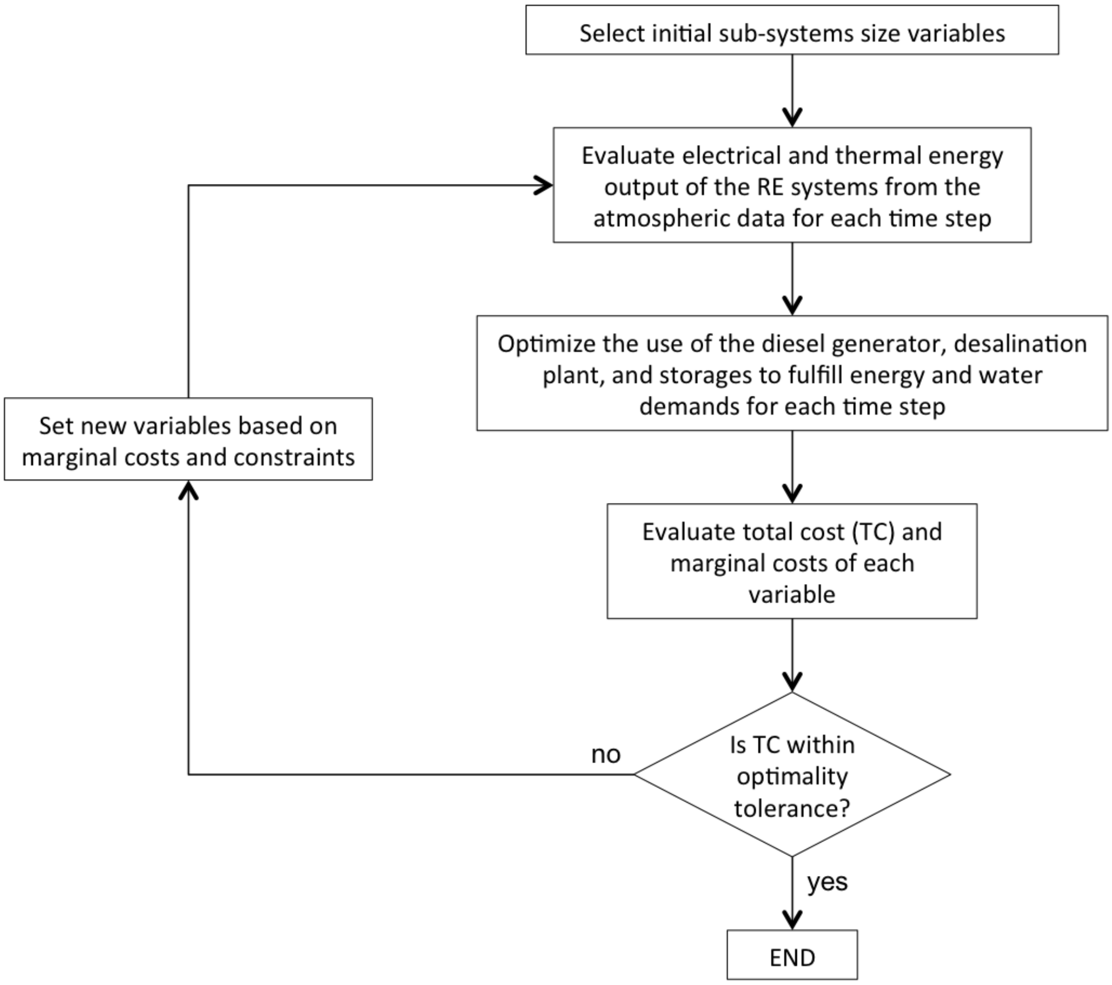

Fig. 3.4: *Flow chart of optimization approach*

The model chooses the optimal energy generation technologies, the storage systems and desalination processes and all capacities within the minimization of net present costs. The optimization approach is minimizing the net present costs (NPC). Levelized costs of electricity (LCoE) and levelized costs of water (LCoW) are further terms that will be used within the calculations and analyses. The NPC is defined as

$$\mathrm{C_{NPC}} = \frac{\mathrm{C_{ann,tot}}}{\mathrm{CRF_{i,N}}} \tag{3.1}$$

with $\mathrm{C_{ann,tot}}$ being the project's annualized costs and $\mathrm{CRF_{i,N}}$ the capital recovery factor, which is calculated with

$$\mathrm{CRF}_{\mathrm{i_r,N}} = \frac{\mathrm{i_r}(1+\mathrm{i_r})^{\mathrm{N}}}{(1+\mathrm{i_r})^{\mathrm{N}}-1} \tag{3.2}$$

whereas $\mathrm{i_r}$ stands for the annual real interest rate and N for the projects lifetime. The inflation adjusted real interest rate is defined as

$$\mathrm{i_r} = \mathrm{i_n} - \mathrm{j} \tag{3.3}$$

with $\mathrm{i_r}$ labeling the real interest rate, $\mathrm{i_n}$ the nominal interest rate and j the inflation rate.

The levelized costs of energy (LCoE) are calculated as shown in Eq. 3.4, the levelized costs of water (LCoW) according to Eq. 3.5. Both equations use the annuity factor ($\mathrm{A_{i,N}}$), where i is equal to 0.075 and N to 20 years (*cf.* Eq. 3.6).

$$\mathrm{LCoE} = \frac{\mathrm{I0_E} \cdot \mathrm{A_{i,N}} + \mathrm{C_{fuel}} + \mathrm{C_{O\&M_E}}}{\mathrm{E_{prim}}} \tag{3.4}$$

$$\mathrm{LCoW} = \frac{\mathrm{I0_W} \cdot \mathrm{A_{i,N}} + \mathrm{C_{O\&M_W}} + \mathrm{C_E}}{\mathrm{W_{year}}} \tag{3.5}$$

$$\mathrm{A_{i,N}} = \frac{\mathrm{i} \cdot (1+\mathrm{i})^{\mathrm{N}}}{(1+\mathrm{i})^{\mathrm{N}}-1} \tag{3.6}$$

In Eq. 3.4 the initial capital costs ($\mathrm{I0_E}$) multiplied by the annuity factor reflect the annual capital expenditures. $\mathrm{C_{O\&M_E}}$ stands for operation and maintenance costs of all components per year, and $\mathrm{C_{fuel}}$ stands for annual fuel costs. All annual costs are divided by the primary load ($\mathrm{E_{prim}}$). The additional energy demand for desalination is not added to the primary load in order to keep the scenarios comparable without minimizing the LCoE due to the increased electricity demand. To calculate the LCoW, the initial capital cost of the desalination plant $\mathrm{I0_W}$ multiplied by the annuity factor is added to the annual costs of the desalination plant, including operation and maintenance costs ($\mathrm{C_{O\&M_W}}$) and electricity costs ($\mathrm{C_E}$). These are divided by the amount of potable water produced in the year ($\mathrm{W_{year}}$).

3.4 Sensitivity analysis

The output of the GAMS/OSICplex model is the optimal system setup for one specific scenario of input values and local constraints. A comprehensive sensitivity analysis is aspired in order to generate outcomes in a wider range. For this reason **SimEnv**, a simulation environment developed at the Potsdam Institute of Climate Impact Research (PIK), was applied to the model. SimEnv is a multi-run simulation environment that focuses on evaluation and usage of models with large and multi-dimensional output mainly for quality assurance matters and scenario analyses using probabilistic, Bayesian and deterministic sampling techniques. A GAMS (main) model interfaced to SimEnv can call GAMS sub-models. Additional include statements have to be inserted into the GAMS model source code files where experiment factors are to be adjusted or model variables are supposed to be output to SimEnv [84].

In a first step the most sensitive parameters of the GAMS/OSIplex model will be determined for the most relevant model output variables with a modified *Morris method* [85, 86]. Its main approach is to derive qualitatively global sensitivity measures for all parameters by computing statistics on a set of local sensitivity measures, the so called elementary effects. The result of this analysis is a ranking of the factors in terms of their importance with respect to specific model output variables [84].

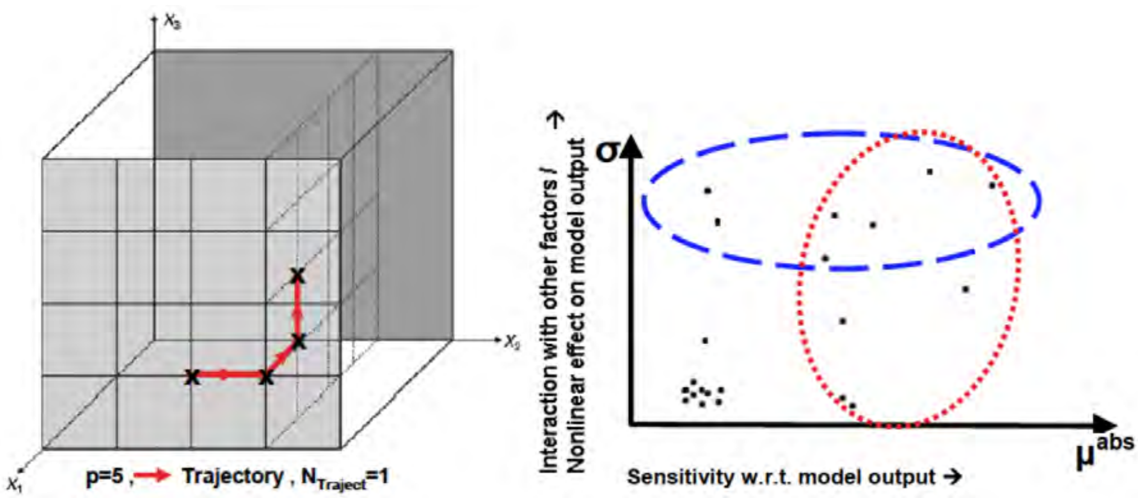

Fig. 3.5: *Trajectory example of Morris analysis (left) and relevance of parameters (right)*

A gridded factor space is needed for this analysis. The gridded factor space $x = (x_1,...,x_k)$ for k parameters has p levels and a grid width of Δ_i for each factor x_i, as shown in the left diagram of Fig. 3.5. In the experiment $N_{Traject}$ trajectories T^j of the length k from k+1 points are selected randomly at the grid where consecutive points differ only in one factor. For each trajectory $T^j=(t_1{}^j ,.., t_{k+1}{}^j)$ and each factor x_i from two consecutive points an elementary effect $ee_{ij} = (y(t_l{}^j+e_i\ \Delta_i) - y(t_{l+1}{}^j)) / \Delta_i$ is determined. The arrows in the left coordinate system of Fig. 3.5 indicate the sequence how each trajectory is generated from sampling points [84]. In a next step distribution measures from the ee_{ij} are determined (refer to [84] for further details) and are characterized by the sensitivity μ_i and variance σ_i. μ_i in this case stands for the overall influence of x_i on y, that means for the sensitivity of a factor with respect to the model output. σ_i shows, whether the factor x_i is involved in interactions with other factors with respect to y or if the effect of x_i on y is nonlinear. The right diagram of Fig. 3.5 gives an idea of how such a qualitative interpretation of sensitive parameters based on a number of elementary effects can be visualized for one model output y. Factors within the red circle can be identified as most sensitive, factors bounded by the blue circle show interactions with other factors and/or a nonlinear effect on the model output y. Parameters can be ranked now with respect to their sensitivity. The computational cost C in terms of the number of single model runs of such an experiment is $C = N_{Traject} \cdot (k + 1)$ [84].

After determining the most sensitive parameters and variables, a sensitivity analysis is performed based on these sensitive parameters by choosing a *Deterministic Factorial Design*. Without going into more detail, the goal of this approach is to show how the model behaviour changes with deterministic changes of factor values, cf. [84] for further information.

For deriving statistical conclusions concerning the distribution of energy mixes and beneficial technology combinations, a *Monte-Carlo-Analysis* is undertaken for the most sensitive parameters as well. The resulting probability density function of model output y can also be interpreted as a stochastic error analysis, but is used here more for determining the relevance from different energy generation and desalination components. The detailed proceeding is documented in combination with the results in section 6.5.

3.5 Real option analysis

Traditionally the cost-benefit analysis [87], the net present value and the discounted cash flow methods are used to evaluate project investments. As soft evaluation methods the cost-utility analysis and the multi-criteria analysis are most commonly used. In the developed model the net present cost approach is employed.

Tab. 3.2: *Analogy between Stock Options and Real Options*

Investment Opportunity	Call Option
Present value of a project's operating assets	Stock price
Present Value of required Investment in each time step	Exercise price
Length of time the decision may be deferred	Time to expiration
Time value of money	Rate of return
Riskiness of the project assets	Variance of returns on stock (price variation) per year

As a further development and alternative perspective additionally to the model-embedded net present cost approach a real option analysis (ROA) is accomplished. The main reason for this is, that todays investments are characterized by high risks and uncertainty, which cannot be included in the previously mentioned approaches. Traditional techniques make implicit assumptions, e.g. concerning the reversibility of investments, where investments can be undone and expenditures recovered [88]. According to *Luehrman* [89], "a business strategy is much more like a series of options than it is like a series of static cash flows."

During the last years an increasing interest for the real option approach for decision making in the energy sector has been noticed. The main reason for the interest are projects with high initial costs at high financial risk due to uncertainties [90]. With the real option method an investment can be delayed theoretically in order to obtain more information and thus reducing uncertainty. Compared to the financial stock market, real options of a project are analogue to stock options. Derived from *Luehrman* [91], real options can be put in relation to call options as shown in Tab. 3.2.

The concept of real options arises from financial options. The theory was developed by *Black, Merton and Scholes* back in 1973. They were awarded with the Nobel Prize in Economics in 1997. The option-pricing theory had applications for all kind of investments, whether they are real or non-financial [92]. There are three general option valuation techniques, cf. [90, 93]:

The most traditional and theoretical option approaches use partial differential equations. Since in real projects no completely closed form solutions are possible (as they are at the stock market, where precise prices are available at any time), approximations for analytical results are required; if no analytical solution is possible, numer-

Tab. 3.3: Option valuation methods

Option valuation technique	Specific method
Partial differential equations	Black-Scholes equations
	Analytical approximations
	Numerical methods
Simulations	Monte-Carlo Analysis
Dynamic programming (Lattices)	Binomial up to multinomial decision trees

ical approaches can be used to solve the partial differential equation. The process is complex and non-transparent, can deal with only one uncertainty and is hardly applicable for real options [93]. The most commonly used method to determine the real option value is the Monte-Carlo-Analysis. The third approach, determining lattices and solving them eventually with dynamic programming is the method applied here. Binomial, trinomial, quadrinomial or multinomial decision trees are handy tools, because intermediate values and decisions become visible [90]. In general, all approaches come up with the same real option value. Therefore depending on the available input data the most applicable method can be used.

Examples of ROA as decision tool in renewable energy projects are reviewed in detail by *Fernandes et al.* [90]. Mainly wind energy and hydropower investment strategies have been reflected with ROA, using partial differential equations as method as well as Monte-Carlo simulations and binomial lattices. A comprehensive research approach and decision support tool was developed by *Burgess et al.* [94]. They considered all currently discussed energy supply systems, assuming relevant risk-data and uncertainties of their cost developments in the next 40 to 50 years. The method used is an adjusted Monte-Carlo approach. The study advises the Australian government for a sustainable energy supply strategy for the next decades.

However, the argumentation line followed here can be compared most suitable with the one argued by *Fleten et al.*[95]. They used real options for determining investment strategies concerning renewable energy technologies in decentralized energy systems. *Siddiqui and Fleten* continued the model development and applied the approach in further real case decisions dealing with renewable energy technologies. The most similar research approach using decision trees as a modification from binomial lattices was chosen and developed by *Brandao et al.* [96].

As mentioned before, the approach is kept simple to guarantee the transparency and is based on the real practice guideline summarized by *Copeland and Tufano*

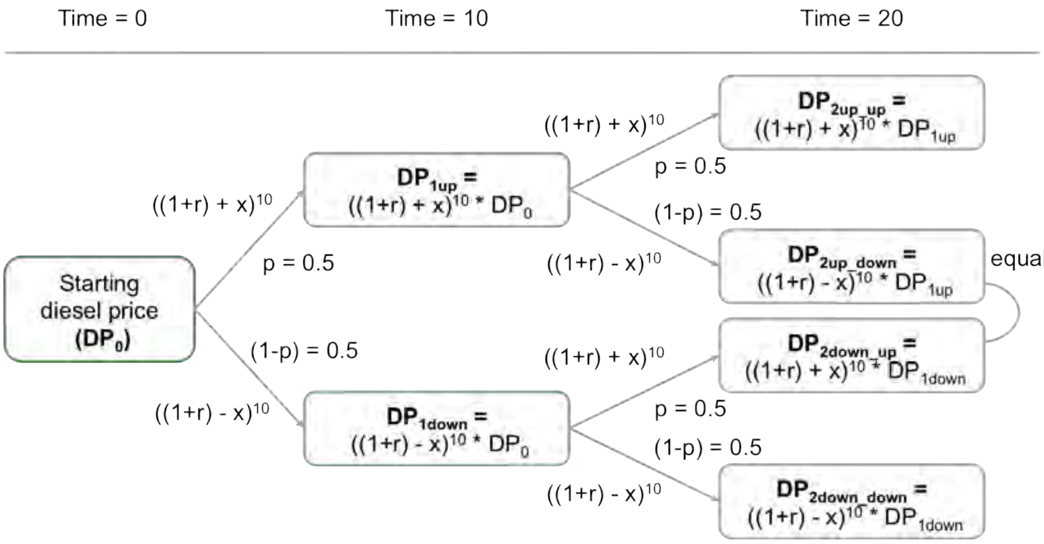

Fig. 3.6: *Binomial pricing tree for two periods: Diesel price development in 20 years*

[97]. Figure 3.6 shows the principle of the binomial pricing tree for two periods where DP is the diesel price, r the risk-free rate of return (here the annual constant growth rate of the diesel price), p the risk-neutral probability and x the deviation of the constant growth rate. The deviation x is directly related to the standard deviation σ^2. The time steps are chosen, because in the range of a project life time of 20 years, energy and water supply infrastructure will most probable not be adjusted more frequently than every ten years, which is already assuming flexibility within the investment strategy.

3.6 Ecological constraints within the model

As basic principle for implementing ecological constraints within the technological and economic optimization, a life cycle assessment has been performed previously. Goal of the life-cycle assessment was to disclose environmental impacts of components used within the model as energy conversion technologies, desalination plants, storage systems etc. Various evaluation methods are in use, e.g. material flow analysis, environmental risk assessment, environmental input/output analysis, life-cycle assessment as well as multi-criteria-analysis or cost-benefit-analysis within economic optimization models. The evaluation method used here is the life cycle assessment, since it provides the most flexibility in addition to the cost-based integration, considering more expansive environmental impacts.

Main ecological problem areas that will usually be considered are the resource consumption, greenhouse effects, human toxicity, ecotoxicity, land use, waste heat and waste accumulation [98, 99]. Within the model waste heat, land use, greenhouse gas emissions as well as resource depletion are included. Not all sub-systems contain all ecological aspects due to the lack of data. Table 3.4 shows an excerpt of such a classification. Only highlighted impact categories are integrated in the developed optimization model. Considering these additional costs, the overall system costs are higher than comparable calculations without considering environmental costs. The complete life cycle assessment for the case study Brava is published by *Ruben* [100].

Tab. 3.4: *Classification and characterization of environmental impacts*

Symbol	Impact category	Unit
GWP	**Global warming potential (100 years)**	**kg CO_2-Equiv.**
ODP	Ozone layer depletion potential (steadystate)	kg R11-Equiv.
AP	Acidification potential	kg SO_2-Equiv.
EP	Eutrophication potential	kg Phosphate-Equiv.
POCP	Photochemical ozone creation potential	kg Ethene-Equiv.
HTP	Human toxicity potential	kg DCB-Equiv.
FAETP	Freshwater aquatic ecotoxicity potential	kg DCB-Equiv.
ADP	**Abiotic resource depletion**	**kg Sb-Equiv.**
ED	**primary energy demand**	**kWh**
LU	**Land use**	**m^2**

Chapter 4

Model

The model consists out of a number of internal sub-systems determining cost functions, electrical and thermal energy flows, water flows and various constraints depending on each technology and the availability of input data. The goal of this chapter is to clarify the model and its elements. Figure 4.1 gives a rough overview of the model structure.

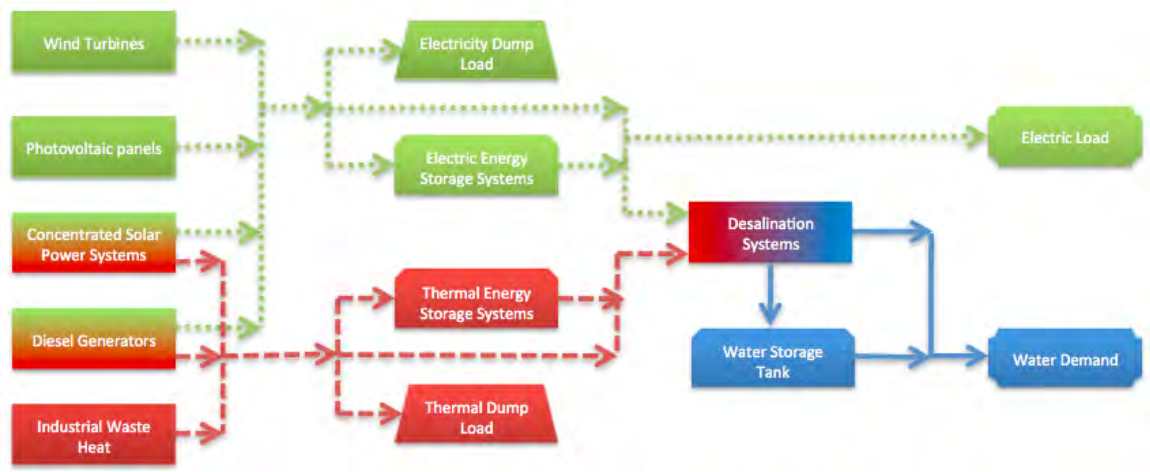

Fig. 4.1: *Overview of model*

The energy and water demand of a region is known, whereas the power demand is available in hourly and the water demand in daily time steps. The main constraint within the model is to meet 100 % of the power and water demand. In "real projects" a supply gap of 5 to 15 % is commonly tolerated, since the last per cents of full supply security endanger only a few minutes or hours of supply shortages. Exactly for these few peaks significantly higher investments are required than for a system with a supply gap. This model assumption makes the overall system costs higher than they would be with a supply gap of e.g. 5 %.

The green dotted arrows in Fig. 4.1 are electricity fluxes, the red segmented arrows are thermal fluxes and the solid blue arrows are water fluxes. The shape of each block indicates what kind of system it is: generating system, storage, dump or demand. Hereafter these blocks will be referred to as *sub-system* comprising one or more technologies, the whole system will often be referred to as *overall system*.

4.1 Objective function and main constraints

The techno-economic optimization model has the main objective to minimize the net present costs of the overall system by meeting technological restrictions. The objective function therefore is:

$$\begin{aligned}\min_{\left\{\substack{\text{Decision}\\ \text{Variables}}\right\}} \text{TotalCost} = &\sum_{\text{tech}_{\text{PV}}} \text{TC}_{\text{PV}} + \sum_{\text{tech}_{\text{W}}} \text{TC}_{\text{W}} + \sum_{\text{tech}_{\text{CSP}}} \text{TC}_{\text{CSP}} + \\ &+ \sum_{\text{tech}_{\text{diesel}}} \text{TC}_{\text{diesel}} + \sum_{\text{tech}_{\text{Desal}}} \text{TC}_{\text{Desal}} + \\ &+ \sum_{\text{tech}_{\text{ess}}} \text{TC}_{\text{ess}} + \sum_{\text{tech}_{\text{tss}}} \text{TC}_{\text{tss}} + \text{TC}_{\text{wss}}\end{aligned} \tag{4.1}$$

The total costs of the whole system are the sum of the net present costs of each integrated sub-system. Each sub-system may have more than one type of technology installed simultaneously. For example, two different desalination processes could be part of the optimal solution. In this case the costs of each desalination unit would sum up to the total costs of the sub-system desalination $\sum_{\text{tech}_{\text{Desal}}} \text{TC}_{\text{Desal}}$. The decision variables of the main model are listed in Tab. 4.1.

Tab. 4.1: *Optimal supply system - default*

Abbreviation	Decision variable	Unit
P_{pv}	rated power of each type of photovoltaic collector system	kW
P_w	rated power of each type of wind turbine	kW
P_{csp}	rated power of each concentrated solar power system used	kW
P_{ess}	rated power of each chosen electric energy storage system	kW
E_{ess}	installed capacity of each electric energy storage system	kWh
Capacity_{desal}	installed capacity of each desalination unit	m^3/day
E_{tss}	installed capacity of each thermal energy storage system	kWh
V_{wss}	installed capacity of the water storage tank	m^3

The minimization of costs has to follow some constraints. The most important ones are to meet the electricity demand, to meet the thermal load for desalination, if required, and to meet the water demand. All three constraints influence more than one sub-system and are shown in Eq. 4.2, 4.3 and 4.4. Equation 4.2 presents the constraint of the electricity balance, that needs to be met in each hour of the simulated year:

$$\begin{aligned} \text{Load} = & \sum_{\text{tech}_{\text{PV}}} \text{E}_{\text{PV,out}} + \sum_{\text{tech}_{\text{W}}} \text{E}_{\text{W,out}} + \sum_{\text{tech}_{\text{CSP}}} \text{E}_{\text{CSP,out}} + \\ & + \sum_{\text{tech}_{\text{diesel}}} \text{E}_{\text{diesel,out}} + \sum_{\text{tech}_{\text{ess}}} (\text{E}_{\text{ess,out}} - \text{E}_{\text{ess,in}}) + \\ & - \sum_{\text{tech}_{\text{Desal}}} \text{E}_{\text{Desal,in}} - \text{Dump}_{\text{el}} \\ & \qquad \forall \text{t} \in [1, 8760] \end{aligned} \tag{4.2}$$

Where:

- Load is the electrical energy load of the island, expressed in kWh/h. It is not a variable, it is set by data of the standard year.
- The different $E_{j,out}$ and $E_{j,in}$ are the outgoing and incoming electrical energy fluxes of each system of the technology "j" , expressed in kWh/h. They are strictly non-negative variables.
- $Dump_{el}$ is the electricity flux sent to the throwaway dump load, expressed in kWh/h and is a non-negative variable.

In other words, at each hourly time step, the required energy has to be either generated by the renewable systems (photovoltaic panels, wind turbines, concentrated solar power systems), by the diesel generators or by the electric energy storage system. This formula also shows what happens if there is an excess of energy: it can be either sent to charge the ESS, to the throwaway dump load or to the desalination plant. Concerning the thermal energy constraint, the following equation is introduced:

$$\begin{aligned} \sum_{\text{tech}_{\text{Desal}}} \text{Th}_{\text{Desal,in}} = & \sum_{\text{tech}_{\text{diesel}}} \text{Th}_{\text{diesel,out}} + \sum_{\text{tech}_{\text{CSP}}} \text{Th}_{\text{CSP,out}} + \\ & + \sum_{\text{tech}_{\text{tss}}} (\text{Th}_{\text{tss,out}} - \text{Th}_{\text{tss,in}}) - \text{Dump}_{\text{th}} \\ & \qquad \forall \text{t} \in [1, 8760] \end{aligned} \tag{4.3}$$

Where all of the next terms are non-negative variables:

- $\mathrm{Th}_{\mathrm{Desal,in}}$ is the thermal energy flux going into a specific desalination system, expressed in kWh/h.
- $\mathrm{Th}_{\mathrm{diesel,out}}$ and $\mathrm{Th}_{\mathrm{CSP,out}}$ are the thermal energy fluxes recovered from the diesel and CSP systems, expressed in kWh/h.
- $\mathrm{Th}_{\mathrm{tss,out}}$ and $\mathrm{Th}_{\mathrm{tss,in}}$ are the outgoing and incoming thermal energy fluxes of the thermal storage systems, expressed in kWh/h.
- $\mathrm{Dump}_{\mathrm{th}}$ is the thermal flux sent to the throwaway dump load, expressed in kWh/h.

This means that the thermal need of all thermal desalination processes must be satisfied using the thermal energy inside the storage or the thermal flux generated in the same time step. Thermal energy demand can be met by diesel generators and the CSP systems. The heat is part of the waste heat of the electricity generation process and is calculated by considering the thermal efficiency. In the case of CSP systems Eq. 4.9 shows the relation of meteorological data and thermal output, for the diesel generators Eq. 4.16. The fuel consumption itself is a function of the electric outgoing flux, which depends on the overall system step-by-step balance.

The desalination plant can use dump load and help to manage the energy balance. As it will be shown in Eq. 4.4, the desalination plant has to satisfy a production constraint as well.

$$\begin{aligned}\mathrm{WaterDemand} = \quad & \mathrm{Water}^{\mathrm{d}}_{\mathrm{reserve}} - \mathrm{Water}^{\mathrm{d+1}}_{\mathrm{reserve}} + \\ & + \sum_{\mathrm{tech}_{\mathrm{Desal}}} \mathrm{WaterGeneration}_{\mathrm{Desal}} \\ & \qquad\qquad\qquad\qquad \forall \mathrm{d} \in [1, 365]\end{aligned} \tag{4.4}$$

Where:

- WaterDemand is the amount of water that the island needs each day, expressed in m^3/d. It is a given set of data.
- $\mathrm{Water}^{\mathrm{d}}_{\mathrm{reserve}}$ and $\mathrm{Water}^{\mathrm{d+1}}_{\mathrm{reserve}}$ are the amount of water inside the storage tank at day d and the next day respectively, expressed in m^3 and non-negative variables.
- $\mathrm{WaterGeneration}_{\mathrm{Desal}}$ is the amount of water that each desalination system produces on day d, expressed in m^3/d. It is also a non-negative variable.

$\text{WaterGeneration}_{\text{Desal}}$ is defined as the sum over the days of a year of the ratio of electricity for desalination and the power consumption for producing one cubic meter of desalted water:

$$\text{WaterGeneration} = \sum_{t \in d} \frac{E_{\text{Desal,in}}}{E_{\text{cons,el}}} \qquad \forall d \in [1, 365] \tag{4.5}$$

Since some desalination technologies require mainly thermal energy, the two incoming fluxes of thermal and electrical energy need to be linked. This is modeled separately and presented in section 4.7 (Eq. 4.26). In other words, Eq. 4.4 sets the daily water balance based on the water demand. The freshwater can be provided either directly from the desalination plant or from the water storage tank, if excess water has been produced previously.

4.2 Modeling total costs

The total costs are built on the decision variables of each sub-system. With increasing installed capacity of each technology the total costs of the sub-system increase respectively. Total costs can take six terms into account:

1. initial investment costs
2. replacement costs
3. maintenance costs
4. fuel-related costs
5. land-use costs
6. environmental costs

Not all total costs of sub-systems include all six terms. Initial investment and maintenance costs appear for almost all considered components. In some scenarios solely the diesel generator sets are considered as existent on the island. Replacement costs are only introduced in sub-systems, where the lifetime of the considered technology is less than 20 years. This is the case for some batteries.

Fuel related costs can be split into purchase, transport and emission costs. Emission costs are defined by the price of emitting one ton of CO_2-equivalents, which can be easily set to 0 in case that no taxation nor fine for the emission of carbon dioxide equivalents is assumed. The costs for land-use are introduced, since especially on small islands available land surface is very limited. The environmental costs in this case cover emission costs and costs for resource depletion. The emission of CO_2-equivalents during the whole product lifetime are considered, excluding the already mentioned greenhouse gases emitted during operation. Costs of resource depletion are also considered in the model, since the scarcity of a number of elements endangers future developments. Defining the resource costs for each component is a highly complex approach. Indicators can be used depending on the scarcity of an element or overall material costs can be taken as reference [100].

4.3 Modeling photovoltaic energy generation systems

4.3.1 Modeling energy flows (PV)

The energy fluxes generated by each technology of the renewable power systems are modeled as a function of the decision variables and the meteorological data of a standard year. More than one photovoltaic technology is considered, therefore the index "j" is introduced. The formula implemented in the model are:

$$\begin{aligned} \mathrm{E_{PV,out}} = \; & \mathrm{SolarRadiation} \cdot \mathrm{Deration_{PV}} \cdot \mathrm{P_{PV}} \\ & \forall \mathrm{t} \in [1, 8760] \end{aligned} \tag{4.6}$$

Where:

- $\mathrm{E_{PV,out}}$ is the outgoing electricity flux from the given technology of each PV-system, expressed in kWh/h. It is a non-negative variable.
- SolarRadiation is the specific incoming solar radiation expressed in $\mathrm{kW/m^2}$; it is part of the meteorological data of the standard year.
- $\mathrm{Deration_{PV}}$ is a parameter that is used to take into account all losses of each sub-system like dirt, wire losses, DC/AC conversion etc.
- $\mathrm{P_{PV}}$ is the installed capacity of the used photovoltaic system or systems. $\mathrm{P_{PV}}$ is a variable that will be defined within the optimization process.

4.3.2 Modeling total costs (PV)

For each technology of the photovoltaic system the total costs have been modeled and implemented in the following way:

$$\begin{aligned} \mathrm{TC_{PV}} = \quad & \mathrm{c_P P_{PV}} \left(1 + \mathrm{f_{O\&M}} \sum_{\mathrm{y}=1}^{\mathrm{Life}} \frac{1}{(1+\mathrm{i})^{\mathrm{y}}} \right) + \\ & + \mathrm{c_{land}} \left(\frac{\mathrm{P_{PV}}}{\eta} \cdot \mathrm{k_{LU}} \right) + \mathrm{P_{PV}} \left(\mathrm{c_{PV,CO_2}} + \mathrm{c_{PV,Res}} \right) \end{aligned} \tag{4.7}$$

The investment cost is modeled as the specific power cost (c_P in €/kW) times the peak installed power of the given technology. The annual operation and maintenance costs are included as a percentage ($f_{O\&M}$ in y^{-1}) of the investment cost and are actualized by the actualization factor. The cost for land use is implemented as the specific mean land cost (c_{land} in €/m^2) on the island times the area occupied by the system.

The net collecting area of the panels is calculated by the division of the rated power by the conversion efficiency. The coefficient k_{LU} takes into account the area needed for the construction, the space between the modules and all equipment required for operating and managing the system. This coefficient has been set to 1.5. It has been assumed that the land area required for the system is 50% more then the collector's net surface. The environmental costs c_{PV,CO_2} and $c_{PV,Res}$ are depending on the installed capacity of the PV system and are put together out of the specific lifetime-emission costs and the resource costs.
Replacement costs and fuel-related costs can be neglected for PV systems.

4.4 Modeling concentrated solar power systems

4.4.1 Modeling energy flows (CSP)

$$\begin{aligned} \mathrm{E_{CSP,out}} = \quad & \mathrm{SolarRadiation} \cdot \mathrm{Deration_{CSP}} \cdot \mathrm{P_{CSP}} \\ & \forall \mathrm{t} \in [1, 8760] \end{aligned} \tag{4.8}$$

$$\begin{aligned} \mathrm{Th_{CSP,out}} = \quad & \mathrm{SolarRadiation} \cdot \mathrm{Deration_{CSP}} \cdot \mathrm{P_{CSP}} \cdot \frac{\eta_{\mathrm{CSP,th}}}{\eta_{\mathrm{CSP,el}}} \\ & \forall \mathrm{t} \in [1, 8760] \end{aligned} \tag{4.9}$$

Where:

- SolarRadiation is the specific solar radiation expressed in kW/m^2; it is part of the meteorological data of the standard year.

- $\text{Deration}_{\text{CSP}}$ is a parameter, that incloses all losses during energy conversion by the CSP technologies, e.g. due to dirt, wire losses, or general conversion losses.
- $\eta_{\text{CSP,el}}$ is the electrical efficiency of each CSP technology
- $\eta_{\text{CSP,th}}$ is the thermal efficiency of each CSP technology; it represents the recovered waste heat divided by the solar radiation. This way, the ratio $\frac{\eta_{\text{CSP,th}}}{\eta_{\text{CSP,el}}}$ is the amount of thermal energy recovered by generating one unit of electrical energy.
- $E_{\text{CSP,out}}$ is the outgoing electricity flux of each CSP technology, expressed in kWh/h. It is a non-negative variable.
- $\text{Th}_{\text{CSP,out}}$ is the outgoing thermal energy flux of each CSP technology, expressed in kWh/h. It is also a non-negative variable.

4.4.2 Modeling total costs (CSP)

The total cost of each CSP technology is modeled similar to the PV system:

$$\begin{aligned} \text{TC}_{\text{CSP}} = \quad & c_P P_{\text{CSP}} + \left(c_{\text{P,O\&M}} P_{\text{CSP}} \sum_{y=1}^{\text{Life}} \frac{1}{(1+i)^y} \right) + \\ & + c_{\text{land}} (\text{LU}_{\text{CSP}} P_{\text{CSP}}) + P_{\text{CSP}} \left(c_{\text{CSP,CO}_2} + c_{\text{CSP,Res}} \right) \end{aligned} \tag{4.10}$$

The investment cost is modeled identical to the PV systems, the operation and maintenance cost though is given as a specific cost ($c_{\text{P,O\&M}}$ in €/kW y) and not as a percentage of the investment cost. The reason for this is solely the availability of data. If needed, the formula can be rewritten as percentage, using the formula $f_{\text{O\&M}} = c_{\text{O\&M}}/c_P$. The costs for land use are not calculated by a factor but by a specific parameter (LU in m^2/kW), multiplying the specific mean land cost by the required area. The environmental costs for emissions and resource depletion are determined as mentioned before for the PV systems.

4.5 Modeling wind energy generation systems

4.5.1 Modeling energy flows (wind)

As wind energy converters three technologies are considered, two with a horizontal axis, one with a vertical one. For all following energy flow formula is valid:

$$E_{W,out} = \text{SpecificOutput(WindSpeed)} \cdot \frac{P_W}{P_{W,nom}} \quad \forall t \in [1, 8760] \tag{4.11}$$

Where:

- SpecificOutput(WindSpeed) is the specific electrical energy output of the standard wind turbine. It is a parameter depending on the wind velocity each hour, modeled with a 6th order polynomial curve that fits the power-windspeed curve given by manufacturers and expressed in kWh/h. Details are discussed below.
- $P_{W,nom}$ is the nominal power of the considered wind turbine. The ratio of P_W serves as a scaling factor under the assumption that the power-wind speed curve grows and is reduced proportionally with the rated power, maintaining the same shape.
- $E_{W,out}$ is the outgoing electricity flux of each wind technology, expressed in kWh/h. It is a non-negative variable.

The wind speed is part of the meteorological data and is given at the height of the measuring anemometer. To evaluate the velocity at hub height, which can change between different types of wind turbines, the following formula is used:

$$V_{HubHeight} = V_{anemometer} \left(\frac{\ln(h_{hub}/z_0)}{\ln(h_{anemometer}/z_0)} \right) \quad \forall t \in [1, 8760] \tag{4.12}$$

Where z_0 is the roughness of the ground around the wind turbine and h is the height. Both are expressed in meters.

The specific output of a wind turbine depends on its power curve. The model is a linear mixed integer program. The non-linear power curve of a wind turbine can be approximated by a polynomial and some further parameters. The power curve of the wind turbines can be fit the best by a sixth order polynomial curve, where the seven coefficients are named k_i (with $i = 1, 2..7$). Additional data needed are the cut-in and cut-off wind speeds as well as the "plateau"-speed, at which some turbines generate a constant rate of power. This is usually the case at high wind speeds before the cut-off speed is reached. The used equation is:

$$\text{SpecificOutput} = \begin{cases} 0 & \text{if } v_{wind} < v_{cut-in} \text{ or } v_{wind} > v_{cut-off} \\ k_1 v_{wind}^6 + k_2 v_{wind}^5 + k_3 v_{wind}^4 + k_4 v_{wind}^3 + \\ \quad + k_5 v_{wind}^2 + k_6 v_{wind} + k_7 \\ & \text{if } v_{cut-in} < v_{wind} < v_{cut-off} \\ P_{max,out} & \text{if } v_{wind} > v_{flat} \end{cases} \tag{4.13}$$

$P_{max,out}$ is not necessarily the rated power P_{nom}. It is much more the value of the "plateau". For wind turbines with no plateau, v_{flat} needs to be set very high.
The complete polynomials and exact coefficients are shown in detail in the model script in Appendix A.

4.5.2 Modeling total costs (wind)

The total cost for the wind turbine system has been modeled in a similar way to the PV system. For each technology the total cost has been implemented as:

$$\begin{aligned} TC_W = \; & c_P P_W \left(1 + f_{O\&M} \sum_{y=1}^{Life} \frac{1}{(1+i)^y}\right) + \\ & + c_{land}(LU_W P_W) \end{aligned} \tag{4.14}$$

The investment cost is again modeled as the specific power cost times the rated power of the system and the maintenance costs are a percentage of the investment cost. The land use cost instead is evaluated by multiplying the specific mean land cost by the used land. This land usage is calculated throw a specific land use (LU_W in m^2/kW) that multiplies the system rated power P_W.

4.6 Modeling diesel generator systems

4.6.1 Modeling energy flows (diesel)

Unlike the specific energy production from renewable energy sources, the energy fluxes of diesel generators are chosen by the model itself in the process of optimization. This technology needs also some specific constraints. One of them is the definition of the maximum energy generation in each time step in relation to the rated capacity of the diesel generator:

$$\mathrm{E_{diesel,out}} \leq \mathrm{P_{diesel}} \quad \forall \mathrm{t} \in [1, 8760] \tag{4.15}$$

In other words the production of each technology of this subsystem cannot exceed the value of the corresponding decision variable $\mathrm{P_{diesel}}$, that the model chooses in order to minimize the overall costs.

A second type of constraint is the definition of the link between thermal and electrical energy fluxes:

$$\mathrm{Th_{diesel,out}} = \mathrm{Fuel_{diesel,in}} \cdot \eta_{\mathrm{th}} \qquad \forall \mathrm{t} \in [1, 8760] \tag{4.16}$$

$$\mathrm{Fuel_{diesel,in}} = \frac{\mathrm{E_{diesel,out}}}{\eta_{\mathrm{el}}} \qquad \forall \mathrm{t} \in [1, 8760] \tag{4.17}$$

Equation 4.16 defines the thermal flux recovered from the diesel generator. The thermal efficiency is assumed to be constant for all loads, even in cases of part-load operation. Combining both equations, the proportionality of the thermal output and the electricity output can be derived with the proportionality factor $\frac{\eta_{\mathrm{th}}}{\eta_{\mathrm{el}}}$. This way by choosing one of both efficiencies, the other one is set automatically. Both efficiencies are used in the overall balances in Eq. 4.2 and 4.3.

The load of the diesel generator is the ratio between the output power and the rated power: $\frac{\mathrm{E_{diesel,out}}}{\mathrm{P_{rated,diesel}}}$. The rated power of the existing diesel generators is given (and constant) while the output power is chosen through the optimization process and may change at each time step.

Equation 4.17 defines the required fuel consumption for meeting the power demand in each time step. The efficiency η_{el} is modeled as a function of the load in order to fit the real behaviour of a diesel generator as good as possible. This assumption complicates the model because of the non-linearity of η_{el}. Dividing the variable $\mathrm{E_{diesel,out}}$ by a function of itself creates a non-linearity. To avoid non-linearity, a linear piecewise continuous approximation is developed, which requires further variables and equations:

$$
\begin{aligned}
E_{diesel,out} &= \sum_{pts=1}^{N_{pts}} E_{val} \cdot \lambda && (4.18)\\
Fuel_{diesel,in} &= \sum_{pts=1}^{N_{pts}} Fuel_{val} \cdot \lambda && (4.19)\\
\textstyle\sum_{pts=1}^{N_{pts}} \lambda &= 1 && (4.20)\\
\lambda &\leq bin_{pts-1} + bin_{pts}|_{pts<N_{pts}} && (4.21)\\
\textstyle\sum_{pts=1}^{N_{pts}-1} bin &= 1 && (4.22)\\
& && (4.23)
\end{aligned}
$$

These equations have to be met in each time step and each diesel technology (i.e. $\forall t \in [1, 8760]$, $\forall tech_{diesel}$).
The linear approximation is done by dividing the possible capacity utilization of the diesel generator ($\in [0\%, 100\%]$) in a number of N_{pts} points (sequences), not necessarily evenly spaced. For each point within these sequences a linear function is deposited, so that the produced electricity and the fuel consumption can be calculated in a linear environment. These N_{pts} values of produced electricity and consumed fuel are collectively defined by the parameters E_{val} and $Fuel_{val}$ respectively.

For each point, a binary variable *bin* and a positive variable λ is introduced. The binary variable *bin* is used to identify the boundaries of each interpolated section, the variable λ is used as a weighting factor of the interpolated variables $E_{diesel,out}$ and $Fuel_{diesel,in}$ (cf. 4.18 and 4.19). The *bin* variable for the last point is not used, as it can be derived by equation 4.21 and 4.22. Equation 4.22 shows that only one *bin* variable can be 1 at a time, all other *bin*s are 0. The corresponding point to this single non-zero *bin* variable is the starting point of the range in which the linear interpolation takes place. Equation 4.21 shows that λ values ($\in [0, 1]$) can only be non-zero for a non-zero *bin* and for *bin*s one after the non-zero *bin*. In Eq. 4.20 it can be seen, that the sum of the two non-zero λ values is 1, which is the obvious constraint to interpolate between the given E_{val} and $Fuel_{val}$ values of the two points, to obtain respectively $E_{diesel,out}$ and $Fuel_{diesel,in}$. The variables bin and λ are functions of the time step, of the diesel technology and of the section point *pts* and are therefore basically matrices of the size $t \times tech_{diesel} \times pts$.

This approach of linearization is suggested by the Gams Support Website [79]. The large dimension of these matrices and especially the introduction of the binary variables in the model makes it much more time consuming to solve. In fact, by introducing binary values to the model the solving method passes from LP (Linear Programming) to MIP (Mixed Integer Programming). As written in the Cplex manual: "One frustrating aspect of the branch and bound technique for solving MIP problems is that the solution process can continue long after the best solution has been found. Remember that the branch and bound tree may be as large as 2^n nodes, where n equals the number of binary variables" [80].

4.6.2 Modeling total costs (diesel)

The total cost of each diesel generator technology is modeled using the following equation:

$$
\begin{aligned}
TC_{diesel} = \quad & c_{E,O\&M} \sum_{t=1}^{8760} E_{diesel,out} \sum_{y=1}^{Life} \frac{1}{(1+i)^y} + \\
& + (c_{diesel} + c_{CO_2} k_{CO_2}) \sum_{t=1}^{8760} Fuel_{diesel,in} \sum_{y=1}^{Life} \frac{1}{(1+i)^y} + \\
& + P_{diesel} \Big(c_P + LU_{diesel} + c_{diesel,CO_2} + c_{diesel,Res} \Big)
\end{aligned} \tag{4.24}
$$

Beginning at the end, the investment costs, costs for land-use, emission costs generated during the lifecycle of the diesel generator (not considering the emissions during operation) and the costs for resource depletion are all cost factors depending on the rated power of each diesel generator set. The total costs are additionally composed of the sum of O&M costs and the costs linked to fuel consumption. The operation and maintenance costs are based on the specific costs ($c_{E,O\&M}$ in €/kWh y) that needs to be multiplied by the energy produced by the diesel generator during the year. The variable cost terms are multiplied by the actualization factor since they occur each year for the whole lifetime of the system.

Two kind of fuel related costs add up: One is the price of the diesel oil itself, defined as the specific cost c_{diesel} (€/kWh_{fuel}), the other one are the emission costs, determined by the combination of the specific emission k_{CO_2} (tCO_2-equivalent/kWh_{fuel}) and the assumed cost of carbon dioxide equivalents c_{CO_2} (€/t CO_2). The sum of these specific costs is multiplied by the total fuel consumption of the standard year.

4.7 Modeling desalination systems

4.7.1 Modeling energy flows (Desal)

Like the energy fluxes of the diesel generators, also the ones of the desalination systems are variable and can be chosen by the model itself in the process of optimization. For this reason they need similar kind of constraints. The constraint on maximum production in each time step is a daily production capacity limit:

$$\mathrm{WaterGeneration} \leq \mathrm{Capacity_{Desal}} \quad \forall \mathrm{d} \in [1, 365] \tag{4.25}$$

The equation says, that the production of each desalination system cannot exceed the capacity of the corresponding plant. This decision variable $\mathrm{Capacity_{Desal}}$ will be determined by the model optimization with the goal to minimize the total cost of the overall system.

The second type of constraint is again the definition of the link between thermal and electrical energy fluxes, which can be written as:

$$\frac{\mathrm{Th_{Desal,in}}}{\mathrm{E_{cons,th}}} = \frac{\mathrm{E_{Desal,in}}}{\mathrm{E_{cons,el}}} \qquad \forall \mathrm{t} \in [1, 8760] \tag{4.26}$$

As for the diesel generator, the formula states a proportionality between the incoming thermal and electrical energy fluxes with a proportionality factor $\frac{\mathrm{E_{cons,th}}}{\mathrm{E_{cons,el}}}$. Both energy consumptions are assumed as constant. The reason for using the energy consumption instead of its reciprocal, the efficiency, is the presence of desalination processes, which do not require any thermal energy (so $\mathrm{E_{cons,th}} = 0$ or $\eta_{\mathrm{th}} = 0$). From a calculation point of view, for these systems it is better to use a zero thermal energy consumption rather than an infinite thermal efficiency.

4.7.2 Modeling total costs (Desal)

For each desalination technology the system costs are modeled as follows:

$$
\begin{aligned}
\mathrm{TC_{desal}} = \quad & \mathrm{Capacity_{desal}}\left(\mathrm{c_{plant}} + \mathrm{c_{land}LU_{desal}} + \mathrm{c_{desal,CO_2}} + \mathrm{c_{desal,Res}}\right) + \\
& + \mathrm{c_{w,O\&M}} \sum_{\mathrm{d}=1}^{365} \mathrm{WaterProduction} \sum_{\mathrm{y}=1}^{\mathrm{Life}} \frac{1}{(1+\mathrm{i})^{\mathrm{y}}}
\end{aligned}
\tag{4.27}
$$

The investment costs are defined as the product of the specific costs of each desalination process (c_{plant} in €/(m^3/d)) and the capacity of the specific desalination plant. The plant capacity, as mentioned before, will be chosen by the model during the optimization process. The land cost is introduced as the specific mean land cost times the used land and depends on the plant capacity. Analogue to the costs for land the emission and resource depletion costs are integrated into the cost function.

The operation and maintenance costs ($c_{w,O\&M}$ in €/m^3) are variable and related to the water production (in m^3/d) in the considered standard year, using the analyzation factor for the lifetime of 20 years.

Desalination technologies requiring thermal energy in the temperature range of 60 to 80 °C use waste heat, so that no additional fuel consumption needs to be considered. Replacement costs can also be neglected, since the lifetime of the considered desalination plants are longer than the assessed lifetime of the overall system.

4.8 Modeling energy and water storages

The water storage tank is modeled with a capacity of meeting the water demand of two days. Within two days no chemical additions are required for keeping water consumable. For irrigation purposes the compliance of these two days is not required. All kind of storage systems are a basic element of the modeled energy system. Electrical, thermal and water storages are all used for shifting energy or water fluxes from periods when surplus is available to periods when deficits occur. This implies that the variables linked to the fluxes are completely dependent from the dynamics of each time step and the whole system. Variables used to fully describe the state of the storage are basically two types: the amount of energy or water stored in each time step and the capacity of the storage. Modeling the storages is based on the research work by *Calvo* in his Master thesis [101].

4.8.1 Modeling electricity storage systems (ESS)

Modeling energy flows (ESS)
The variable charging state of an electrical energy storage system is defined by the following equation:

$$\begin{aligned} \mathrm{Stored}_{\mathrm{el}}^{\mathrm{t+1}} = \quad & \mathrm{Stored}_{\mathrm{el}}^{\mathrm{t}}(1 - \mathrm{Losses}) - \mathrm{E}_{\mathrm{ess,out}} + \mathrm{E}_{\mathrm{ess,in}}\eta \\ & \forall \mathrm{t} \in [0, 8759] \end{aligned} \tag{4.28}$$

Where:

- $\mathrm{Stored}_{\mathrm{el}}^{\mathrm{t}}$ and $\mathrm{Stored}_{\mathrm{el}}^{\mathrm{t+1}}$ are the amount of electrical energy stored in time-step t and $\mathrm{t}+1$, expressed in kWh.
- Losses are the hourly parasitic losses of the system as a fraction of the energy stored h^{-1}.
- η is the round-trip efficiency of the energy storage.

Equation 4.28 states that the energy stored in a time step is equal to the one in the previous time step minus the losses occurred plus the incoming net electricity flux, which also considers the conversions that take place in the storage system. The round-trip efficiency is defined as the ratio between the electrical energy coming out of the storage system and the one going into the system in case of absence of parasitic losses, which are determined separately. A very accurate approach would take two efficiencies into account: one (η') for the conversion from electricity to the type of energy the system uses (e.g. chemical energy) and the other one (η'') for the opposite conversion. The product between these two efficiencies is the round-trip efficiency:

$$\begin{cases} \mathrm{Stored}_{\mathrm{el}} = \mathrm{E}_{\mathrm{in}}\eta' \\ \mathrm{E}_{\mathrm{out}} = \mathrm{Stored}_{\mathrm{el}}\eta'' \end{cases} \quad \text{so} \quad \begin{cases} \eta'\eta'' = \eta_{\mathrm{roundtrip}} \\ \mathrm{E}_{\mathrm{out}} = \mathrm{E}_{\mathrm{in}}\eta_{\mathrm{roundtrip}} \end{cases}$$

However, usually only the roundtrip efficiency is given by manufactures. Instead of dividing the efficiency artificially ($\eta' = \eta'' = \sqrt{\eta_{\mathrm{roundtrip}}}$), the roundtrip efficiency is used only by taking $\eta' = \eta_{\mathrm{roundtrip}}$ and $\eta'' = 1$. This approach is common in the literature, cf. *Coppez et al.*[102]. Using this assumption is like slightly changing the meaning of $\mathrm{Stored}_{\mathrm{el}}$. If, for example the storage is a chemical one, $\mathrm{Stored}_{\mathrm{el}}$ changes from the chemical energy stored to the possible electrical energy that the system can discharge with the current amount of chemical energy inside. The range of t in the formula reminds that in order to calculate $\mathrm{Stored}_{\mathrm{el}}^{t=1}$ a value for $\mathrm{Stored}_{\mathrm{el}}^{t=0}$ is needed. This value is set equal to the charge state of the last time-step, $\mathrm{Stored}_{\mathrm{el}}^{t=8760}$, giving the time a circular shape. The reason for this assumption lays in the fact that each year is considered equal to the standard one, but it is also a correct condition for avoiding a non-zero energy difference between the beginning and end of the overall life time-frame. A last comment on the formula (4.28) is on the units: They seem not to fit. In point of fact the energy fluxes and the losses are implicitly multiplied by the time step of one hour h, which completes the dimensions. The state of charge of the storage system, being a positive but otherwise free variable, needs to be subject to some physical constraints:

$$\mathrm{Stored}_{\mathrm{el}} \leq \mathrm{E}_{\mathrm{ess}} \qquad \forall \mathrm{t} \in [1, 8760] \tag{4.29}$$

$$\mathrm{Stored}_{\mathrm{el}} \geq \mathrm{E}_{\mathrm{ess}}(1 - \mathrm{DOD}_{\mathrm{lim}}) \qquad \forall \mathrm{t} \in [1, 8760] \tag{4.30}$$

These inequalities set the maximum and minimum value of energy that the energy storage can hold. Equation (4.29) states that the energy stored cannot be more than the installed capacity of the respective system. Equation (4.30) on the other hand sets the minimum energy that must be kept in the storage in order to preserve the health and correct working of the storage system itself. For a more precise simulation, the lifetime of a storage system can be modeled by depth-of-discharge-cycles (DOD) using a lifetime prediction algorithm, as the ones suggested by *Sauer and Wenzl* [14] for electrochemical storages. However, since the present model takes many technologies into account, there is no intention to reach such detailed optimizations, therefore the lifetime and the minimum level of DOD are defined as constant scalars. Some constraints though still need to be defined for electrical energy storage systems:

$$\mathrm{E}_{\mathrm{ess,in}} \leq \mathrm{P}_{\mathrm{ess}} \qquad \forall \mathrm{t} \in [1, 8760] \tag{4.31}$$

$$\mathrm{E}_{\mathrm{ess,out}} \leq \mathrm{P}_{\mathrm{ess}} \qquad \forall \mathrm{t} \in [1, 8760] \tag{4.32}$$

These constraints state that both, the incoming and outgoing fluxes, must be lower than the rated power at each time step. Some technologies improve their life time performance by charging the battery at a lower flux, but such characteristics are not taken into account.

Modeling total costs (ESS)
Electricity storage systems have the most complex total cost model. It uses two decision variables to determine costs: the rated power P_{ess}, expressed in kW, and the installed capacity E_{ess}, expressed in kWh. This way the model is free to chose independently the size of the power section and the size of the storage capacity of the particular storage. Some technologies, like flow batteries or storages based on hydrogen, present such a great independence between the rated power and storage capacity, that a separation within the model seemed required for an optimal system definition.

Implying these two decision variables the optimization process becomes time consuming. In order to keep the storage model solvable in a reasonable time frame, the installed capacity is linked to specific hours of autonomy. This adjustment can be helpful to find a good estimation of the solution but can also be removed for a further degree of freedom. The equations describing the electrical energy storage systems' total cost are the following:

$$\begin{aligned} TC_{ess} = \quad & c_P P_{ess} + c_E E_{ess} + \\ & + (c_{rep,P} P_{ess} + c_{rep,E} E_{ess}) \sum_{y=1}^{Life-1} \left\{ \frac{1}{(1+i)^y} \bigg|_{\frac{y}{y_{rep}} = \left[\frac{y}{y_{rep}}\right]} \right\} + \\ & + c_{O\&M} P_{ess} \sum_{y=1}^{Life} \frac{1}{(1+i)^y} + \\ & + (c_{fuel} + c_{CO_2} k_{CO_2}) \sum_{t=1}^{8760} (E_{ess,out}) Cons_{fuel} \sum_{y=1}^{Life} \frac{1}{(1+i)^y} + \\ & + E_{ess} \Big(c_{land} (LU_{ess} + c_{ess,CO_2} + c_{ess,Res} \Big) \end{aligned} \tag{4.33}$$

As introduced before, the investment cost depends on the two decision variables P_{ess} and E_{ess}, both multiplied by specific costs: c_P in €/kW and c_E in €/kWh. The replacement costs are also a function of these two decision variables multiplied by the specific costs $c_{rep,P}$ and $c_{rep,E}$. Depending on how many times the storage system needs to be replaced during the considered time frame of 20 years, the replacement costs incur in different loops, expressed in $\frac{Life}{y_{rep}}$. The actualization factor needs to be set to zero in all years without replacement, for the other years with replacement $\frac{1}{(1+i)^y}$ for every year "y" is true. In these cases the ratio $\frac{y}{y_{rep}}$ is equal to its own ratio. The sum of the actualization factor ends at $y = Life-1$, since no further replacement is required for the supply system. A similar approach was used by *Kaldellis et al.* [103], described with a more mathematical and less programming-oriented set of equations.

The costs for operation and maintenance are assumed proportional to the rated power. The land cost, emission costs and costs for resource depletion are modeled similar to previously described sub-systems, where the specific cost is based on the energy capacity of the system. The costs linked to the use of fuel, as needed for the Compressed Air Energy Storage system (CAES), are modeled as the ones for the diesel generators.

4.8.2 Modeling thermal energy storage systems (TSS)

Modeling energy flows (TSS)

As for the electrical storage systems, also for the thermal ones balance constraints need to be defined:

$$\begin{aligned} \mathrm{Stored}_{\mathrm{th}}^{\mathrm{t+1}} = \; & \mathrm{Stored}_{\mathrm{th}}^{\mathrm{t}}(1 - \mathrm{Losses}) - \mathrm{Th}_{\mathrm{TS,out}} + \mathrm{Th}_{\mathrm{TS,in}}\eta \\ & \forall \mathrm{t} \in [0, 8759] \end{aligned} \tag{4.34}$$

Where $\mathrm{Stored}_{\mathrm{th}}^{\mathrm{t}}$ and $\mathrm{Stored}_{\mathrm{th}}^{\mathrm{t+1}}$ are the amount of thermal energy stored at each time step t and t + 1, expressed in [kWh]. Losses and the efficiency η are defined and used as the losses and efficiency in the ESS model. The round-trip efficiency and further assumptions concerning storage behavior are valid here as well. The intuitive constraint, which states that the stored thermal energy cannot be greater than the installed capacity of the storage is modeled as follows:

$$0 \leq \mathrm{Stored}_{\mathrm{th}} \leq \mathrm{E}_{\mathrm{tts}} \qquad \forall \mathrm{t} \in [1, 8760] \tag{4.35}$$

Modeling total costs (TSS)

Analogue to the electrical storages the cost equation is defined as:

$$\begin{aligned} \mathrm{TC}_{\mathrm{tss}} = \; & \mathrm{c_E E_{tss}} + \mathrm{c_{O\&M} E_{tss}} \sum_{\mathrm{y=1}}^{\mathrm{Life}} \frac{1}{(1+\mathrm{i})^{\mathrm{y}}} + \\ & + \mathrm{E_{tss}} \Big(\mathrm{c_{land}} (\mathrm{LU_{tss}} + \mathrm{c_{tss,CO_2}} + \mathrm{c_{tss,Res}} \Big) \end{aligned} \tag{4.36}$$

All single terms of the total cost are modeled along the lines of other sub-systems introduced before.

4.8.3 Modeling water storage systems (WSS)

Modeling water flows (WSS)

The water balance has already been introduced and discussed previously. For the water storage tank no losses nor efficiencies are considered. For the water storage following constraints are defined:

$$\mathrm{Water}_{\mathrm{reserve}} \leq \mathrm{V}_{\mathrm{wss}} \qquad \forall \mathrm{d} \in [1, 356] \tag{4.37}$$

The equation states again, that the amount of stored water in each time step cannot exceed the water storage capacity.

Modeling total costs (WSS)

As part of a large energy and water supply system, the type and cost of water storage is not that relevant. Therefore only one type of water storage tank is considered. The costs of this sub-system add up as follows:

$$\mathrm{TC}_{\mathrm{wss}} = \mathrm{c}_{\mathrm{wss}}\mathrm{V}_{\mathrm{wss}} + \mathrm{c}_{\mathrm{land}}(\mathrm{LU}_{\mathrm{wss}}\mathrm{V}_{\mathrm{wss}}) \tag{4.38}$$

The only cost units arising, are the investment cost and the cost of the land, where the storage is implemented. Both values are proportional to the storage volume $\mathrm{V}_{\mathrm{wss}}$. Operation and maintenance costs as well as environmental costs are assumed to be negligible. Additional fuel costs or replacement costs do not occur during the lifetime of the overall supply system.

4.9 Limitations of the model

A main limitation of the model is, that no electricity grid and no water piping and pumping systems are modeled. The costs of energy and water supply systems depend significantly on the existent infrastructure. Costs that incur for all supply systems, no matter which technology combination is the optimal, are not considered within the optimization model. Converters and other not mentioned devices are also either neglected or included in the costs of the corresponding sub-system, cf. previous sections. Some limitations though need to be discussed in detail.

4.9.1 Time discretization

One general constrain of the model is the long calculation time. Overall about 3.800 single runs were calculated as multi-run simulations parallel on two servers and various clusters, mostly limited to 12 hours solver-time. The overall computing costs were about 17 months wall clock time. (Thank to the researchers of the Potsdam Institute for Climate Impact Research, the sensitivity analysis could be calculated using their server capacity.)

A weakness of the model is the usage of a standard year for the calculation period of 20 years. That means, that all meteorological data as well as the water and electricity demand is assumed to be identical for all 20 years. Values of a specific time-step of the year are equal to the corresponding specific time-step of all previous and following years. These discretizations are thought to be a good compromise between the expected output, the level of detail and the model's calculation speed.

4.9.2 Boundaries and mutual exclusivity

Some technologies cannot be implemented in all sizes and capacities and are therefore combined with some minimum or maximum restrictions. These technologies are scattered mainly in the sub-systems of concentrated solar power plants, electricity storages and desalination processes. Especially large-scale power plants as some CSP-technologies, can be excluded at the very beginning of the optimization process. Such constraints are implemented in the following way:

$$\mathrm{P_i} \geq \mathrm{Exist_i} \cdot \mathrm{MinP_i} \tag{4.39}$$

$$\mathrm{P_i} \leq \mathrm{Exist_i} \cdot \mathrm{MaxP_i} \tag{4.40}$$

Where $\mathrm{MinP_i}$ and $\mathrm{MaxP_i}$ are the minimum and maximum bounds for the technology of subsystem "i", $\mathrm{P_i}$ is the decision variable indicating the size of the system (in this case the power) and $\mathrm{Exist_i}$ is a binary variable that allows to decide within the optimization process, whether or not the dimension of a technology and/or a subsystem is inside the accredited range. If not, the binary variable is set to zero and the technology will not be installed in the optimized system.

Another set of equations that supports the model to fasten the approach towards the solution, is to force the mutual exclusivity of some energy fluxes. Some are bound to be mutually exclusive, but along the process of optimization they may not be. in some cases the model would not even reach the exact optimum. That is why an additional definition of these characteristics is required. The mutual exclusivity is set for the incoming and outgoing fluxes of the storage systems, e.g. the ESS may either be charged or discharged, but not both simultaneously. Another mutual exclusivity is defined for the diesel generation and electrical dump load fluxes: in the optimal solution none of the diesel electricity produced must be dumped. Following conditions are defined:

$$X(t) - 10^{10} * \xi_X(t) \leq 0 \qquad \forall t \in [1, 8760] \tag{4.41}$$

$$Y(t) - 10^{10} * \xi_Y(t) \leq 0 \qquad \forall t \in [1, 8760] \tag{4.42}$$

$$\xi_X(t) + \xi_Y(t) \leq 1 \qquad \forall t \in [1, 8760] \tag{4.43}$$

Where X(t) and Y(t) are the non-negative variables that must be set mutually exclusive. $\xi_X(t)$ and $\xi_Y(t)$ are binary variables that are used to trigger the exclusivity. The coefficient of the various ξ needs to be a very big number, so that the variables X and Y are always smaller. In the model the coefficient is set to 10^{10}. This approach was applied and suggested by *McCarl and Spreen* [104].

4.9.3 Reduction of computational cost

In terms of computational costs, the model as it has been discussed so far, is quite time consuming. If no adjustments are made, the starting matrix that the mixed integer programming (MIP) solver has to handle, consists out of 106,804 rows, 89,315 columns, counting 321,735 non-zero elements. With this amount of data, the model is solvable in three to seven days (depending mainly on the considered storage technologies). This is for more than one calculation no acceptable amount of time. One adjustment to reduce computational cost was done in the electricity storage model. It can be applied, if more than a few calculations are planned to be executed and calculation time (server space) is limited.

Variable linking and pre-screening of ESS

The more storage technologies are considered, the more time the model takes to be solved. This was tracked down to the fact that for this kind of system two totally independent decision variables were taken into account: P_{ess} and E_{ess}. To solve this problem a new constraint was introduced linking the two decision variables using ordinary values of hours of autonomy. The values are based on a study published by *Sandia National Laboratories* [31]:

Tab. 4.2: *Hours of autonomy used for electrical energy storage systems*

Technology	$h_{autonomy}$
LA	4
NiCd	4
NaS	7,2
CAES	8
PHS	8
ZnBr	4
Li-ion	4
V-redox	4
$H2_{PEMFC}$	4
$H2_{Engine}$	4

To reduce the computational cost further from about four days to more or less 12 hours, a preventive analysis of the data in TAB. 5.5 was made. After calculating scenarios with all ESS technologies, only a single ESS has been considered for the sensitivity analysis. Based on this introduced relation, the total cost equation for the sub-system ESS (4.33) was rewritten substituting $E_{ess} by P_{ess} h_{autonomy}$.

$$TC_{ess} = \Bigg[c_P + c_E\, h_{autonomy} + c_{O\&M} P_{ess} \sum_{y=1}^{Life} \frac{1}{(1+i)^y} + c_{land}\, LU_{ess}\, h_{autonomy} + \\ + (c_{rep,P} + c_{rep,E}\, h_{autonomy}) \sum_{y=1}^{Life-1} \left(\frac{1}{(1+i)^y} \bigg|_{\frac{y}{y_{rep}} = \left[\frac{y}{y_{rep}}\right]} \right) \Bigg] \cdot P_{ess} \tag{4.44}$$

The characteristics of ESS technologies, that are not considered in this equation anymore are the fuel consumption, the electric efficiency, the depth of discharge, the parasitic losses, and the minimum size limit. The fuel consumption is only needed for the compressed air energy storage. It is closely linked to the energy outgoing fluxes and in case, CAES would be the optimal energy storage system, a further analysis with the original model would need to be calculated, eliminating as many other ESS technologies as possible.

The parasitic losses are very small for most technologies. They can be treated as efficiency losses, if a specific time period is set between charging and discharging. This way the losses can be eliminated from the main model and computational costs can slightly be minimized. Setting the time to 24 hours, the new efficiency can be written as

$$\eta^* = \eta - \text{Losses} \cdot 24 \tag{4.45}$$

The depth of discharge affects the energy capacity of an electricity storage system. It can be lower than the rated capacity if DOD $<$ 100%. However, from test calculations it has been observed that the most important constraint for the optimization is the rated power and not the installed capacity, so the DOD has little influence on the choice of the storage system. Therefore neglecting the depth of discharge does not distort the optimal result significantly.

The pumped hydroelectric storage, the hydrogen-systems, the compressed air energy system as well as the sodium-sulphur battery require a relatively high rated power and are often dependent on geographical conditions, so that it needs to be decided individually, if they are applicable for a specific region and case or not.

4.9.4 Capacity of diesel generators

Due to the simplification requirements as previously mentioned, the diesel generator sets are not free variables. There are only two options: One caterpillar diesel generator with a nominal capacity of 800 kW_{el} can be in operation or two of them with a total capacity of 1600 kW_{el}. This static determination can distort the optimal system design. E.g. when the demand changes in the sensitivity analysis, the model would maybe replace the diesel generator set by a larger one or install further ones, what is not possible in the model. A further drawback of this simplified approach is, that in real life projects, probably two smaller diesel generator sets would be implemented instead of one large one. Two smaller ones can react more dynamic on the load curve than one large diesel generator. Most of the time the diesel generator operates in part-load and performs not in the optimal capacity range. Higher fuel consumption is the consequence and unfortunately the accuracy of the model shrinks. But to model the complex interaction between two diesel generators performing in their optimal capacity ratio, is beyond the scope of this model.

Chapter 5

Case Study: A Cape Verde island

5.1 Background of Cape Verde

In this work an exemplary case study has been carried out for one of the Small Island Developing States: a small island of the Cape Verde Islands named Brava. When looked at from a global perspective, Cape Verde is one of the poorest countries ever since its independence from Portugal in 1975. Due to international projects and support, Cape Verde's economic situation has improved during the past 30 years.

The island state Cape Verde consists of fifteen islands, nine of them inhabited, with a total land area of 4,036 km^2 and a population of about 506,000. The Cape Verde islands are volcanic and around 600 km away from the west coast of Africa (Senegal) in the Atlantic Ocean. Brava is the smallest inhabited, southernmost island of Cape Verde with a surface area of 67 km^2 and about 6000 inhabitants, cf. Fig. 5.1 [105].

The islands can be divided into windward islands in the north and leeward islands in the south (Maio, Santiago, Fogo and Brava). The capital, Praia, is located on Santiago, which is the largest island of Cape Verde. The island state is semi-dry to dry with relatively constant annual temperature averages from 24 to 29 °C. Water shortage is one of the main reasons behind its limited development. Cape Verde is highly dependent on oil imports, which are mainly used for electricity generation, air traffic and for daily use, e.g. cooking (kerosine or butane gas). Power is supplied with 99 % by diesel generators. Currently the price of 1 kWh is 0.31 € (for higher consumption than 60 kWh/month) and 0.25 €/kWh respectively (for lower consumptions than 60 kWh/month) on Cape Verde [106]. ELECTRA provides not only power but also water and sewerage services in Cape Verde. Water prices of 2.35 €/m^3 ($<$ 6 m^3), 4.36 €/m^3 ($>$10 m^3) and 4.93 €/m^3 for tourists and tourism

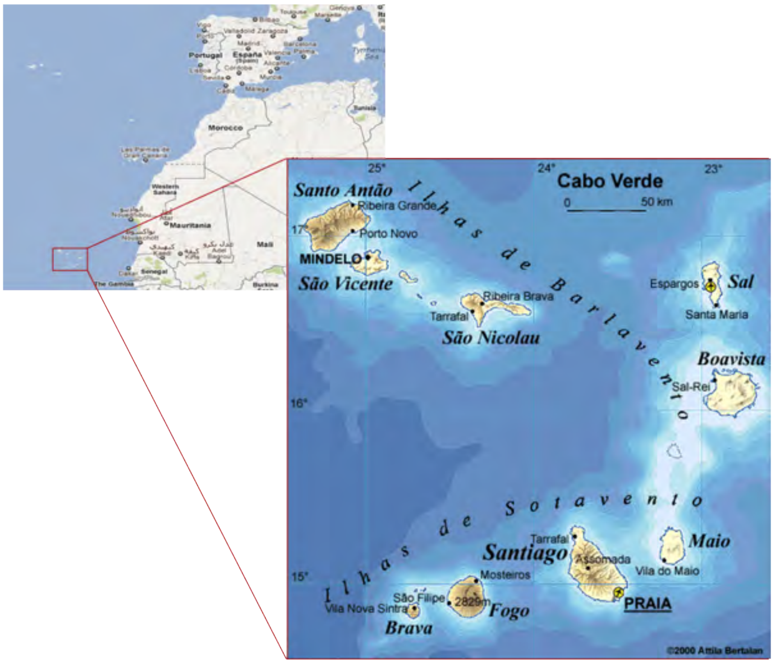

Fig. 5.1: *The island state Cape Verde*

related industry, are about seven times higher than on the mainland and about three times higher than in most European countries [107]. Due to high electricity costs and an expected increase in fuel prices in the future, the utility ELECTRA and the government of Cape Verde are encouraged to seek for solutions in order to increase the share of renewables. The government is the first in West Africa passing a renewable energy law aiming at drawing 50 % of the country's supply from renewable energy sources [108]. Compared to other countries in Africa, Cape Verde has a relatively well expanded electricity and water infrastructure (being provided by Austria) reaching about 70 % of the population [107]. But despite the fact that almost all villages are connected to the grid by now, many inhabitants are simply not able to pay for electricity. Illegal power consumption (robbery) is widespread and inhibits investors to invest into infrastructure. A further obstacle for investing companies is the unreliability of the grid: within a single year, in (2009) for example, there were 150 blackouts.

With an annual power consumption of 550 kWh per capita on Cape Verde, the currently installed capacity for electricity generation is 116 MW with a share of 72 % of diesel generators, 22 % of wind and 6 % of solar energy. Up to now, a relatively high share of renewable energies is already installed, only less than 1 % of the energy being produced is generated by renewables, since the energy supplier ELECTRA owns and operates only a few per cent of the installed capacity of renewable energy technologies. Furthermore some of the wind parks need to be repowered, e.g. a wind park of 2.4 MW (eight 300 kW Nordtank turbines) installed in 1994 [109], as well as solar modules are often installed as stand-alone systems and are not connected to the grid [110]. 6.3 % of the total electricity consumption on Cape Verde is used for seawater desalination. Since water shortage was still the main obstacle for development on Cape Verde, seawater desalination plants (all reverse osmosis) were installed on three islands, Sao Vicente, Sal and Santiago. Hence, ELECTRA operates all these plants. Water shortage could be minimized with added value through agriculture all-season. The island's agricultural products serve primarily for domestic use and add value with fishing, farming, and tourism. Only a small share of fish and bananas are free for export. In order to meet the demand for food, imports are still necessary.

5.2 Energy and water demand on Brava

Although the climate of Cape Verde is semi-arid and on most islands much warmer and dryer, the weather on Brava in the very south of the islands is humid tropical with temperatures ranging from 20 to 25°C. In 2010 around 601,000 liters of diesel were used on Brava (219 g per kWh) [111]. In the context of the previously mentioned ECREEE-program next to a sustainable energy and water supply concept two concrete projects are currently being planned on Brava: In the north, in Furna, an iron extraction company is supposed to be supplied with a 10 kW peak photovoltaic system as well as in Nova Sintra, in the center of the island, where two thermal solar systems are planned for two hotels with 8.4 kW and 5.6 kW peak.

According to measured data from ELECTRA, the energy supplier of Cape Verde, the peak-load on Brava is 815 kW with an overall demand of 6.3 MWh/day. Currently three diesel generators are installed with a total capacity of 1.056 kW, but a maximum of two are operating simultaneously. The load curve is available from logsheets in one-hour time steps for typical weekdays and weekends for each month of the year (2008). With a deviation of 15 % from hour to hour and day to day a typical load curve of one year was generated, shown in Fig. 5.2. The daily profile is characterized by an evening peak of power consumption between 6 and 9 pm.

The water demand on Brava is assumed to be about 800 m^3/day. Considering a daily water consumption of 600 m^3/day of the local residents, the additional 200 m^3/day can supply sufficient water for 400 tourists (calculating with a daily consumption of 0.5 m^3/day and per tourist). The precipitation on Brava and water from wells is

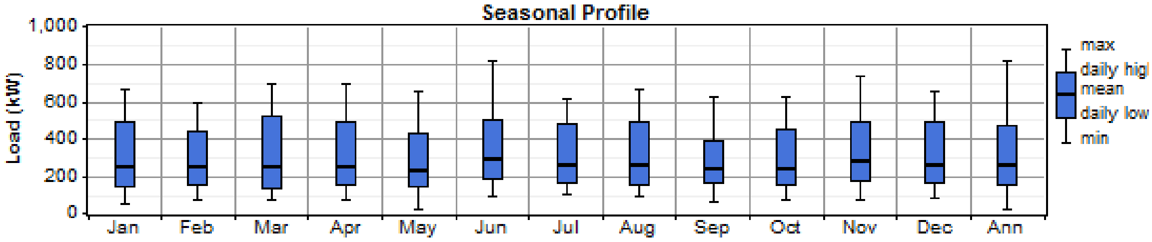

Fig. 5.2: *Seasonal profile of electricity demand on Brava*

currently sufficient for meeting the water demand. Excessive usage of groundwater though is endangering the supply and thus alternative water supply concepts are being discussed.

5.3 Renewable energy potential

On the Cape Verde islands there are no explored fossil fuel deposits as for example coal, oil or natural gas, but there is a number of renewable energy sources available. Due to their high average wind speed and high solar radiation, the Cape Verde islands are predestinated for implementing wind energy converters or solar power plants.

The average solar irradiation on Cape Verde is 6.3 kWh/m^2·day with more than 3.500 hours of sunshine per year [108]. Due to frequent cloudiness on Brava though, PV and CSP technologies cannot perform as beneficial as on other Cape Verde islands. The renewable energy potentials are inserted in the model as hourly data sets of one year, that means in 8760 time steps. Solar irradiation data, in kW/m^2, and typical daily temperature profiles are taken from the NASA satellite database [112]. Uncertainties of the measurement and data sources are addressed in chapter 6.5. Figure 5.3 describes the daily solar irradiation and the clearness index on the Cape Verde islands.

As Brava is a very small island, the wind conditions seem to be very favourable to generate wind power due to the long coastline. The average wind speed measured in 10 meter height is 7.03 m/s. The monthly distributions are shown in Fig.5.4. The Weibull factor is 2.2, which describes the relatively low fluctuation of the wind velocity. The one-hour correlation factor between wind speeds is 0.85 and the diurnal pattern of how strongly the wind speed depends on the time of day is 0.25. All these values stand for a relatively constant, stable and reliable wind speed pattern. Wind turbines could be installed most effectively in the north-eastern part of the island,

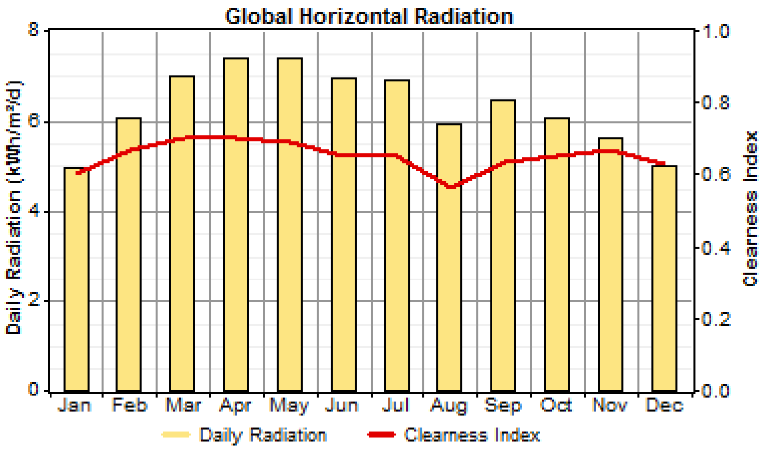

Fig. 5.3: *Solar irradiation in Cape Verde*

where the wind will not be slowed down, cf. the wind directions illustrated in Fig. 5.5.

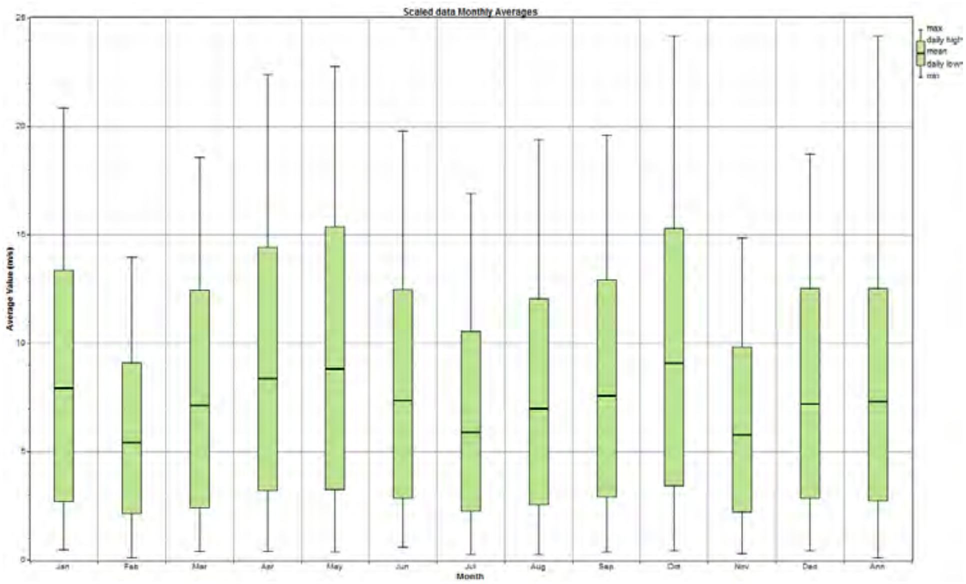

Fig. 5.4: *Monthly average of wind speeds on Brava*

As addressed in Appendix B, hydro energy would require a river or two connected lakes with a certain height difference. Owing to the absence of such natural resources in Brava the use of hydro power for electricity generation or as pumping station for energy storage is no option, cf. top left of Fig. 5.6 [113]. Ocean power technologies start to have an increasing potential to be implemented, improving in handling corrosion issues. The general potential of wave power utilization in Cape Verde is visualized in the top right picture of Fig. 5.6. However, due to the absence of commercialized technologies and still high costs, ocean power technologies are not modeled.

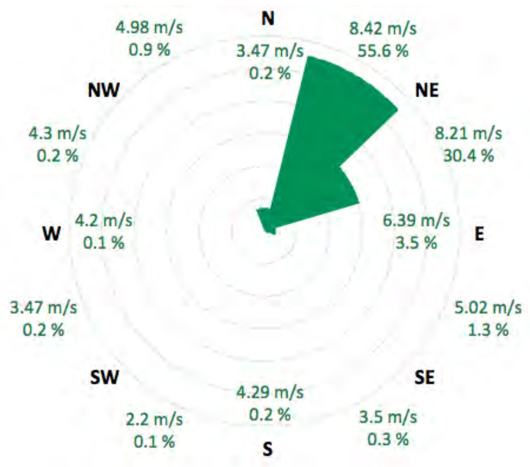

Fig. 5.5: *Wind directions in Cape Verde*

Considering the proportionality, the use of deep geothermal energy is in no relation to the small energy demand on Brava. Even if a high potential could be assured on the volcanic island, the high drilling costs are unjustifiable. Geothermal heat utilization near to the surface could be an option but is not considered in this case. The bottom left picture of Fig. 5.6 shows the principally high potential of geothermal energy on Fogo, the very next neighboring island of Brava, what is an evidence for a principally existent potential on Brava as well [110].

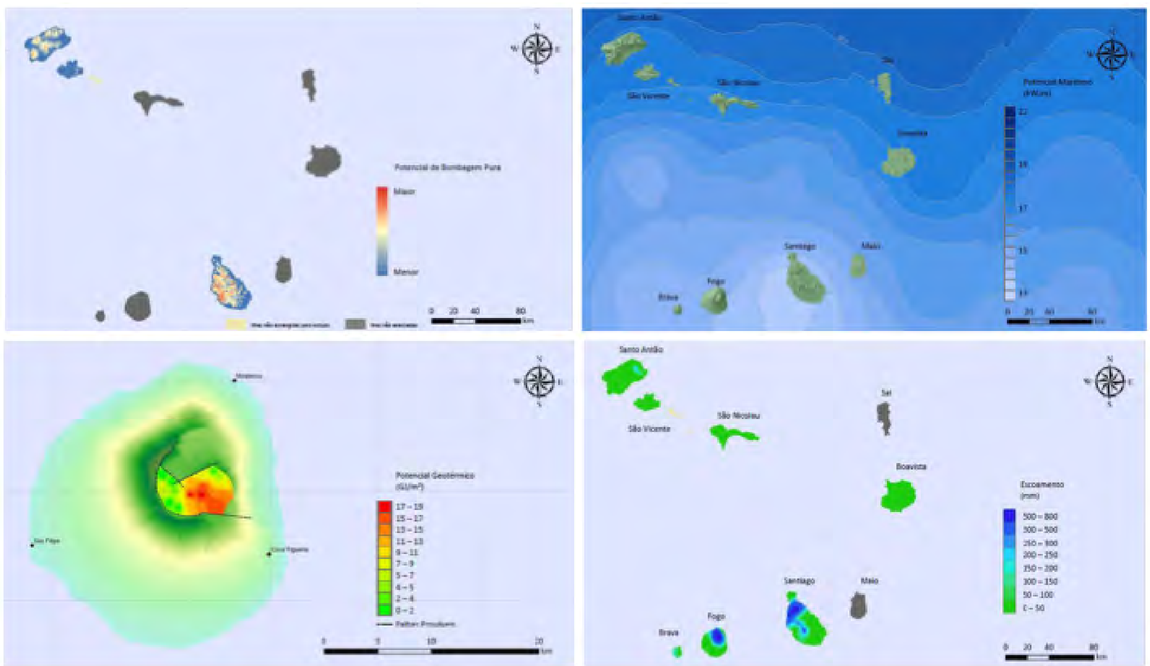

Fig. 5.6: *Renewable energy potentials on Brava (top left: pumped hydro, top right: ocean powers, bottom left: geothermal (Fogo), bottom right: precipitation/biomass) [110]*

Biomass as another potential energy source is neither being considered, since the natural vegetation is not sufficient for such an utilization. Since even the agricultural demand for domestic use cannot be met, cultured energy crops are no option. Advancing the mass and energetic recovery of farmed algae can be a support as biofuel in the future, but is beyond the scope of this research. The bottom right picture of Fig. 5.6 confirms the low precipitation and low potential of biomass utilization on Cape Verde.

5.4 Input data in the model

5.4.1 Economic input data

The lifetime and investment period of almost all components is set to 20 years, only the energy storage systems vary significantly in their lifetimes. To evaluate the economic performance of the project an interest rate of 5 % is being employed. The exchange rate between the US-Dollar and the Euro is considered with an average of 1.3 USD = 1 €. All other currencies are also converted to Euro. Fuel prices are assumed to be constant for the whole lifetime period. The effect of varying diesel prices is addressed later within the scenario and real option analyses. A very moderate diesel price of 0.07 € per liter is assumed initially. In the model the unit for the diesel price is €/kWh. Based on the heating rate, the liter-price divided by 9.7 kWh/liter, results in a diesel price of 0.072 €/kWh. The cost of natural gas used in the Compressed Air Energy Storage system is amounting to 0.06 €/kWh [114]. The price of CO_2-equivalents is set to a currently unrealistically high price of 20 €/t CO_2. The specific emission of diesel fuel is 0,248 kg CO_2/kWh, adopted from the specific volumetric emission of diesel fuel multiplied by the volumetric energy density. In case that the Compressed Air Energy Storage system is part of the optimal solution, the specific emission of the natural gas is 0,179 kg CO_2/kWh [115]. The price for land is set to 30 €/m^2, which is the mean value of real estate prices on the Cape Verde islands.

5.4.2 Input data PV-systems

Three different technologies of photovoltaic panels are taken into consideration: a multi-crystalline, wafer based silicon technology (c-Si), an amorphous micro-crystalline silicon technology (a-Si) as well as a cadmium telluride technology (CdTe). Detailed information have already been presented in chapter 2.2. In the given case costs are relatively high, because inverter and converter costs are already included and hence, are not referred to separately. Technological and economic data are derived from *Doni et al.* [116] and *The World Bank* [11] as well as from interviews and data sheets provided by suppliers. The derating factor is assumed to be 80 % for all the technologies, taking into account losses due to dirt, wire losses and DC/AC conversion. Costs for land-use are calculated by using a factor per m^2 instead of absolute numbers per kW. Emission costs of the photovoltaic panels are derived from *Jungbluth et al.* [117].

Tab. 5.1: *Technological data for PV systems*

Parameter with symbol	Unit	c-Si	a-Si	CdTe
Efficiency η	%	16	9	11
Derating factor	-	0,8	0,8	0,8
Investment cost c_P	€/kW	2443	2000	2105
O&M cost factor $f_{O\&M}$	-	0,015	0,020	0,020
Land-use factor k_{LU}	m^2/kW_{el}	7.6	7.6	7.6
Resource depletion costs c_{Res}	€/kW	0	0	0
Emission costs c_{CO2}	t CO_2/kW	1.43	1.43	1.43

5.4.3 Input data CSP

Concentrated solar power systems that are taken into account are Parabolic Trough, Solar Tower, Fresnel Reflectors, Solar Dish and a small size Organic Rankine Cycle combined with parabolic trough.
One main advantage of solar thermal power plants are the potential of using thermal energy storages for enabling a continuous power supply as constant as possible. More detailed information of each CSP technology have already been presented previously. Used input data in the model are shown in Tab. 5.2.

Due to the turbines, most CSP systems can not be installed efficiently under a peak electrical capacity of 10 MW. Within the model the minimum size of Parabolic Trough, Solar Tower and Fresnel Reflector systems are set to 10 MW_{el} rated power, while the minimal capacity of Solar Dish- and ORC-based technologies is set to 10 kW_{el}.

Tab. 5.2: Technological data for CSP systems

Parameter	Unit	Parabolic Tr.	Solar Tower	Fresnel	Solar Dish	ORC
η_{el}	%	14 [a]	16 [a]	10 [b]	21 [a]	7 [c]
η_{th}	%	28 [d]	32 [d]	20 [d]	16,7 [d]	14 [d]
Deration	-	0,9	0,9	0,9	0,9	0,9
c_P	€/kW	5450 [f]	6288 [f]	2033 [f]	8035 [f]	2538 [c]
$c_{P,O\&M}$	€/kW/y	71,5 [f]	133,3 [f]	110,4 [f]	103 [f]	100 [e]
LU_{CSP}	m^2/kW	11,04 [g]	12,39 [h]	8,62 [g]	25 [i]	35 [c]
c_{Res}	€/kW	0	0	0	0	0
c_{CO2}	t CO_2/kW	70x10^{-6} [f]	46x10^{-6} [f]	25x10^{-6} [f]	25x10^{-6} [f]	46x10^{-6} [f]

[a] source [118]; [b] source [119]; [c] source [23]; [d] thermal efficiency assumed as double of the electrical one, except from Dish technology, where they are assumed to be equal; [e] values assumed; [f] source [120]; [g] source [18]; [h] source [21]; [i] source [20]

5.4.4 Input data wind energy converters

Based on a market research three different wind turbines are included in the model: A 275 kW-turbine from Vergnet, a 225 kW-turbine from Norwin and the Gyro10k with a rated power of 10 kW. Due to the small harbour and installation restrictions of heavy and big size equipment, larger wind turbines are not considered. Vergnet275 and Norwin225 are horizontal axis wind turbine technologies, the Gyro10k instead represents the vertical axis technologies. All used technological data and costs are shown in Tab. 5.3 and are taken and derived from data sheets and offers from the manufacturer. Costs for CO_2-equivalents are based on data collection and analysis within the life cycle assessment [100].

The points given by manufacturers and the fitting curves are shown in the following graphs for all three considered wind turbines.

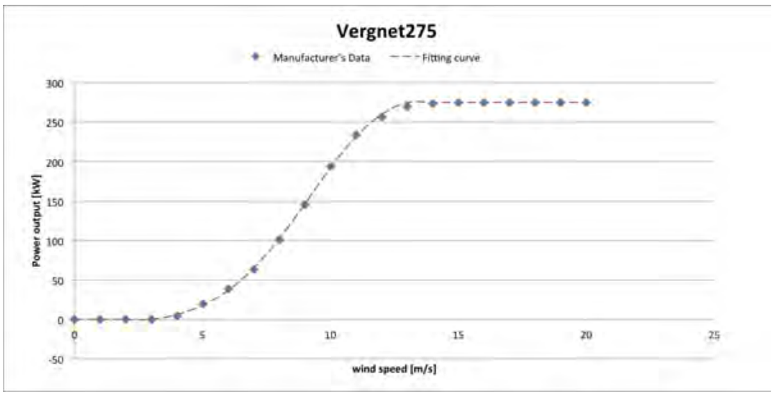

Fig. 5.7: Power curve of the Vergnet 275 kW turbine

Tab. 5.3: *Technological data for wind turbine systems*

Parameter	Unit	Vergnet275	Norwin225	Gyro10k
P_{nom}	kW	275	225	10
$P_{max,out}$	kW	275	228	12
V_{cut-in}	m/s	3.5	4	3,5
V_{flat}	m/s	13	999	14
$V_{cut-off}$	m/s	20	25	24,6
Hub-height	m	55	30	11
c_P	€/kW	1818	2050	6278
$f_{O\&M}$	-	0.02	0.02	0.01
LU_W	m^2/kW	0.93	0.93	0.93
c_{Res}	€/kW	0	0	0
c_{CO2}	t CO_2/kW	0.43	0.43	0.43

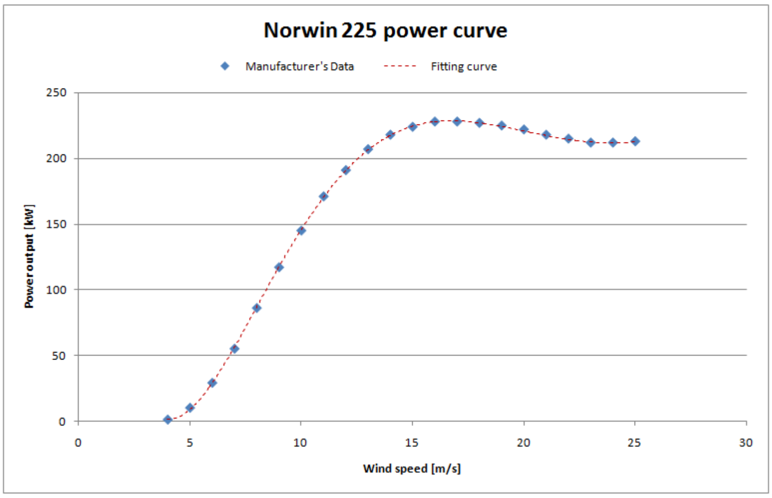

Fig. 5.8: *Power curve of the Norwin 225 kW turbine*

The Norwin turbine does not have a plateau at high wind speeds, so the parameter V_{flat} is set very high. Therefore V_{flat} and $P_{max,out}$ are of no use for this particular wind turbine. For the Vergnet and the Gyro wind turbine on the other hand they are in fact relevant, as shown in Fig. 5.7 and 5.9.
All polynomial coefficients can be found in the model script in appendix A.

5.4.5 Input data diesel generators

Taking into account the already existing diesel generators on the island, the diesel generator sets applied in this model are two Prime 800 kW_{el} from Caterpillar. In the model they may have a higher performance curve, since it is a state-of-the-art technology compared to the older ones existent on the island. However, no detailed

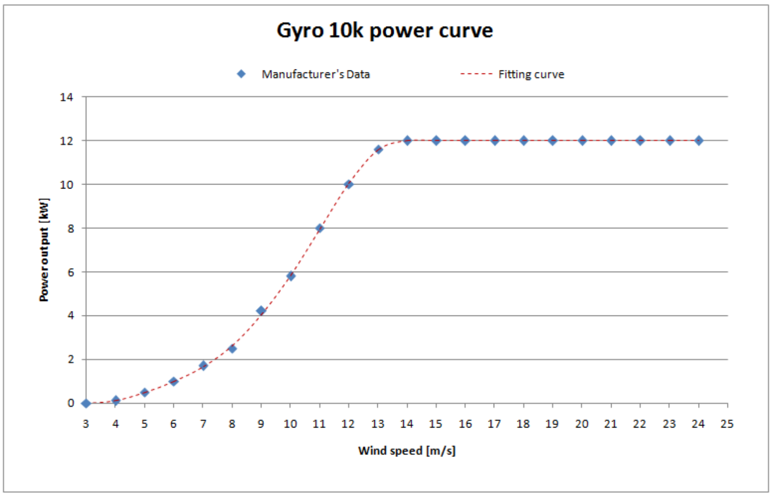

Fig. 5.9: *Power curve of the Gyro 10 kW turbine*

information on the current diesel generator sets are available. Table 5.4 shows all assumed input data based on data sheets and interviews with representatives from Caterpillar and MAN.

Tab. 5.4: *Technological data for diesel generators*

Parameter	Unit	Caterpillar 800 kW_{el}
P_{nom}	kW	800
η_{th}	-	30 / 60 %
$c_{E,O\&M}$	€/kWh	0.01
c_P	€/kW	0
LU_{diesel}	m^2/kW	0.02
c_{Res}	€/kW	0
c_{CO_2} [a]	t CO_2/kW	0.22[b]

[a] only emissions of life cycle, no fuel related emissions; [b] source [100]

The electrical efficiency is not constant and depends on the utilized capacity of the generator set. The function being used is a piecewise linear function and has been introduced before. The function is depicted by the graph in Fig. 5.10. In a later stage of the model development some of the small final linearization sequences have been summed up and described by a single linear function.

5.4.6 Input data Electricity Storage Systems

A large number of electricity storage systems is modeled. Not all modeled ones are considered within the optimization though due to computational costs. A pre-

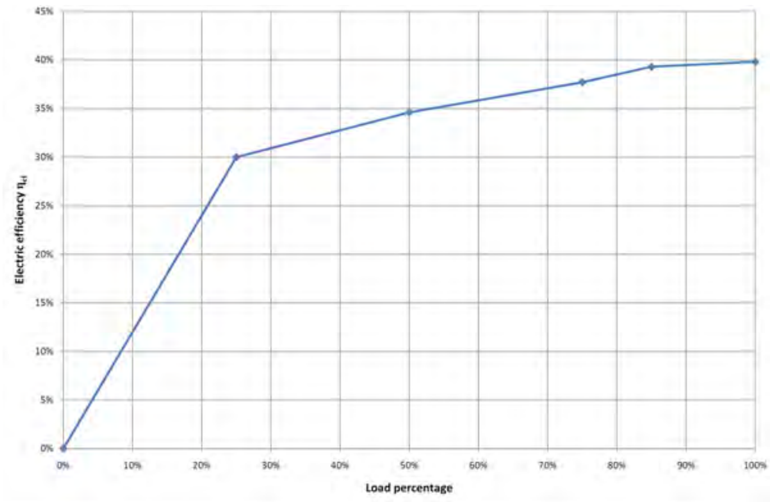

Fig. 5.10: *Diesel efficiency curve*

selection helped to identify the most beneficial technology options as shown in Tab. 5.5. In addition to section 2.3 here all data are listed in comparison.

Some of these systems are usually of large scale. All storage technologies are provided with specific size constraints. Some of them are limiting the rated power, e.g. for NaS batteries and pumped hydroelectric systems 1 MW and for above-ground compressed air electric storage systems 50bkW. These data are based on the above mentioned sources and on interviews with producers. Limits for pumped hydro storage and hydrogen-systems would be reasonable, but due to variable data, an elimination of these technologies should be considered subsequently after the optimization process, depending on local conditions.

Although environmental costs for greenhouse gases emitted during the whole life cycle as well as costs for resource depletion are integrated in the model, they are not considered in the calculation process due to insufficient and inexact data at hand.

5.4.7 Input data thermal energy storage systems

General data of thermal storage systems as water vessels, molten salt, concrete or eventually phase change materials are considered. Only one representative storage technology has been modeled though. The analysis should eventually be extended and further technologies could easily be taken into consideration as it has already been done in the case of electricity storage systems. The implemented data are shown in Tab. 5.6.

At present thermal storage systems are of little importance in the model. Thermal desalination processes, which would require continuous energy fluxes, are not first

Tab. 5.5: *Technological data for electricity storage systems*

Parameter	Unit	LA	NiCd	NaS	CAES	PHS
c_P	€/kW	195,97[a]	195,97[a]	130,65[a]	522,60[a]	914,54[a]
c_E	€/kWh	130,65[a]	522,60[a]	217,75[a]	104,52[a]	12,19[a]
η	-	75%[a]	65%[a]	7%[a]	79%[a]	78%[a]
$c_{rep,P}$	€/kW	0[a]	0[a]	0[a]	0[a]	0[a]
$c_{rep,E}$	€/kWh	130,65[a]	522,60[a]	200,33[a]	0[a]	0[a]
y_{rep}	y	6[a]	10[a]	15[a]	30[b]	50[b]
DOD	-	75%[c]	100%[c]	100%[c]	62,5%[e]	95%[e]
$Cons_{fuel}$	-	0	0	0	1,29[d]	0
$c_{O\&M}$	€/kW/y	15[a]	25[a]	20[a]	10[a]	2,5[a]
Losses	1/h	8,33E-07[f]	1,67E-06[f]	8,34E-05[f]	0[f]	0[f]
LU_{ess}	m^2/kWh	0,058[h]	0,042[g]	0,037[i]	0,214[h]	0,186[h]
Parameter	Unit	ZnBr	Li-ion	V-redox	$H2_{PEMFC}$	$H2_{Engine}$
c_P	€/kW	152,42[a]	152,42[a]	178,55[a]	1567,79[a]	261,30[a]
c_E	€/kWh	348,40[a]	435,50[a]	522,60[a]	13,06[a]	13,06[a]
η	-	60%[a]	85%[a]	70%[a]	53%[a]	44%[a]
$c_{rep,P}$	€/kW	0[a]	0[a]	0[a]	130,65[a]	95,81[a]
$c_{rep,E}$	€/kWh	87,10[a]	435,50[a]	522,60[a]	0[a]	0[a]
y_{rep}	y	8[a]	10[a]	10[a]	6[a]	6[a]
DOD	-	100%[c]	80%[c]	100%[d]	90%[e]	90%[e]
$Cons_{fuel}$	-	0	0	0	0	0
$c_{O\&M}$	€/kW/y	20[a]	25[a]	20[a]	3,8[a]	2,5[a]
Losses	1/h	0[f]	8,33E-07[f]	0[f]	0[f]	0[f]
LU_{ess}	m^2/kWh	0,023[h]	0,010[g]	0,037[i]	0,042[h]	0,005[h]

[a] source [30], costs actualized using Consumer Price Index[121]; [b] source [29]; [c] source [102]; [d] source [122]; [e] source [103]; [f] source [123]; [g] Manufacturer manual & environmental assessments; [h] source [31]; [i] source [124]

choice on an electrified island. Environmental and land-use costs of thermal energy storages are not considered.

5.4.8 Input data Desalination

Taking on the technological backgrounds from desalination technologies in chapter 2.5, the detailed energy consumptions and costs of each considered process are compiled in Tab. 5.7. All data are based on information from manufacturers of each desalination technology and are verified. However, increases in energy efficiency and cost reductions are expectable in near future due to continuous development.

Tab. 5.6: *Technological data for thermal storage systems*

Parameter	Unit	TSS
c_E	€/kWh	115
η	-	0,9
$c_{O\&M}$	€/kWh/y	5
Losses	h^{-1}	1,00E-05

Tab. 5.7: *Technological data for desalination systems*

Parameter	Unit	HDH	MED	MD	MVC	RO	var-RO
$E_{cons,th}$	kWh/m^3	100[a]	110[b]	175[c]	0[d]	0[e]	0
$E_{cons,el}$	kWh/m^3	2.4[a]	1.7[b]	0.1[c]	11[d]	4[e]	variable
c_{plant}	€/(m^3/d)	3000[a]	3400[b]	5000[c]	2350[e]	2000[e]	2200[g]
$c_{w,O\&M}$	€/m^3	0.18[a]	0.16[b]	0.2[c]	0.29[d]	1.04[e]	1.04[g]
LU_{desal}	$m^2/(m^3/d)$	0.3[a]	0.2[b]	0.3[c]	0.3[d]	0.3[e]	0.3[e]

[a] source [40] [b] source [76]; [c] source [46]; [d] source [47]; [e] source [54].

All technologies require electrical energy, even if some desalination processes are mainly thermally driven. Power is needed in these processes for operating water pumps and auxiliary systems. A minimum capacity of 50 m^3/d is set for all desalination processes, in order to avoid unrealistically small capacities. Environmental costs for greenhouse gases emitted during the whole life cycle of the desalination plants as well as costs for resource depletion are modeled but set to zero due to inadequate data.

5.4.9 Input data water storage system

The considered water storage is nothing else than a water tank where water is being stored in times of surplus freshwater production and from where it is taken from in periods with less water production than is in fact needed. As mentioned before, only one representative type has been applied to the model. The water storage cost is set to 180 €/m^3 and its land use factor is 0,5 m^2 of surface occupied for every m^3 of stored water. Both values are estimated by using the mean value of manufacturer data.

Chapter 6

Results

Energy and water supply systems were exemplary calculated and determined for various islands. The following results and detailed analysis though are accomplished only for the Cape Verde island Brava. Nevertheless, a summary of the simulation and optimization results of further islands can be found in chapter 6.7.

6.1 Validation of model

Before analyzing the results in more detail comparable parts of the GAMS model are validated by means of results of the commercial available energy system simulation tool HOMER. Differences between both calculation methods are, that HOMER is commonly considering a single technology in the framework of the optimization. Desalination, concentrated solar power as well as a number of energy storage systems cannot be modeled in HOMER. Usually within the optimization only one primary selected power generation or storage technology is considered. In any case, the technology needs to be chosen in advance. An optimization concerning the optimal wind converter technology for a specific region e.g., cannot be calculated in HOMER. Therefore also in the GAMS model a comparable set of components is considered. (Converter costs are allocated and covered by the PV and battery costs respectively.)

For the validation common commercial multi-crystalline PV modules were considered, 275 kW Vergnet wind turbines, 800 kW caterpillar diesel generators and conventional lead-acid batteries, in this case Hoppecke OPzS 3000 with a capacity of 6 kWh. Within the GAMS model other generation and storage technologies have been outlined for identifying differences between the two optimization approaches. Table 6.1 and 6.2 show the optimal supply systems for Brava calculated with HOMER and with the developed GAMS-model including mentioned constrictions. The first table considers only the energy demand on the island without desalination, the second table shows the validation of the optimal supply system considering also the energy demand of a constantly operating desalination plant. Assumptions in the GAMS model are adjusted to the ones used by HOMER as default.

Tab. 6.1: *Comparison of optimal energy supply system using HOMER and GAMS-model*

ES 1 without Desal.	Technology	Inst. Capacity	Full load hours* [h/y]	Diesel cons. [L/y]	Costs in 20 y [€]
GAMS	PV (a-Si)	26 kW	890		78,200
	Vergnet275	723 kW	3,324		1,723,786
	Caterpillar	800 kW	806	88,934	2,010,905
	LA	2001 kWh	253		905,754
Total costs					**4,718,645**
Annuity					378,636
LCoE [€/kWh]					**0.17 €/kWh**
HOMER	PV (a-Si)	-			-
	Vergnet275	550 kW	4,396		1,229,398
	Caterpillar	800 kW	1,107	198,316	2,689,959
	LA	1296 kWh	274		814,146
Total costs					**4,733,503**
Annuity					379,829
LCoE [€/kWh]					**0.17 €/kWh**

* Capacity factor in full load hours per year

Introducing all relevant resource data, economic data, technological data and the annual electricity demand on Brava with and without desalination, the results are comparable. The odd installed capacities in the GAMS-configurations arise from the continuous mathematical optimum without adjustments to unit-dimensions of the components.

Main differences between the solutions are the fuel consumption, the installed capacities of the battery bank and eventually the corresponding costs. As mentioned before, the diesel generators operate a lot in part-load under nominal capacity, which is not at all efficient and a main reason for high fuel consumption. The diesel generator modeled in HOMER is consuming more fuel. The part-load behavior of the diesel generator is set on the minimal value of 30 % in both approaches. The dispatch strategy is load-following, that means, the diesel generator operates whenever the load cannot be met by the other (renewable) generation technologies. An alter-

Tab. 6.2: *Comparison of optimal energy and water supply system using HOMER and GAMS-model*

ES 2 with Desal.	Technology	Inst. Capacity	Full load hours [h/y]	Diesel cons. [L/y]	Costs in 20 y [€]
GAMS	PV (a-Si)	88 kW	2,125		219,515
	Vergnet275	919 kW	4,224		2,086,786
	Caterpillar	800 kW	1,254	135,155	2,773,234
	LA	2594 kWh	986		1,124,414
Total costs					**6,203,949**
Annuity					497,821
LCoE [€/kWh]					**0.15 €/kWh**
HOMER	PV (a-Si)	300 kW	1,936		749,547
	Vergnet275	825 kW	4,396		1,873,866
	Caterpillar	800 kW	1,045	341,488	3,119,362
	LA	2016 kWh	761		1,053,687
Total costs					**6,796,462**
Annuity					545,366
LCoE [€/kWh]					**0.16 €/kWh**

native dispatch strategy would be to run the diesel generators always in the optimal performance range and charge the batteries in case of surplus electricity.

The HOMER algorithm employs the diesel generator especially during periods of frequent load changes, whereas the developed GAMS algorithm would rely on batteries instead. The reason for this is the restriction in the GAMS model, that the diesel generators start only if they operate at least for three hours. With weather predictions such operation modes are realistic for state-of-the-art management systems. Therefore in the GAMS model instead of the diesel generators, mainly the batteries act as a so to say short-term back-up system. It is also for this reason that the installed capacity of the battery bank is higher in GAMS than in the HOMER solution. The costs of the battery bank are not conform to each other, which results from different cost calculation approaches, since in the GAMS model the costs depend on both, the installed power and energy capacity and not only on fix costs per battery unit.

In this comparison however, costs for desalination are not considered at all, only its energy demand and costs for energy. In the following calculations therefore the overall system costs will be increasingly higher than the ones discussed here, which is subsequently being dealt with as additional water costs, e.g. levelized costs of water.

6.2 The optimal energy and water supply system

Considering all elements of the model introduced in chapter 4, the mathematical optimal supply system for the Cape Verde island Brava might look like as depicted in Tab. 6.3 below. The system has to meet an average primary load of 6.3 MWh/day with a peak load of 815 kW and an additional energy demand for desalinating 800 m^3 freshwater per day, which means an additional load of around 3.2 MWh/day.

Tab. 6.3: *Optimal supply system - default*

Component	Inst. Capacity	Capacity factor- Full load hours/year	Total costs in 20 years [million €]
Vergnet275	1,166 kW	4,020 h	2.78
Caterpillar	800 kW	636 h	1.59
NaS-battery	1000 kW/ 7200 kWh	1,194 h	2.65
RO-desalination	800 m^3	8760 h	5.39
Water storage	1600 m^3	-	0.17
Total costs			**12.57**
LCoE			**0.16** €/kWh*
LCoW			**1.53** €/m^3

* considering overall energy consumption of 3,451 MWh/year (Primary load for electrification of island 2,283 MWh/year and secondary load for desalination 1,168 MWh) but no costs of desalination system and water storage

The mathematical optimal solution of 4.24 wind turbines (1,166 kW) is brought up to a round figure of four wind turbines. Converters are not modeled separately, but are integrated in the cost functions of the energy storage system. The sodium-sulphur battery is the optimal energy storage system chosen within the optimization process. Although a pumped hydro storage and hydrogen combined with a combustion engine would perform better and require less investment costs, these storage technologies are not considered due to the previously mentioned local restrictions on Brava. For the levelized costs of electricity the annuity of the overall energy system costs are considered (leaving aside desalination and water storage costs) related to the overall energy consumption of 3,451 MWh/year (primary load for electrification is 2,283 MWh/year, secondary load for desalination 1,168 MWh). The levelized costs of water take into account all desalination and water storage costs. The desalination plant is a modular implemented, conventional, constantly operating reverse osmosis unit with an energy consumption of 4 kWh/m^3.

Solving the entire mixed-integer program takes about three days. Scenarios and components are investigated in more detail throughout the upcoming sections. The majority of the limitation controls are employed, excluding irrelevant components of the model and minimizing computing costs without affecting the accuracy of the result.

6.3 Supply scenarios in comparison

Depending on the demand on an inland, in this case on the Cape Verde island Brava, different supply scenarios can be considered. In order to understand what effect renewable energies would have on the current system and how desalination could contribute to such a specific energy generation mix, several energy systems are looked at in detail:

ES 0: Business as usual, current system
ES 1: Energy supply only
ES 2: Energy and water supply with conventional operating desalination plant
ES 3: Energy and water supply with variable operating desalination plant

For a better understanding of the effect of desalination on the energy supply system, no installation changes on the supply side are done. The recommended nominal capacities of energy system 1 (ES 1) are also being used for ES 2 and ES 3. The calculations and analyses are based on a joint research work with *Pohl* as published in *Bognar et al.* [57]. The scenarios are calculated with the developed model, but using a conventional lead acid-battery as default, which has no minimal installed capacities and can therefore be implemented more flexible.

6.3.1 Integrating renewable energies into the current supply system

Energy system zero (ES 0) stands for the current energy system using only diesel generators. Table 6.4 shows the optimal installed capacities and costs of relevant components of each scenario.

In scenario ES 1 it is assumed, that Brava can meet its water demand by using partly groundwater and partly desalinated water from the neighboring islands, presuming these islands have an over-capacity. In this case expensive water imports from the mainland or desalination on site are not needed. The optimal energy supply is based on a mixture of renewable and fossil energy sources, in this case three Vergnet wind turbines with a nominal capacity of 275 kW per turbine and two Caterpillar diesel generators with a rated power of 800 kW_{el} respectively. Generally, a single generator set is in operation. The diesel generator capacity is constant for all scenarios. In case that no wind is blowing and the battery is empty, a second generator can operate simultaneously. The lead-acid batteries have an overall capacity of 1.4 MWh. Due to the LA instead of the NaS battery, the ESS faces less capacity restrictions and can be installed also under 1 MW. The batteries are connected to the grid through AC/DC-converters, which is not depicted in more detail. About 45 % of the wind energy is unused dump load, as shown in the energy balance overview in Tab. 6.5. Transmission losses are not accounted for the energy balances.

Tab. 6.4: *Supply systems of energy scenarios*

	Wind [kW]	Battery [kWh]	Diesel cons. [1000 L]	NPC_{ES} [million €]	$LCoE_{prim\text{-}load}$ [€/kWh]	LCoW [€/m^3]
ES 0	-	-	1,090	9.27	0.35	-
ES 1	825	1,440	190	5.35	0.21	-
ES 2	825	1,728	380	7.67	0.19	1.47
ES 3	825	1,296	310	6.65	0.16	1.40

NPC_{ES} net present costs of the energy system, not considering desalination and water storage costs

Tab. 6.5: *Energy and water balances per year*

	Wind [MWh]	Diesel gen. [MWh]	Primary load [MWh]	Desalination load [MWh]	Dump load [MWh]	Water produced [1,000 m^3]
ES 0	-	2,280	2,280	-	-	-
ES 1	3,630	470	2,280	-	1,820	-
ES 2	3,630	950	2,280	1,170	1,130	292
ES 3	3,630	790	2,280	1,250	890	289

Photovoltaic power generation is not part of the optimal solution. As a breakdown showed, relatively high investment costs and temperature effects of the modules can be assumed as main reasons for the unprivileged implementation of this technology. Compared to the current system, by implementing wind energy converters, batteries, and other required applications, the overall costs of electricity can be minimized significantly from 0.35 €/kWh to 0.21 €/kWh for a period of 20 years, cf. Tab. 6.4. The calculation demonstrates, that although changing the supply infrastructure implies high investment costs, it can still be attractive for business. LCoE in Tab. 6.4 do not consider environmental and land-use costs (as generally programmed in the model and used later on) and are therefore comparable with other LCoE-data in the literature.

Gaining increasing independence from oil imports and, therefore, stable energy prices in the long-term represents beneficial opportunities of ES 1. There is also a clear ecological benefit: by introducing renewable energy technologies to the current supply system (scenario ES 1), 895,789 liter of diesel could be saved and about 2160 tons of CO_2-emissions cut down.

Analyzing the deviation of every hour within the one-year simulation of ES 1, a remarkable excess of electricity, generated by the wind turbines, is unused, cf. Tab. 6.5. Especially in dry regions, using the dump load for water production, supplementing existing water stocks, can be a beneficial solution.

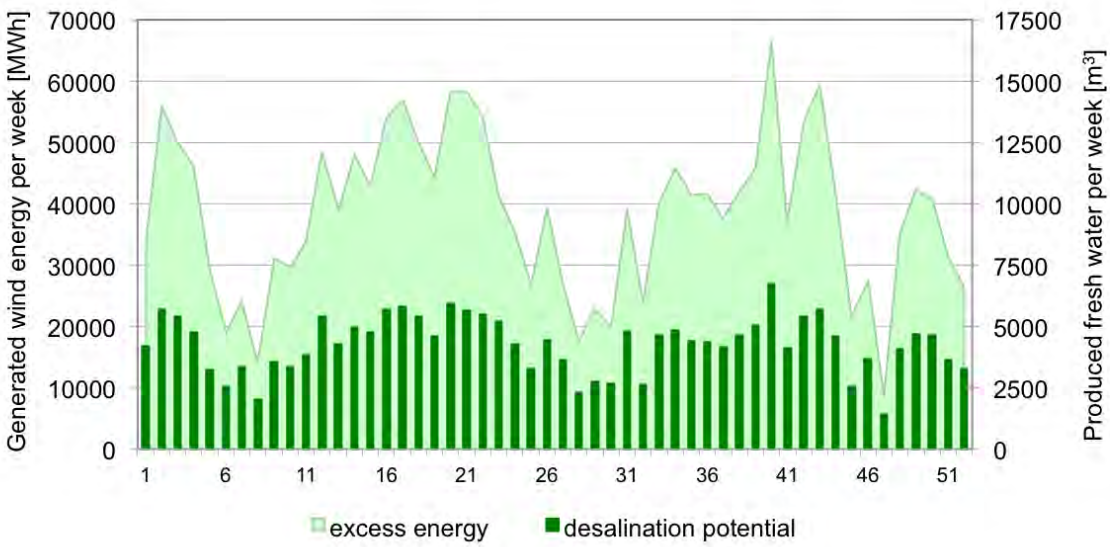

Fig. 6.1: *Desalination potential by excess wind electricity*

Figure 6.1 shows the potential of water production only by wind energy surplus on the island Brava. The light green area in the background is illustrating the excess wind energy generated in ES 1. The dark green bars in the front symbolize the potential of freshwater production per week by the surplus wind energy, taking into consideration capacity constraints of an applicable desalination plant (maximum production rate 33 m^3 freshwater per hour). The weekly freshwater demand on Brava is 5,600 m^3. As it can be seen, only a few weeks this amount can be provided just by excess wind energy, without having taken into consideration water storage tanks and alternative energy sources as back up technology. Figure 6.1 exemplifies, that excess electricity by renewable energies is able to meet a significant energy demand of a desalination plant as considered here. However, it also proves that wind energy alone cannot guarantee a continuous and reliable water supply throughout the whole year and back up technologies are required.

6.3.2 The optimal desalination process

Motivated by the fact of excess electricity by integrated renewable energies, the integration of desalination as additional load is looked at in more detail in scenarios ES 2 and ES 3. From the five desalination processes considered in the model and described in chapter 2.5 in this particular case a commonly used reverse osmosis plant is simulated for ES 2 and a variable operating reverse osmosis plant, as developed by *Synlift Systems GmbH* [55], for ES 3. Existing research proves that thermal desalination processes as MED, HDH or MD cannot compete with electrical driven processes in island grids as the one discussed here, cf. *Bognar et al.* [69]. The major question is whether or not a desalination process needs to be able to operate discontinuously and in part-load for serving as deferrable and beneficial load in hybrid micro-grids. For this investigation the comparison of a conventional reverse osmosis process with a variable operating one is necessary.

ES 2: Energy supply with constantly operating desalination plant
In ES 2 a conventional reverse osmosis desalination plant is being considered as a secondary load. Desalination units, as usual in process engineering, are designed to operate continuously and to perform as constant as possible at the plant's nominal rate. In this scenario such a conventional reverse osmosis plant is integrated as additional load with a constant load all year round, neglecting periods of interruptions as for maintenance. That means, this secondary load is not adjusting to the wind conditions, and the diesel generators need to operate whenever wind energy cannot meet the desalination unit's demand. Although the supply mix would change in this case and further wind capacity would have been installed, the installed capacities of wind converters and diesel generators are kept as in ES 1. In this way the dimension of the battery bank, the fuel consumption, the costs and the energy balances are comparable. The final system configuration of ES 2 is illustrated in the third row of Tab. 6.4. Additional to the daily average demand of 6.3 MWh/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 minimized as shown in 6.5.

ES 3: Energy supply with variable operating desalination plant
In ES 3 a variable operating reverse osmosis desalination unit is employed, that can adjust to a fluctuating energy supply. The desalination unit's operation and therefore its energy demand can be deferred within a given period, what gives this deferrable load its name. The deferment is usually limited by a temporary buffer storage, in this case by the dimension of the water storage tank, here 1600 m^3, covering the island's water demand of two days. In periods of water shortage when no excess wind energy is available, the diesel generator acts as a backup. The variable operating desalination unit has on average an energy consumption of 3.4 MWh/day, a peak load of 215 kW and a minimum load ratio of 17 %. In ES 3 significantly less energy storage capacity is required than in ES 1 and ES 2, cf. Tab. 6.4. What is also being demonstrated, are the low levelized costs of electricity (LCoE), namely 0.16 €/kWh compared to 0.19 and 0.21 €/kWh in ES 2 and ES 1 respectively. These costs include only costs of the energy supply system, where no investment or operation and maintenance costs of the desalination unit are included. These costs are taken account of by the levelized costs of water (LCoW), shown in the last column of Tab. 6.4.

The permeate production over the entire range of power consumption in ES 3 differs a bit from ES 2. This is due to the fact, that the variable operated system is producing slightly less freshwater per day than the constantly operating one. Comparing all three energy supply scenarios a number of immediate results can be seen: Although the overall costs for energy generation in ES 2 and ES 3 are higher, the LCoE are lower than in ES 1. One of the reasons for that is the delivered and from an economic perspective sold electricity for desalination that minimizes the costs per kWh. Since the variable desalination unit (ES 3) can adjust to wind conditions, the diesel generator set reduces the hours of operation by 17.4 % compared to the constantly operating one in ES 2. Less fuel needs to be consumed and energy costs can be kept at a low level. Accordingly the overall dump load of ES 3 is the lowest of all scenarios as well.

Further results can be drawn from this study: For the additional load of the constantly operating desalination unit (ES 2), the largest energy storage capacity is needed, cf. Tab. 6.4. Storing electricity is much more expensive than storing water. In ES 2 batteries with the overall capacity of 1,728 kWh and investment costs of 374,400 e are required. A battery with this capacity can store sufficient energy for producing 432 m^3 freshwater (with an energy consumption of 4kWh/m^3, neglecting energy losses of the battery). Storing freshwater is significantly 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 a further reason, why energy supply systems with less electricity storage capacities, as in ES 3, can perform economically beneficial.

A comparative illustration, shown in Fig. 6.2, was published in *Bognar et al.* in collaboration with *Pohl* and *Synlift Systems* [57]. It shows the levelized costs of water and electricity. Since in ES 1 no water production is considered, for the levelized costs of water only ES 2 and ES 3 are considered. In both diagrams constant fuel prices of 0.7 €/liter as well as fuel prices with a yearly increase of 4% and 8% are calculated respectively, over the investment period of 20 years. Within the comparison of the scenarios, the installed capacities of wind converters, the diesel generator and batteries are kept constant (as in ES 1) in order to uncover the effects deriving from the particular desalination process and to make the scenarios comparable. The fuel costs influence the energy costs and therefore also the water costs. They only account for price differences of 0.05 - 0.1 €/m^3. If, for any reason, a variable operating RO 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 as the first part of Fig. 6.2 shows. Looking at the levelized costs of electricity instead of water, the impact of an additional or a deferrable load appears more significant. It can be confirmed that ES 3 is the most beneficial energy supply system. The main reason for this is the high fraction of renewable energy used and the minimized fraction of unused dump load, as concluded before in relation to Tab. 6.5. Since due to desalination more electricity is used and can be sold, ES 2 and ES 3 can perform at lower electricity costs than ES 1.

Figure 6.3 depicts the relation of specific costs in more detail: The diagram illustrates the dependency of water costs on energy costs and prices respectively. At each point in 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 are marked with the corresponding levelized costs of water and electricity, cf. Tab. 6.4. The reference line symbolizes the levelized 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 0.21 €/kWh 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 levelized price of electricity instead of levelized

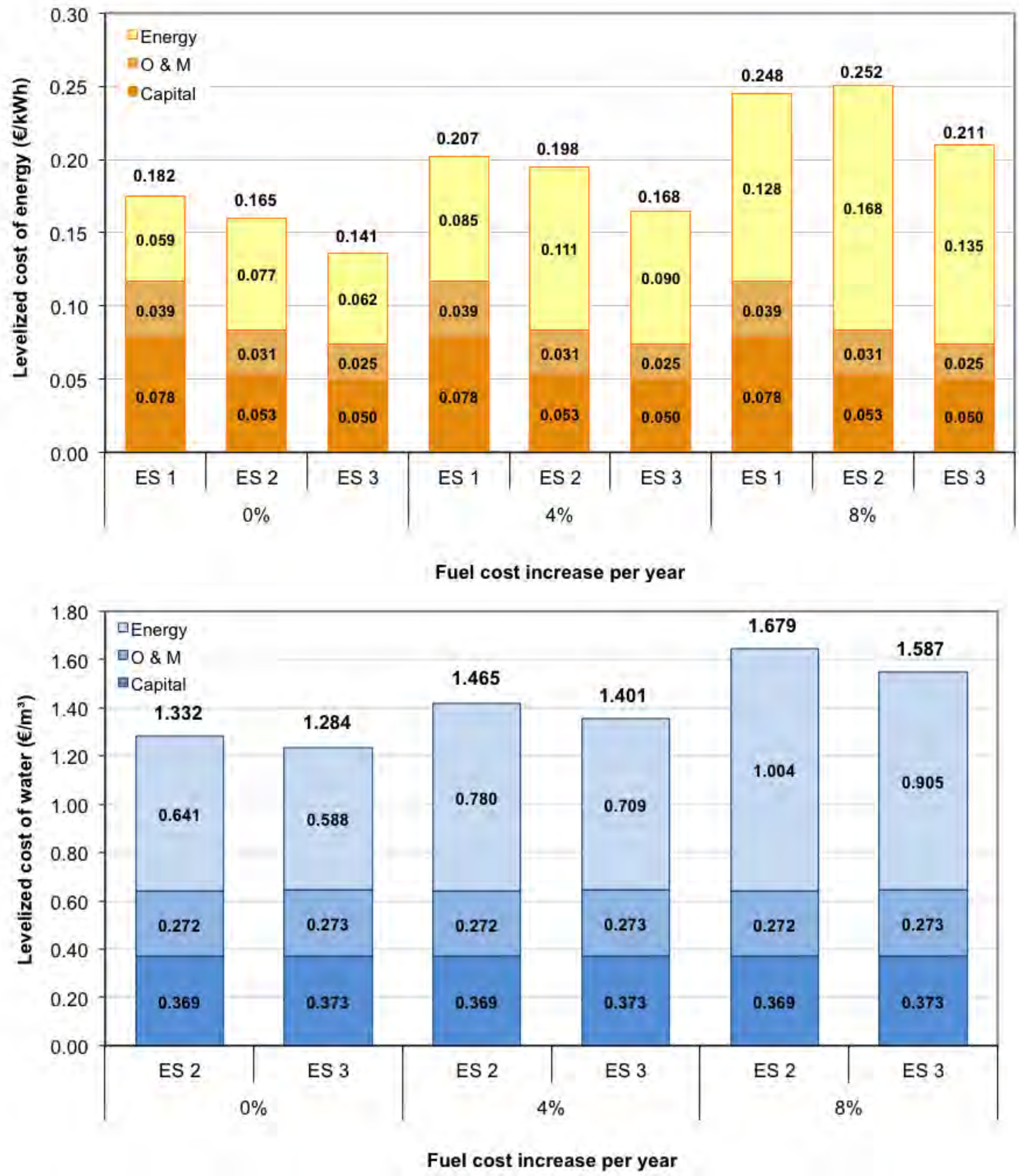

Fig. 6.2: *Levelized costs of electricity and water depending on fuel costs*

cost. For each supply system, payback strategies can be derived by determining water and electricity costs and shifting the break even point on the graphs.

Challenges of intermittent desalination

Technological challenges that variable operating reverse osmosis desalination processes face are analyzed and discussed by *Pohl, Käufler, Bognar et al.* [54, 55, 57] and hence are not discussed in the framework of this research.

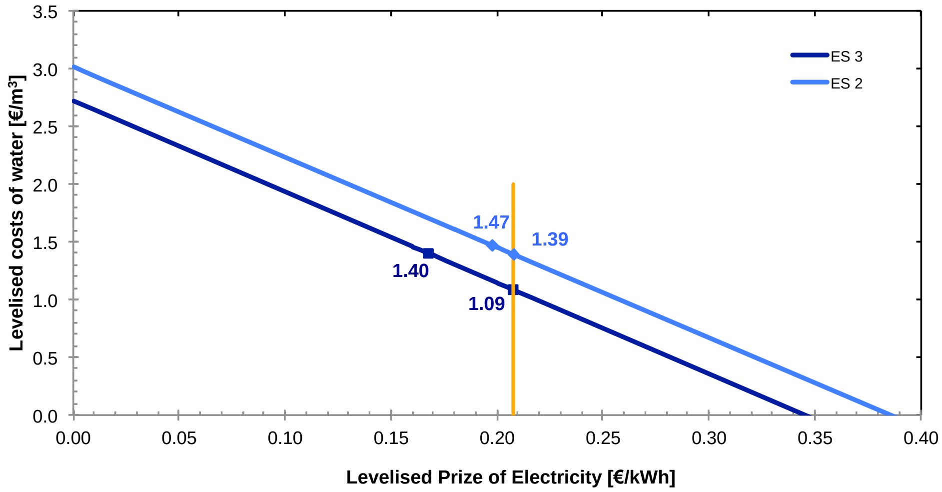

Fig. 6.3: *Levelised costs of electricity and water*

However, some simulation results of the case study on Brava should still be mentioned here: 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 modeled, an unrealistic high amount of starting sequences of the diesel generator and the desalination unit is given. The desalination unit in ES 3 would start 950 times, whereas 114 out of these the desalination plant would operate or pause only for one or two hours. Realistically, a load management should avoid such short operation periods by optimizing the collaboration of diesel generator, battery bank and desalination unit.

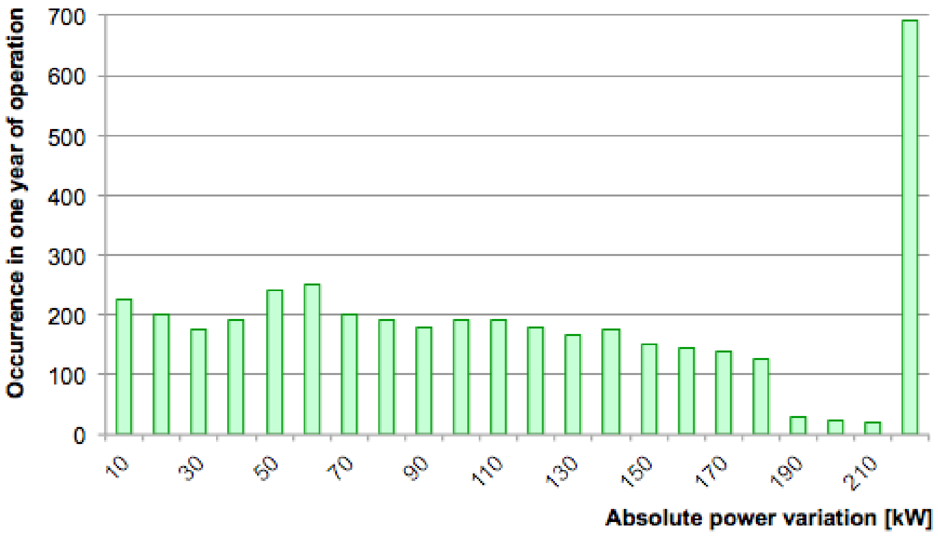

Fig. 6.4: *Power variations of a variable operating reverse osmosis plant*

In Fig. 6.4 the classified occurrence of absolute power variations of the variable operating desalination unit within the period of one year being looked at in more detail. 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, representing the power variations related to activations and deactivations, their is a tendency that the larger the power variations 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 operating at all. In effect that means, part-load operation is not required as often as assumed.

6.3.3 Robustness of the optimal desalination system

After having compared fixed energy systems with each other in terms of conventional or intermittent desalination, the previously presented optimal system in section 6.2 is looked at in more detail in the following sections. Since in that default result the conventional RO desalination system was chosen within the optimization process and not the variable RO one, it is important to investigate the local optimality of the result, since even slight changes could eventually change the overall result and conclusions with low validation would eventually be derived.

Tab. 6.6: *Deviations within the local sensitivity analysis concerning desalination*

Installed capacity [m^3/day]			changed parameter
RO	MVC	var-RO	
750	50	–	+1 % energy consumption of RO
692	108	–	+1 % O&M costs of RO
–	–	1200	- 1 % energy consumption of var-RO
750	50		- 1 % energy consumption of MVC
750	50		- 1 % O&M costs of MVC

Considering the solution space of 1% around the optimal solution (16 input parameters of the model are changed by 1 %), in 84 % of all results, the conventional reverse osmosis plant was the optimal solution. From the 32 single runs with a variation of plus/minus 1 %, in five cases the optimal desalination system differs from the default result. The recommended installed capacities of these special cases and their reason is depicted in Tab. 6.6. In each case the cause is a 1 % change of the variable costs or electricity demand of one of the desalination processes. A high sensitivity of these variable parameters can be concluded. For all the other eleven parameters no changes of the optimal desalination system occur. There are no further parameters that may influence the local robustness of the RO-system. The local sensitivity analysis has shown, that the determined solution using a conventional reverse osmosis plant is locally robust.

6.3.4 Optimal electricity storage system

In the scenarios outlined in the previous sections only a single battery type was used. But as introduced in chapter 2.3 and 4.8 there are numerous energy storage systems that have been considered in the model. Depending on the electricity storage used, the overall costs, the optimal system setup and the behaviour within the hourly simulation change. In Fig. 6.5 the economic effects of varying energy storage systems are illustrated.

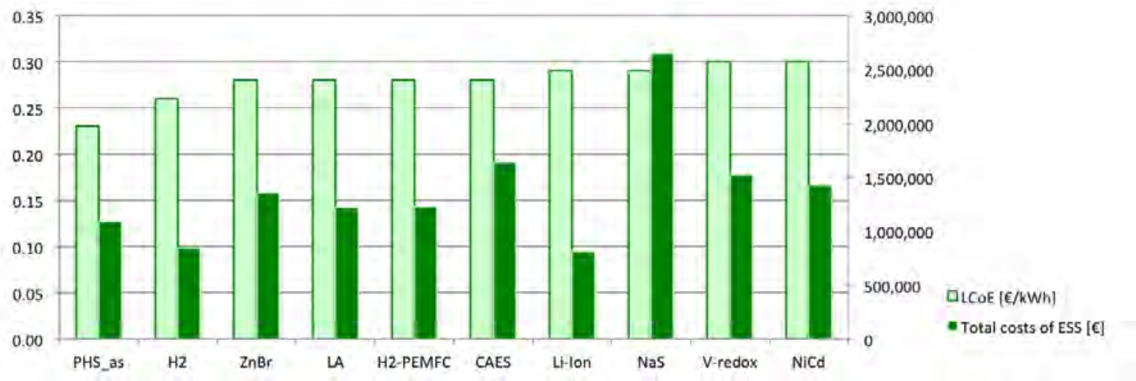

Fig. 6.5: *Economic effects of varying energy storage systems*

The levelized costs of electricity are shown on the left y-axis ranging from 0.23 €/kWh to 0.30 €/kWh. These levelized costs do also include all external costs as e.g. land-use and emission costs. Compared to the current electricity prices of 0.25 €/kWh (for less consumption than 60 kWh per month) and 0.31 €/kWh (for higher consumption than 60 kWh per month) on Cape Verde, the calculated levelized costs are comparable. Of course costs cannot be compared to prices, since a margin of profit needs to be considered as well. Although the share of costs of the energy storage systems differ a lot, the overall costs of the supply system and the levelized costs of electricity, respectively, are similar. The installed capacity of each storage technology and the dispatch strategy within the model adapts to the specific costs and optimizes the system, reaching the comparable overall system costs. In the scenarios using a pumped-hydro-storage or an engine-coupled hydrogen-storage the lowest overall system costs could be reached. In all energy storage-scenarios electricity can be provided at more or less similar price of around 0.28 €/kWh. Compared to the previous scenario analysis ES 1 to ES 3 the LCoE are higher, because the results include all external costs as for example land-use, CO_2 and other environmental costs. The total costs of each energy storage system over the period of 20 years, including replacement costs, O&M costs, costs of land-use and fuel costs, where applicable, are shown on the right y-axis of Fig. 6.5. The costs of each storage system differ significantly, due to diverse cost structures and therefore differing installed capacities. More detailed information can be found in Tab. 6.6.

As it can be seen in Fig. 6.5, the mathematical optimal solution storing electricity for the island Brava is a pumped-hydro-storage or a hydrogen storage driving an engine. Both storage technologies though come along with significant infrastructure interventions and are hence a second best option for both the community and the government. Eliminating the options of using a pumped-hydro or a hydrogen-storage, the electricity storage technology selected by the program is a sodium-sulphur battery. This is rather surprising because when comparing the single run scenarios, using only one single energy storage technology at a time, the sodium-sulphur battery is not (always) the third optimal storage device, cf. Fig. 6.5. The reason for this is the 5 % optimality gap. As mentioned previously, this solver-setting is important for keeping the calculating costs as low as possible. Without this gap, solving the program would probably take several weeks. Due to this optimality gap, slight deviations can occur as in this case. Considering all storage technologies (without the pumped-hydro- and hydrogen-engine-storage), the sodium-sulphur battery has been chosen as part of the optimal solution. However, taking the sodium-sulphur battery as the single storage technology into account, other storage devices perform better, when looked at from an economic perspective, cf. Fig. 6.5. Still, the optimal system used for further analysis is based on the program considering all storage technologies, which is using the sodium-sulphur battery, cf. section 6.2.

Depending on the various electricity storage technologies, the supply system is also changing. An overview of all chosen energy mixes by the model results is presented in Tab. 6.6. Since supply systems with completely different energy storage technologies and strongly differing installed capacities generate very similar overall system costs, it can be concluded, that the storage technology can be selected according to other factors than the costs.

Most ESS are oversized. One reason are the minimal installed capacity restrictions for some technologies, another explanation is the assumption in the model that the energy demand is met completely in every single hour of the year. In real case engineering designs would accept supply shortages of approximately 5 % (mentioned in chapter 4. Since in the model no shortages are allowed costs are higher. That is why costs and argumentations are not focusing on exact numbers but much more on relations and general results.

Energy storage system			Wind energy converter		Photovoltaic system		Diesel generator set	
ESS	Storage capacity [kWh]	Rated power [kW]	Inst. capacity Wind [kW] (adjusted to units)	FLH-Wind [h/y]	Inst. capacity PV [kW]	FLH-PV [h/y]	FLH-GenSet [h]	Diesel consumption [L]
PHS	8.000	1.000	1.375	3.751			422	147.237
H2	6.595	1.649	1.375	3.792			666	148.210
ZnBr	2.474	619	1.100	3.415			1.233	275.935
LA	2.686	671	1.100	3.693			864	190.786
H2-PEMFC	2.578	645	1.100	3.779			867	191.513
CAES	4.921	615	1.100	3.480			796	175.237
Li-Ion	823	206	825	3.991	4	2.085	1.751	392.763
NaS	7.200	1.000	1.100	4.020			636	139.754
V-redox	1.325	331	1.100	3.195			1.504	335.159
NiCd	1.219	305	1.100	3.887			1.384	309.226

FLH=Full load hours, dimension for capacity utilisation

Fig. 6.6: *Influence of varying storage technologies on the supply system*

6.4 Interference of energy storage systems and desalination processes

As shown in the previous section, the used energy storage system influences the system setup significantly. To understand the reason behind this, the 8760 simulated hours need to be analyzed in detail. A special focus is set on the question, why the installations, the desalination processes and the fuel consumption depend on the energy storage system used. Since an annual visualization of energy flows is not reasonable for hourly data sets, all months, weeks and days with each energy storage system were looked at, in order to find a reasonable and sophisticated answer to the above mentioned question and to define characteristic differences between the energy flows.

Sodium-sulphur, lead-acid and lithium-ion represent three recurring behaviour patterns of all considered ESS in various periods within the simulated year. Figure 6.7 illustrates one period of 48 hours comparing the energy flows of these three differing system designs. All input data are kept constant, only the allowed energy storage device changes. The main result, illustrated in Fig. 6.7, is that in the sodium-sulphur scenario the battery is acting as complement to wind energy most often. In case of the Lithium-ion battery it is the diesel generator that acts frequently as complement. In case of the lead-acid battery the variable operating desalination plant is acting as deferrable load using excess electricity and the water storage as backup. Desalination therefore is able to disburden energy conversion and storage components and to contribute to a balanced power grid. Herewith one of the main research questions has been answered.

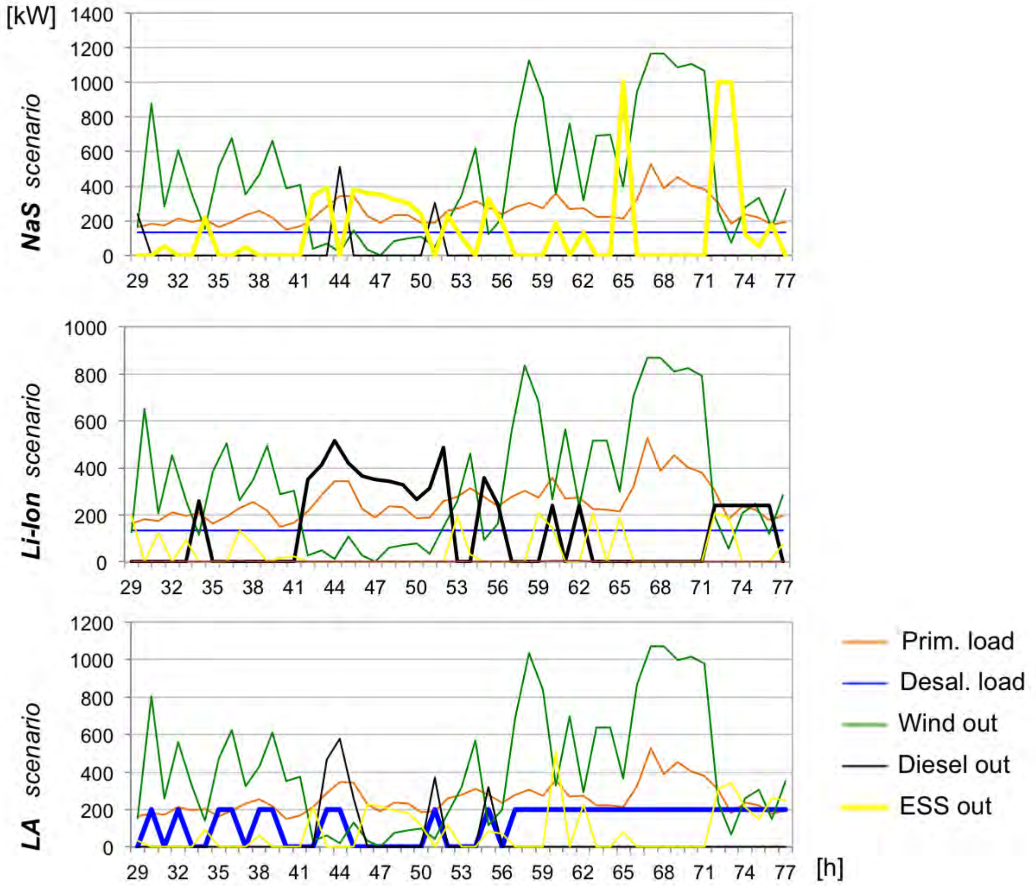

Fig. 6.7: *Energy flows of 48 hours depending on ESS*

In the referred to 48 hours period, which is of course not representing the entire year, the wind velocities fluctuate strongly and the lack of available energy needs to be provided by other technologies. In the top part of Fig. 6.7 it is distinguishable that the sodium-sulphur battery is operating most of the time, when shortages occur. As the pumped hydro- and hydrogen-based-energy storage, the high-temperature NaS-battery is operating at the maximal nominal power of 1 MW. Since system setups with these three storage technologies provide the best performance results, it seems to be very lucrative for an energy supply system to implement large-scale energy storage systems if geographically possible and affordable from an economic perspective - in this case, a 1 MW NaS-battery with a capacity of about 7 MWh. Such a system, for example, is already installed in Graciosa (by the company Younicos in Berlin, Germany).

The middle chart of Fig. 6.7 is showing the energy flows of the system using a lithium-ion battery. Probably due to higher investment costs the installed capacity of this ESS is kept low. With 206 kW it is the smallest energy storage system, followed by the nickel-cadmium and vanadium-redox-flow battery. Most dispatch and activations have to be covered by the diesel engine, what increases the fuel consumption and lowers its capacity factor. In this system a photovoltaic system is integrated with a peak nominal power of 4 kW. Although its capacity is very low and the technology is hardly contributing to the supply, it is still stabilizing the system, keeping it flexible and robust in periods of fluctuation.

In the bottom part of Fig. 6.7 the system using a lead-acid battery is shown. Here the variable operating desalination unit is chosen within the optimization process. The battery has an installed capacity of 671 kW. Although the diesel generator is employed more frequently than in the NaS-system, the main energetic adjustments are carried out by the variable operating desalination plant. Storage capacity and fuel consumption can be kept low by shifting the demand to periods when renewable excess electricity is available. Additional to the cost-effectiveness shown in previous sections, the technological advantages of desalination as deferrable load can also be proven by investigating energy flows in hourly resolution. The energy flows with energy storage systems as the zinc-bromine battery, the hydrogen-fuel cell and the compressed-air-energy storage are mainly behaving as the LA-scenario with slightly varying characteristics.

6.5 Approach and results of a global sensitivity analysis

The motivation behind the global sensitivity analysis is to determine those factors that influence the respective model the most and subsequently to distinguish them from factors that are negligible. Contrary to a local sensitivity analysis during this experiment type the entire space is considered, in which factors may vary. What is not addressed in the sensitivity analysis is the impact of volatile energy resources, such as the wind velocity and solar irradiation. A short analysis addressing this uncertainty is presented before accomplishing the global sensitivity analysis in more detail.

6.5.1 Impact of wind velocity and solar irradiation

All results are based on the initial data inserted in the model. The potential of renewable energy sources, in this case the wind velocity and the solar radiation, can underlie various error sources. Accuracy or calibration errors of the anemometer, turbulences, climatic changes, height differences between the anemometer and the installed wind converter, unpredictability etc. cause deviations of the wind velocities used in the model compared to real wind conditions. Exact measurement uncertainties from calibration drift, operational uncertainties, or data gaps are unknown for ground site data sets. It is assumed that quality measured data on site are more accurate than satellite-derived values. Nevertheless, the solar radiation data used in the model are satellite-derived with estimated uncertainties from 6 to 12 % [112].

For both, wind and solar data, a further and decisive source for inherent errors are the static data sets for the period of a single year. Deviations from hour to hour and day to day are included but can certainly not precisely depict real life for an investment period of 20 years. A sensitivity analysis can help in exemplifying the impact of initially implemented wind velocity and insolation data.

As shown in Fig. 6.8, the optimal system setup consists out of a wind-diesel-system. The figure clarifies that for the given case the wind speed has a higher impact on the supply system than the solar irradiation. Since the measured average solar irradiation is about 6.3 kWh/m^2/day and the average wind velocity 7.3 m/s (marked in Fig. 6.8), the reliability of the model output is high, even if the assumed solar and wind potentials were inaccurate. At an insulation of about 7 kWh/m^2/day and an average wind velocity of under 6 m/s, the integration of photovoltaics would

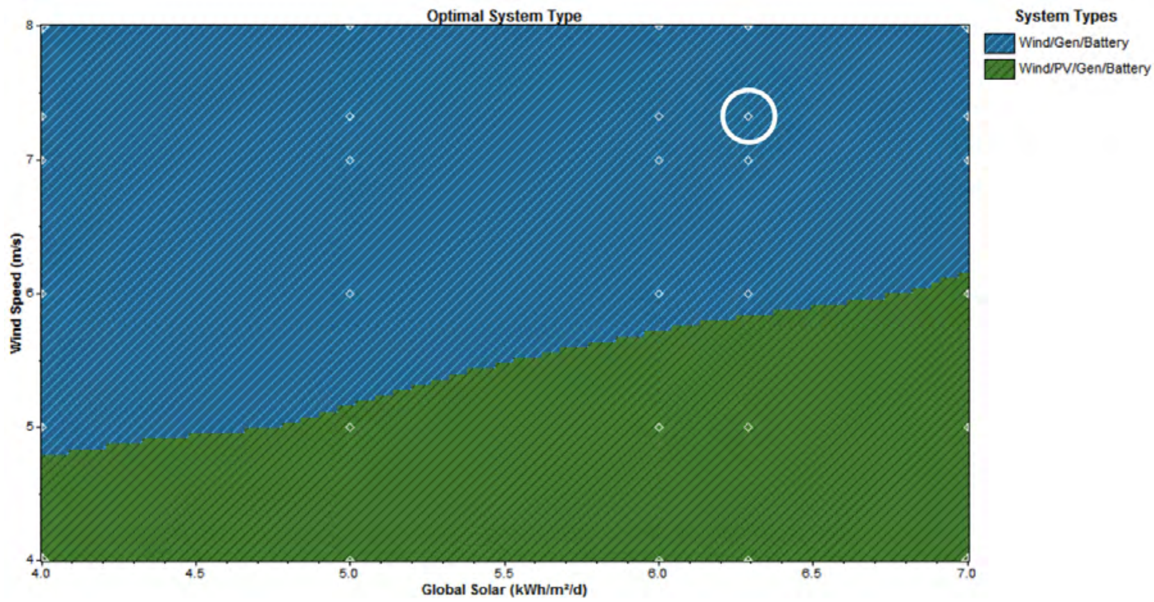

Fig. 6.8: *Sensitivity of solar irradiation and wind velocity*

optimize the supply system. The installed capacities cannot be determined by this visualization, only the installed components.

6.5.2 Definition of parameters

Technological parameters and economic data were collected in particular for the given case but can change over time. Technological evolution or price changes can influence results of a model and significantly in real cases. To understand which parameters are the most sensitive ones to the overall model output, 16 parameters were analyzed in more detail, investigating their influence on 22 output variables. Considered parameters and variables are outlined in Tab. 6.7 and Tab. 6.8. All abbreviations of considered input parameters in the model begin with fac_ for factors, all output variables with out_ for outputs.

Within the determined ranges, shown in Tab. 6.7, ten equidistant values are used of each parameter. For some parameters a new factor k has been introduced, because some parameter consist out of a set of data instead of just a single one. This way SimEnv is able to adjust one specific parameter within the sensitivity analysis. Such an additional factor was introduced for the demand, for the energy consumption of the variable operating reverse osmosis desalination unit and for the energy storage costs. In order to change the demand values a single factor was needed, because the data sets consist out of 8760 values. The energy consumption of the variable desalination unit depends on its varying operation and cannot be statically determined.

The factor k_{desal} is integrated in the main model. The factor for changing the costs of storing energy is needed, because more than one technology is considered and the costs are supposed to change relatively for each technology instead of absolute values for only a single storage device. The demand can be changed by the factor k_{demand}.

Tab. 6.7: *Input parameters for sensitivity*

Parameter	Description	Base	Sensitivity range from	until
c_diesel	€/kWh_f : Cost of fuel for diesel	0.07	0.05	0.5
c_co2	€/tCO_2 :Cost of the CO_2	20	5	40
interest_rate	interest rate of the project	0.05	0.03	0.12
e_cons_el of ro	energy consumption of RO-desalination plant	4	3	15
e_cons_el of mvc	energy consumption of MVC-desalination plant	11	8	20
k_desal	factor for energy consumption of variable operating desalination plant	1	0.5	4
k_ess	factor for prices of energy storage systems	1	0.5	4
k_demand	factor for energy demand on island	1	0.5	4
c_plant of ro	investment costs of RO-desalination unit	2000	1000	3500
c_plant of MVC	investment costs of MVC-desalination unit	2350	1000	3500
c_plant of RO_ES3	investment costs of variable RO-desalination unit	2000	1000	3500
c_om of MVC	O&M costs of MVC-desalination unit (factor 0.5 - 4)	0.29	0.145	1.16
c_om of RO	O&M costs of RO-desalination unit (factor 0.5 - 4)	1.0385	0.519	4.154
c_om of RO_ES3	O&M costs of variable operating RO-desalination unit (factor 0.5 - 4)	1.0385	0.519	4.154
c_P of PV	investment costs of photovoltaic panels (factor 0.5 - 4)	2300	1150	9200
c_P of Wind	investment costs of wind energy converters (factor 0.5 - 4)	1818	909	7272

The model simulations are accomplished for all combinations considering interferences between the parameters, creating a multidimensional sample space. Relevant output variables are installed capacities, energy flows, water flows and total costs of most components, cf. Tab. 6.8.

Output data as diesel consumption, renewable energy fraction, CO_2-emissions and the full load hours of each component can be derived from the mentioned output

Tab. 6.8: *Output variables for sensitivity*

p_pv	installed capacity of the photovoltaic system
p_w	installed capacity of the wind turbines
p_csp	installed capacity of the concentrated solar power system
p_ess	installed storage capacity of the electrical energy storage system
p_diesel	installed capacity of the diesel generator
capacity_ro	installed capacity of the reverse osmosis desalination plant
capacity_mvc	installed capacity of the mechanical vapour compression desalination plant
capacity_ro_es3	installed capacity of the variable operating reverse plant
e_sum_pv	annual electricity generation by the photovoltaic system
e_sum_w	annual electricity generation by the wind turbines
e_sum_csp	annual electricity generation by the concentrated solar power system
e_sum_diesel	annual electricity generation by the diesel generator
e_sum_ess	electricity stored in total by the electrical energy storage system
e_sum_desal	annual energy consumption by the desalination plants
w_sum	annual water production
tc	total costs
tc_pv	total costs of the photovoltaic system
tc_w	total costs of the wind turbines
tc_csp	total costs of the concentrated solar power system
tc_diesel	total costs of the diesel generator
tc_ess	total costs of the electrical energy storage system
tc_tss	total costs of the thermal energy storage system
tc_wss	total costs of the water storage system
tc_ro	total costs of the reverse osmosis desalination plant
tc_mvc	total costs of the mechanical vapour compression desalination plant
tc_ro_es3	total costs of the variable operating reverse osmosis desalination plant

variables and the log-files of each simulation run. The optimal supply system presented in section 6.2 is the base for the global sensitivity analysis. Mainly due to computational costs of the used experiment designs and the computational costs of each single simulation run in terms of its central processing unit, the only energy storage system considered, is the high-temperature sodium-sulphur battery.

6.5.3 Sensitivity of parameters

For determining sensitive parameters a factor analysis is required. Initially a qualitative analysis is done identifying some of the most relevant parameters, so that less parameters need to be considered in a further detailed analysis. For this qualitative analysis the modified Morris approach is employed, cf. section 3.4. The Morris approach is an elementary effects method. A qualitative ranking of a large number of factors with respect to their sensitivity on the model output can be derived from statistical measures of local elementary effects at randomly selected trajectories in the factor space [84]. Table 6.9 shows a small excerpt of the analysis. Parameters with correlating model outputs usually have mean and variance values above 0.2. By completing and analyzing the results as depicted in this matrix, the most sensitive parameters and variables can be determined.

Tab. 6.9: *Numerical results of Morris approach*

output	/ input	c_diesel	c_co2	interest_rate	k_desal	k_ess	k_demand	...
p_pv	mean	**0.128**	0.024	0.015	0.025	0.066	**0.219**	...
	variance	0.038	0.0056	0.0018	0.0056	0.015	0.132	...
p_w	mean	**0.189**	0.03	0.047	0.07	0.09	**0.411**	...
	variance	0.032	0.0047	0.0089	0.01	0.013	0.1	...
p_csp	mean	**0.189**	0.012	0.026	0.045	0.08	**0.306**	...
	variance	0.091	0.001	0.002	0.01	0.048	**0.202**	...
p_ess	mean	**0.306**	0.045	0.099	0.11	0.37	**0.885**	...
	variance	0.08	0.006	0.014	**0.103**	**0.11**	**0.166**	...
...	...	...	...	...	...	...	...	...

Eight from sixteen factors can be identified as relevant for the further sensitivity analysis:

- (1) Demand: The most relevant parameter is the change of electricity demand on the island, mainly depending on the development of tourism,
- (2) Diesel price: The fuel price influences significantly the composition of the energy system,
- (3)-(4) Investment costs of wind turbines and photovoltaic systems respectively,
- (5)-(8) Energy and other variable costs of desalination technologies (RO, var-RO, MVC).

A visualization as mentioned in 3.4 is helpful for interpreting the qualitative Morris approach from Tab. 6.9. Figure 6.9 shows the effect of all parameters on the sum of annually generated kWh electricity by photovoltaics, wind turbines, concentrated solar power systems, diesel generators and the sum of energy flows from the NaS-battery and to the desalination unit. Some relevant factors in Fig. 6.9 are marked. μ in this case stands for the influence of each of the 16 parameters on the model output, that means for the sensitivity of a factor with respect to the model output.

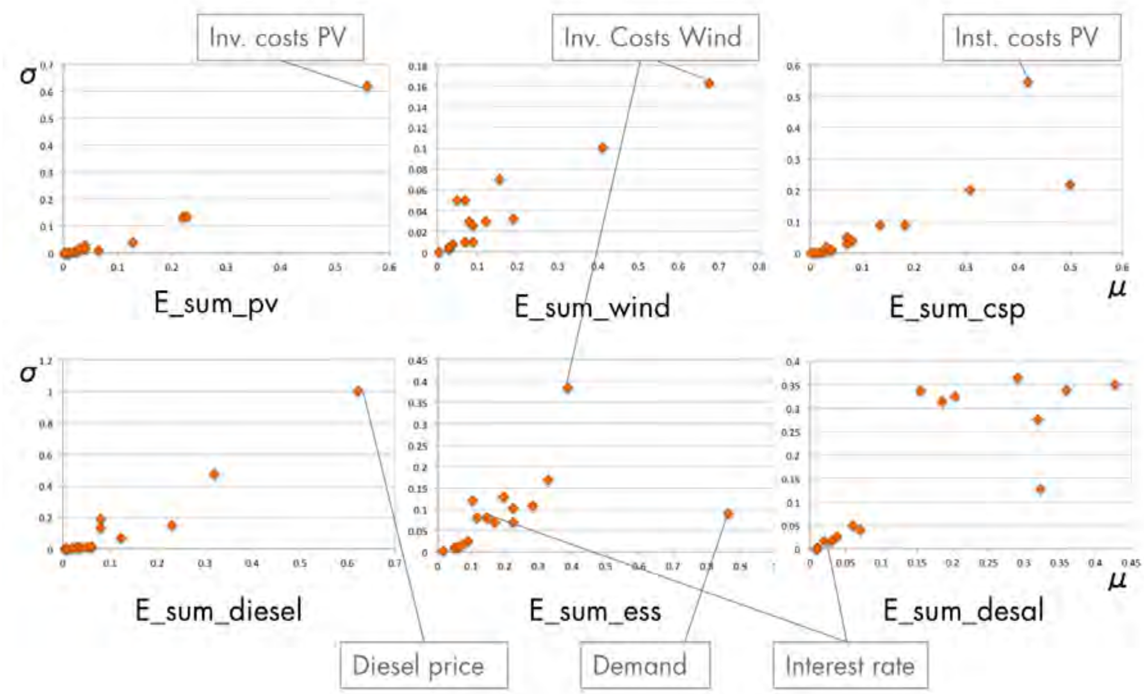

Fig. 6.9: *Sample of Morris results*

σ shows, whether the factor is involved in interactions with other factors or if the effect of it on the model output is nonlinear. Factors with a high μ-value can be identified as sensitive, factors with high σ-values show interactions with other factors and/or a nonlinear effect on the model output [84].

All other parameters as the interest rate, the price of CO_2-emissions or variable costs of energy generation technologies are less relevant for the model outputs. In case of the interest rate, effects of interest rate changes do not show up in relation to other variables. The reason behind it is that the optimal solution is determined by the model itself, taking into account all cost parameters and shifting the system design in a way, that less capital intensive technologies are used. The effect of interest rate changes on the model results is shown in the left diagram of Fig. 6.10. The right diagram shows the *real* effect of interest rate changes, if the components and installed capacities of the supply system would be kept constant and would not be optimized by the optimization algorithm depending on the initial input parameters. However, the interest rate is a basic parameter with high economic influence, but due to the optimization approach the effect is not presentable as a key sensitivity parameter.

Although a global sensitivity analysis is presented later on, Fig. 6.10 shows the results of a selective sensitivity analysis considering some of the main cost drivers.

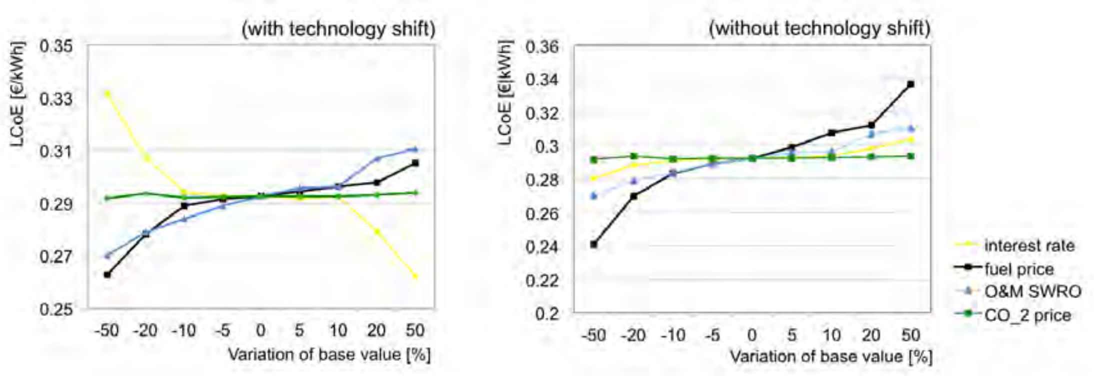

Fig. 6.10: *Local one-dimensional sensitivity analysis*

Each cost value is 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 levelized cost of electricity can be seen on the ordinate.

6.5.4 Probability of technology implementations

To understand the constellation of the energy supply system and the influence of relevant input parameters independently from the weighted and most sensitive parameters as before, a Monte-Carlo-Analysis has been accomplished for a smaller sample of 400 simulation runs (only for the already determined sensitive parameters), compiling a distribution function of the output values. Previously the correlation of parameters and variables was analyzed. Thus, subsequently simulation runs are looked at, without considering and emphasizing identified relations. Input parameters are still changed, but no weighting and no interferences are considered in these 400 runs. This way statistical distribution functions can be derived. The Monte-Carlo-Analysis is calculated for all 22 output-variables, but only some are addressed in more detail. The distribution function of the installed capacity of each component is representing the distribution function of the total cost and the overall provided power per year of each component.

The solution set of each considered output variable is divided in ten equidistant and uniformly distributed columns (bins), representing the distribution function. As statistical method for generating representative values from the multidimensional distribution, latin hypercube sampling is being employed. Some technologies are either not used at all, or if they are, always at full load. Desalination processes e.g., are mostly installed at maximum capacity or not in use, therefore their heuristic density function does not matter. However, the distribution of energy generation components can be very informative concerning the most probable installed capacities. As shown by the Morris analysis and variance decomposition, these parameters have the highest impact on the energy related output variables. The main question remains, how probable each installed capacity of various technologies is. Since the high amount of zero-values (when a technology is not used in a simulation run) distorts the distribution function of each component, only simulation runs are considered, where the technology is actually in use. The results of the Monte-Carlo-Analysis are shown in Fig. 6.11.

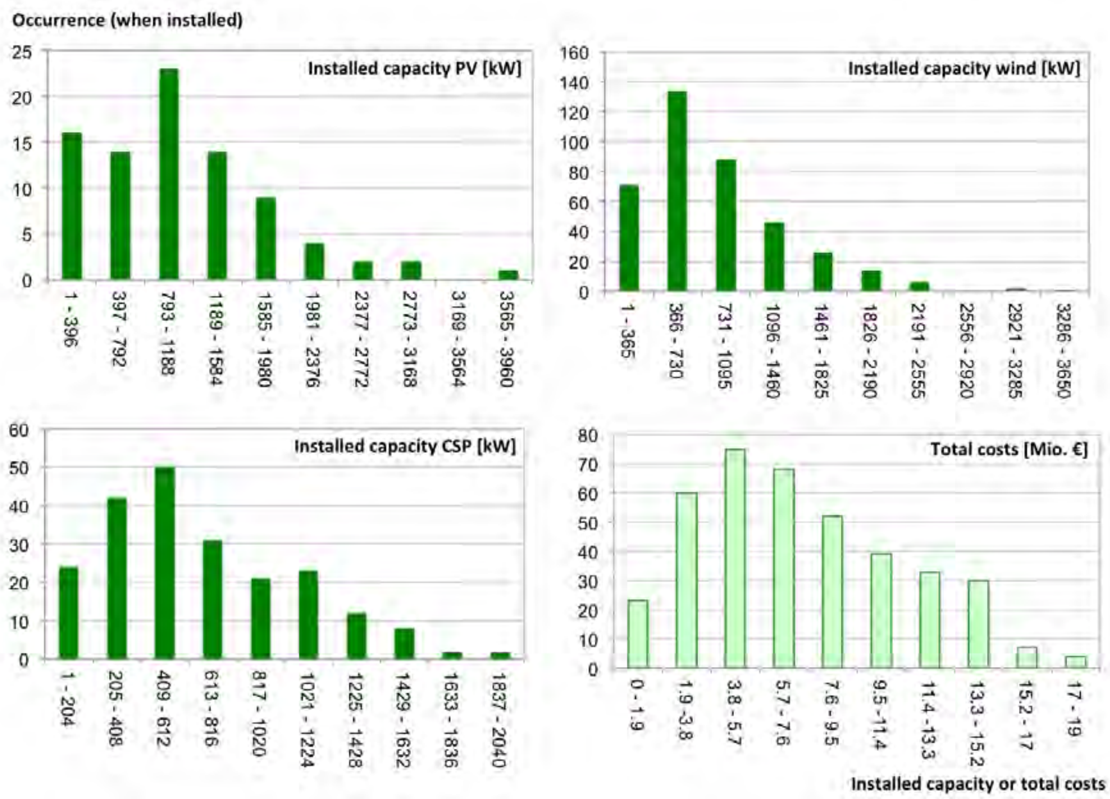

Fig. 6.11: *Distributions of the Monte Carlo Analysis*

Figure 6.11 shows the distribution function of the installed capacities of the photovoltaic system, the wind energy converters, the concentrated solar power plant and the total costs of the overall system including desalination depending on the four parameters (energy demand, fuel-price, investment costs of PV-system and wind turbines). Non of the distributions is a normal Gaussian distribution, rather a skew distribution. Although the installed wind energy capacity in the optimal solution is about 1100 kW, the Monte-Carlo-Analysis shows, that in 134 of 388 simulation runs, installing around two or three 275 kW Vergnet wind converters (366 to 730 kW installed capacity) is the most probable, cf. top right diagram in Fig. 6.11. The installed capacity-distribution of CSP-systems mostly favours a normal distribution with its peak at installed capacities of around 400 to 600 kW, which is about the half of the installed capacities of PV within the distribution function. That means, that the installation of PV is preferential to CSP. This is especially recognizable, because only relatively inefficient ORC- and solar-dish-CSP-technologies can perform under the nominal capacity of 10 MW_{el}. CSP technologies though, seem to be a beneficial amendment to wind converters, diesel generators and desalination systems. Looking at the total costs of the entire energy and water supply system in most cases the total costs are between three and six million Euros. These total costs are carried by electricity and water prices. The costs may be higher than calculated in comparable programs, due to the mentioned external and environmental costs considered in the model.

From the 400 main simulation and optimization runs, where only changes of a single parameter are considered, neglecting interferences with other changed parameters and statistical weightings, furthermore tendencies of system designs can be derived. Figure 6.12 (and Fig. 6.17 later on) show the statistical distribution of technology mixes for electricity generation and water production. As recollection, the ESS used in all simulation runs is the sodium-sulphur battery and diesel generator is set to a nominal capacity of 800 or 1,600 kW respectively.

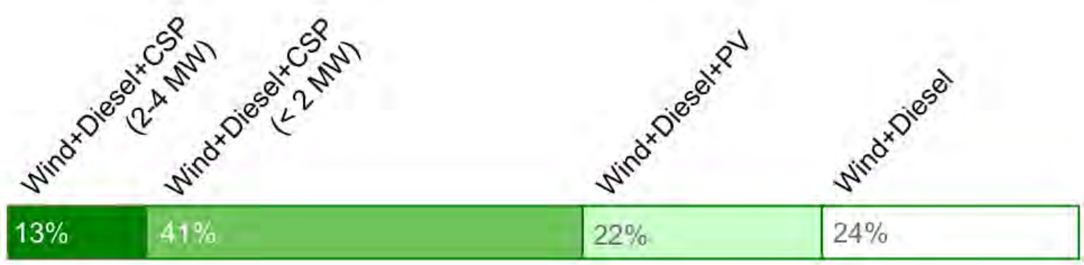

Fig. 6.12: *Distribution of the energy generation mix*

It can be seen, that CSP-technologies up to 2 MW play a significant role in the majority of the depicted scenarios, as soon as electricity demand and the fuel price increase significantly. However, it has to be taken into account that due to technological restrictions of turbines, the minimal installed capacity of parabolic through, Fresnel and solar tower systems is 10 MW_{el}. The only CSP-technologies under 2 MW are solar dish or ORC-processes. A market maturity especially of ORC-processes though is not reached yet. The linearized cost function of small CSP-plants is also a simplification within the model, that potentially distorts the real costs of small CSP-plants.

Figure 6.13 gives an impression of technology interactions within the 400 single runs. The immediate correlation of total system costs and the installed capacity of photovoltaics to the diesel price increase is recognizable. One outliner is marked green to show the relations of one single scenario in all scatterplots. No further relations could be concluded with considering the investment costs of CSP within the scatterplots, what is the reason for the neglected technology.

6.5.5 Impact of sensitive parameters on the energy supply system

The energy demand on the island is generally the most sensitive parameter. It decisively influences the overall system design and each single output value. The diesel-price is the second most sensitive parameter. Increases in demand and the diesel price result in a significant rise of total costs of a system and electricity prices respectively. Figure 6.14 gives a quantitative overview of the effects energy demand and fuel prices have on the levelized costs of electricity. It needs to be kept in mind, that these LCoE are already accounting for costs for desalination and water storage costs as well as external costs for land-use, emissions and resource depletion and are therefore significantly higher than commonly calculated electricity costs. LCoE without these additional costs were presented and discussed in section 6.3. The current energy consumption on the island, named "demand", is represented by the factor 1.0. In case, that the population on the island shrinks due to emigration, a bisection of the current energy demand is considered. If the island and investors are making an effort to develop its tourism sector, depending on the number and standard of hotels, significant increases of energy consumption can be expected, especially including also higher water consumption. That is why the range of increasing energy consumption is considered up to the factor 4. A similar assumption is made for the diesel price. The current price is around 0.07 to 0.1 €/liter. A decrease of the diesel price is not expected, much more oil price increases. That is why the range goes up to a fuel price of 0.5 €/liter. Although such high increases are not that probable within the next 20 years, the sensitivity analysis is supposed

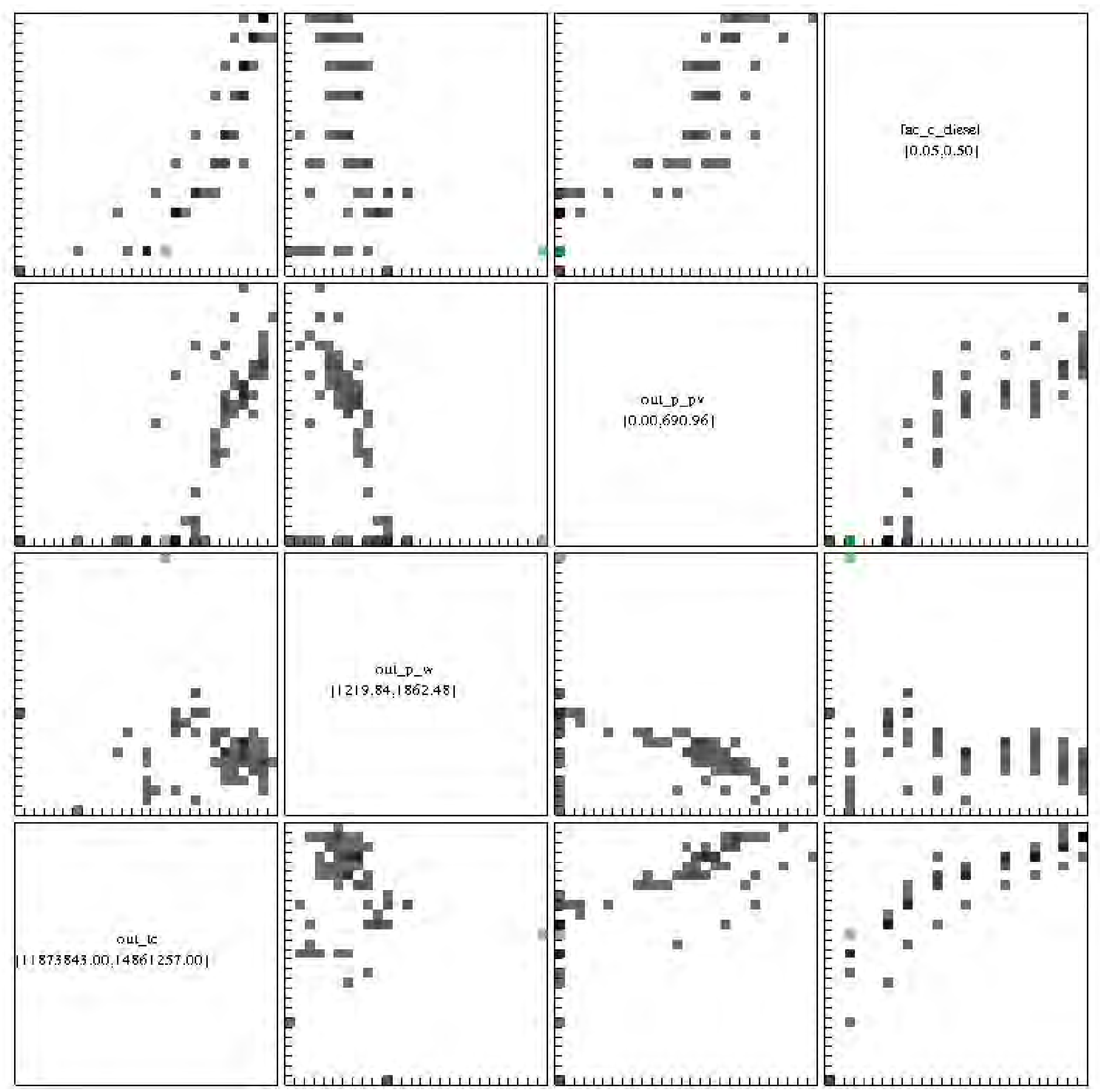

Fig. 6.13: *Comparative distribution of energy generation technologies*

to show the optional outcome of even such a development. The white parts in the diagram are symbolizing a lack of results. In these regions the single runs within the sensitivity analysis could not be solved within 12 hours, which was the forced limit of calculation time. Since the optimal solution, presented at the beginning of this chapter, was found in about three days, it is understandable, that between others this simulation run is not visualized in Fig. 6.14.

Since under current conditions CSP is not part of the optimal solution, only the interactions of wind turbines, the photovoltaic system and the battery bank are analyzed in more detail.

The analysis in Fig 6.15 aims at finding hidden patterns and relationships in the high-dimensional space of model parameters and output variables. The installed

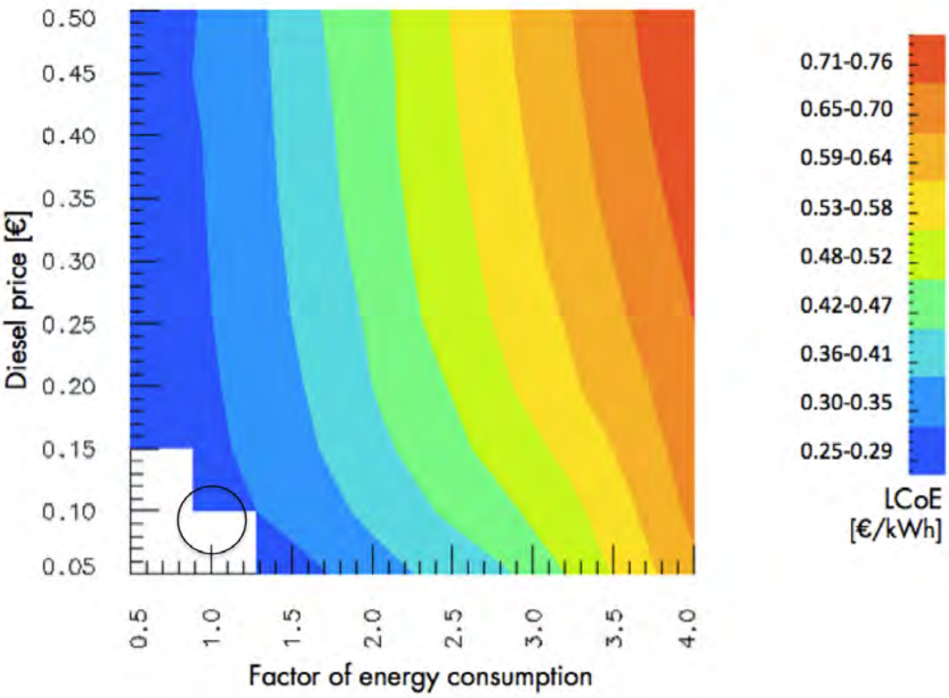

Fig. 6.14: *Effect of increasing energy consumption and fuel price on the system and electricity costs*

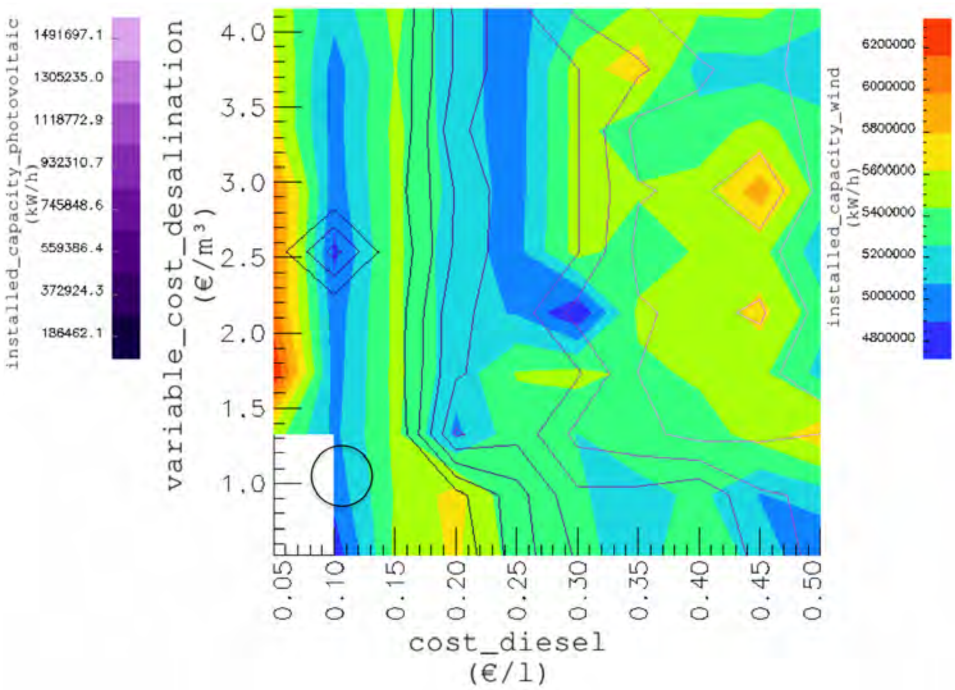

Fig. 6.15: *Renewable energy mix depending on diesel price and variable desalination costs*

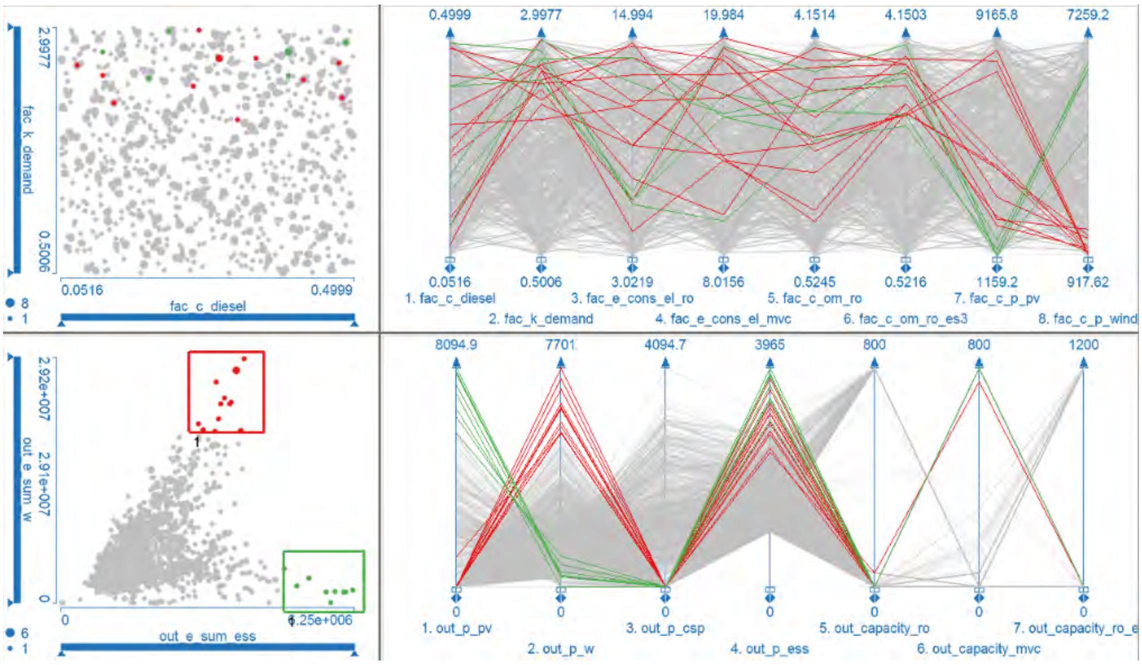

Fig. 6.16: *Effects of demand and fuel prices on the energy system*

capacity of photovoltaics is encoded by isocontours and the installed capacity of wind turbines by colour. The resulting image reveals that the dependency on low diesel costs is high for both installed capacities, which is indicated by parallel lines for photovoltaics and by parallel bands for wind capacities. However, this pattern decreases for higher diesel costs indicating that other factors are playing a more decisive role (the demand, not visualized here). The O&M cost of the variable desalination unit is the most sensitive water related parameter but has no visible influence on the energy mix.

Although scientific visualization techniques illustrate several information, they are not always representative for the whole solution space. By choosing a greater set of variables and an alternative illustration method, several answers can be specified. With the ComVis technique multiple views and brushing functionality is provided.

Figure 6.16 shows all results of 2000 runs (based on a variance decomposition considering the weighted distribution functions of the most sensitive parameters) and connects a number of information with each other: The left bottom part of the figure shows the sum of generated kWh of wind energy converters over the annual sum of stored and provided kWh of the sodium-sulphur battery. Filtering extreme points in this diagram, some more system details of the marked single runs can be clarified. In the right bottom illustration of Fig. 6.16 it becomes obvious, that the red scenarios, with a high share of wind energy go along with high installed capacities of wind turbines. The much more interesting result though is, that the highest amounts of energy stored and the corresponding installed capacities of the energy storage system are in the simulation runs, when only photovoltaics and no wind energy converters are being installed. Land-use restrictions that can occur on a small and mountainous island like Brava are only considered by costs for land, but not by GIS-data for guaranteeing the feasibility. Due to the daily periodic character of solar radiation, large energy storage capacities are required to meet the power demand. Peak capacities of a sodium-sulphur battery of about 4 MW_{el} though are not in use put to now. Based on the current technological parameters and costs the implementation of such a battery would be beneficial compared to diesel generators relying on fuel imports. Related to this result it is interesting to see in the left upper coordinate system, that for all marked simulation and optimization runs the diesel price is absolutely irrelevant. The extremely high installed capacities of wind turbines, photovoltaic systems and batteries are explicable with an electricity demand that is three times higher than the current one. All marked scenarios are at high demand rates. The same time the dots are equally distributed between diesel fuel prices from 0.05 to 0.50 €/liter. One reason for this result is the fact that the modeled diesel generators are fixed to the maximum of two 800 kW_{el} peak generators. But the main reason is, that installing a new energy infrastructure, a coupled system of renewable energies and batteries can compete with fossil based diesel generators even with current fuel prices. The multi-dimensional coordinate system in the right top of Fig. 6.16 shows some of the corresponding input factors used for the calculated results in the bottom part of the figure. It can be seen that no further correlations exist between the input and output factors, except the obviously low investment costs for photovoltaics in the green scenarios and low investment costs for wind energy converters in the red scenarios. Hence, in conclusion high values of wind energy generation and stored electricity per year (out_e_sum_w and out_e_sum_ess) appear only in case of high energy demand development in the range of two or three times higher energy demand. The same time it can be concluded, that high energy storage capacities are proportionally needed for higher installed capacities of photovoltaics. In the given case PV systems depend more on batteries than wind turbines. Even if prices of photovoltaics decreased significantly in near future, such systems would still require high electricity storage capacities.

6.5.6 Impact of sensitive parameters on the desalination unit

In Tab. 6.6 the local robustness of the constantly operating reverse osmosis desalination plant has been proven. From a global perspective though, a conventional RO plant is not necessarily the optimal desalination process. Figure 6.17 is a statistical analysis and shows the distribution of the chosen desalination processes in the previously introduced 400 independent simulation runs. The variable operating reverse osmosis plant can act more flexible to parameter changes and is used most often.

Fig. 6.17: *Distribution of desalination technologies*

To understand in more detail the dependencies, whether or not a desalination technology is chosen, a multi-dimensional coordinate system is employed. For statistical completeness all 2000 simulation runs from the variance decomposition are mapped from Fig. 6.18 to Fig. 6.20. Influences of relevant input parameters can be determined by the visualization.

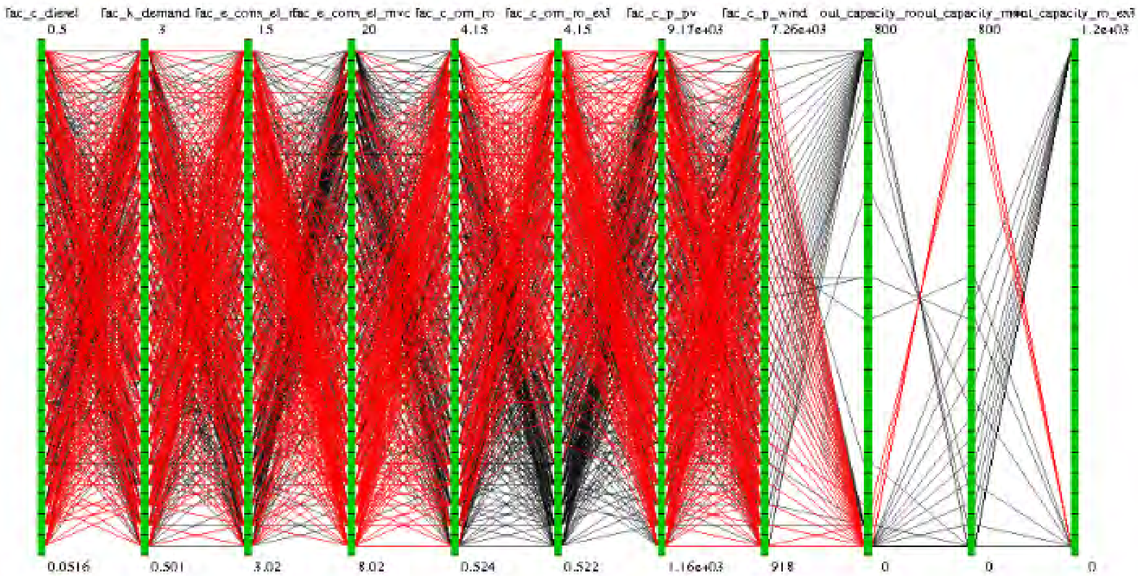

Fig. 6.18: *Selection pattern of desalination process: mechanical vapour compression (MVC)*

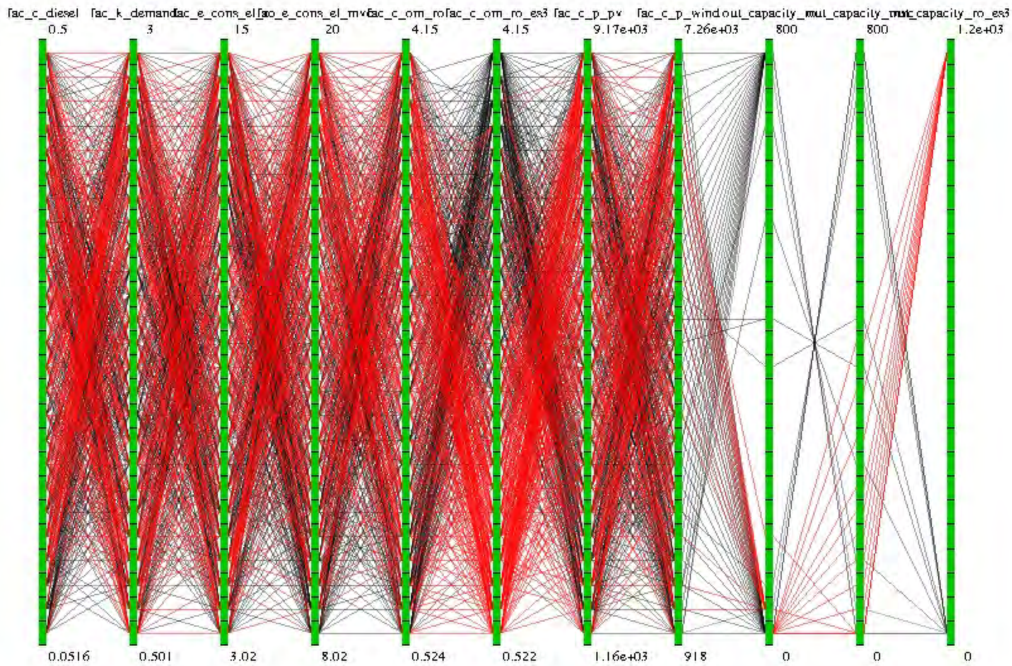

Fig. 6.19: *Selection pattern of desalination process: variable reverse osmosis (var-RO)*

In Fig. 6.18 the simulation runs using MVC as desalination process are selected and marked in red, located next to the last coordinate. Not all considered input and output factors are shown in the multi-dimensional coordinate system. For the ones that have been neglected no correlations could be identified. All considered factors (input parameters) are shown as one coordinate of the multi-dimensional coordinate system. Only the last three coordinates illustrate output variables: the installed capacities of the used desalination processes, RO, MVC and the variable operating RO system. Thermal desalination processes have never been part of the optimal solution. In all three cases the only relevant input parameters, affecting the choice of the desalination technology, are the energy consumption and the variable costs of each process. Between other input parameters no correlations could be identified.

What becomes obvious is that mechanical vapor compression is the optimal desalination process, when the energy consumption of MVC is very low, whereas the energy consumption of RO and var-RO is very high. Concerning the variable costs, neither the O&M costs of MVC itself, nor of the conventional RO-process are relevant. The choice of MVC as desalination process reacts most sensitive on the O&M costs of the variable operating reverse osmosis process. That means, MVC has only a chance to be the optimal desalination technology, if the O&M costs of the variable RO-plant were significantly higher than the currently assumed costs.

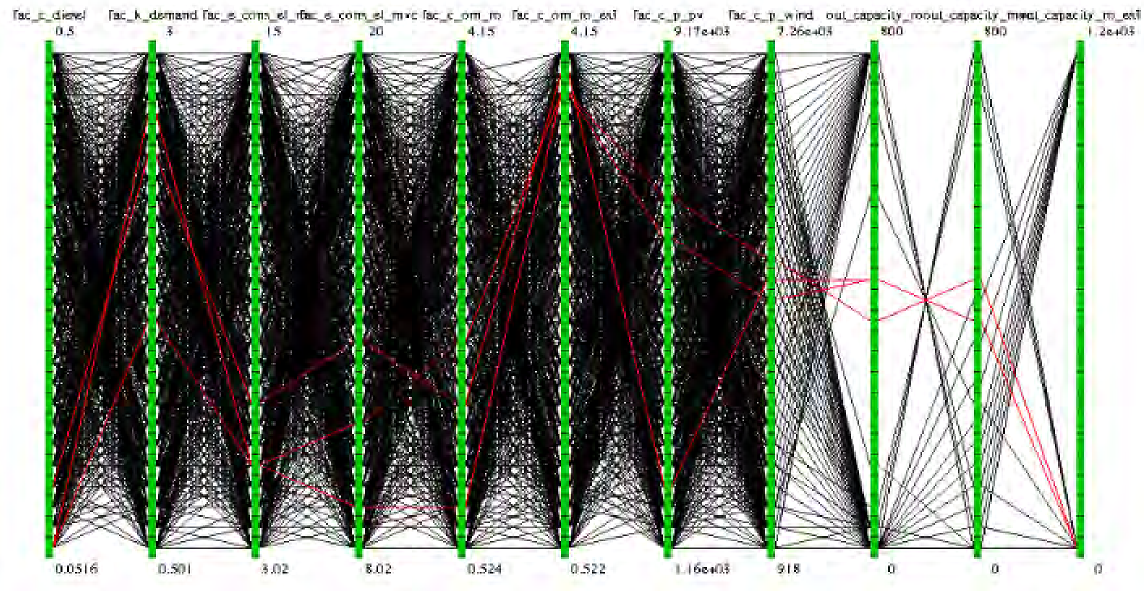

Fig. 6.20: *Selection pattern of desalination process: MVC and RO*

Selecting the runs, when RO is employed, no correlations are to be seen. Independently from all parameters that can be changed, RO seems to be robust in its factor space of optimality, although the distribution function showed, that without the weighted analysis it is used only in 15 % of all simulation runs, cf. Fig. 6.17.

In Fig. 6.19 the characteristics of a variable operating reverse osmosis desalination plant are looked at. The diagram highlights, that a variable RO process is employed, whenever its O&M costs are low. It can be the optimal solution under all conditions as long as its O&M costs do not exceed currently assumed costs of about 1 €/m^3 produced freshwater. This is a very clarifying result putting the conditions of optimality of variable desalination in a nutshell.

The very rare and special case of applying two desalination plants simultaneously is addressed in Fig. 6.20. This result appears just a few times and cannot be interpreted that easily. The only correlation is, that O&M costs of the variable RO-process are at maximum and that the power consumption of the RO and MVC process are relatively low, but not minimal. These results are interesting outliers but have no relevance for the overall results.

6.6 Economic reflection: Investment strategies based on the real option approach (ROA)

Since up to now no touristic development is planned on Brava and the main goal of the local government is to find ways to become more independent from fossil fuels and to increase their share of renewable energies, the uncertainty of the future oil price is considered by the following real option analysis. As described in the methodology chapter 3.5, the real option analysis is an alternative economic approach for evaluating optimal supply systems considering uncertainty. The goal is to determine, whether a statical optimal system still remains the optimal one, even when sensitive parameters are volatile or change significantly.

In this context a single parameter is considered separately and in more detail for guaranteeing transparency and measurability. As real option method the binomial lattice approach is chosen, without implementing it in a dynamic program, because this way intermediate values and decisions become visible. If the practicability can be verified, other sensitive and uncertain parameters can be included in a dynamic programming approach subsequently.

Figure 6.21 shows the results of a one-dimensional sensitivity analysis considering only the diesel price. In some cases relevant scenarios can be derived for the binomial decision tree approach.

Depending on various diesel price developments, for four various diesel prices optimal scenarios were identified, cf. Tab. 6.10. In all these scenarios conventional lead acid batteries to have the highest flexibility concerning the installed storage capacity. As analyzed before (cf. section 6.1) the optimal energy supply system including the energy demand of the desalination plant at current fuel prices of €0.7/liter consists out of three 275 kW wind turbines, a small capacity of PV modules (88 kW), one 800 kW diesel generator and LA batteries with a storage capacity of around 2500 kWh.

Scenario *BaU* (Business as Usual) describes the current system with power supply by diesel generators only. In scenario *Wind1* a smaller share of wind energy is installed (three WECs), in *Wind2* five WECs. In scenario *Wind1+PV* again three WECs are implemented but also a photovoltaic system with a nominal capacity of 800 kW_{peak}. It cannot be decided that easily, which scenario would be the most robust against oil price uncertainties. Each scenario is optimal for different constant fuel prices.

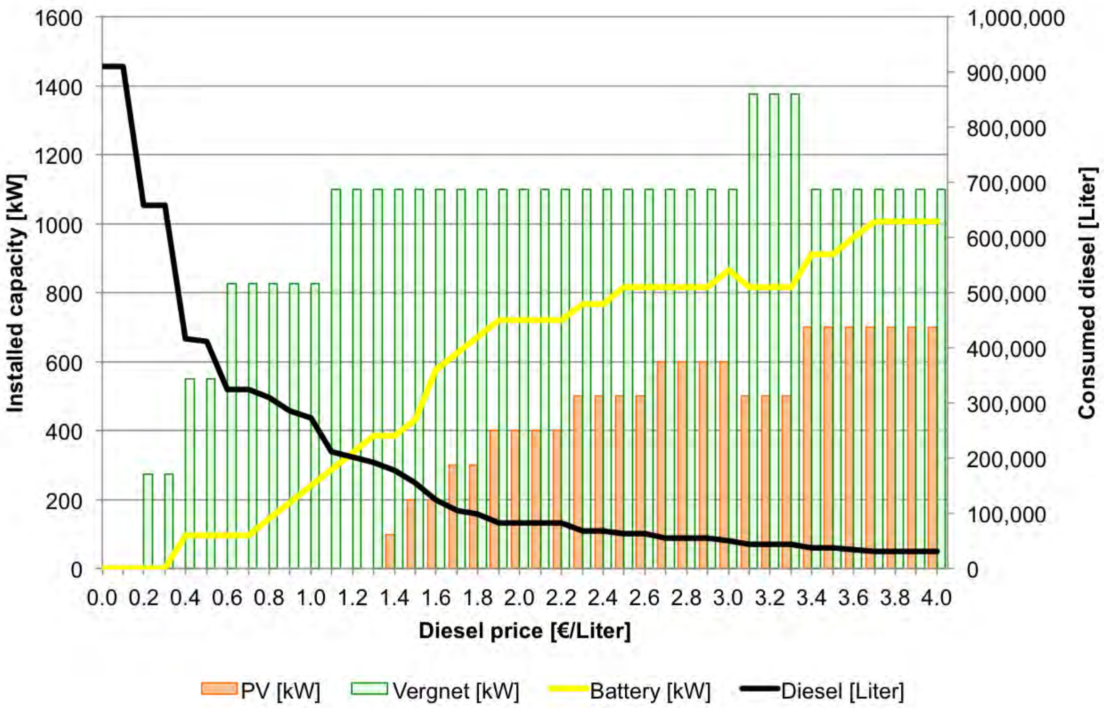

Fig. 6.21: *Results of sensitivity analysis considering the diesel price*

Tab. 6.10: *Supply system scenarios for the real option analysis*

Scenario	Wind [kW]	PV [kW]	Battery [kWh]	Diesel GenSet [kW]	Diesel cons. [1000 L]
BaU	-	-	-	800	910
Wind1	825	-	2,592	800	238
Wind2	1,375	-	4,320	800	102
Wind1+PV	825	800	4,896	800	65

Based on the binomial option valuation explained in chapter 3.5, a binomial decision tree with two steps is developed considering the four scenarios, cf. Fig. 6.22. For all scenarios it is defined, that investments are irreversible once they are executed. Components can only be added but not removed. An extension of the *BaU*-scenario, e.g. is always possible. A re-investment from scenario *Wind2* back to *Wind1* though, would not be possible within the real option analysis. Depending on the diesel price development (if it goes up or down), the decision tree evolves around the two decision points in the year zero and after ten years of the investment period. A fuel price increase of 4 % is assumed with a standard deviation of 0.054 per year [125].

In order to calculate the option value for a certain diesel price and deviation, the decision tree is calculated backwards. The cash-flows for each scenario are deter-

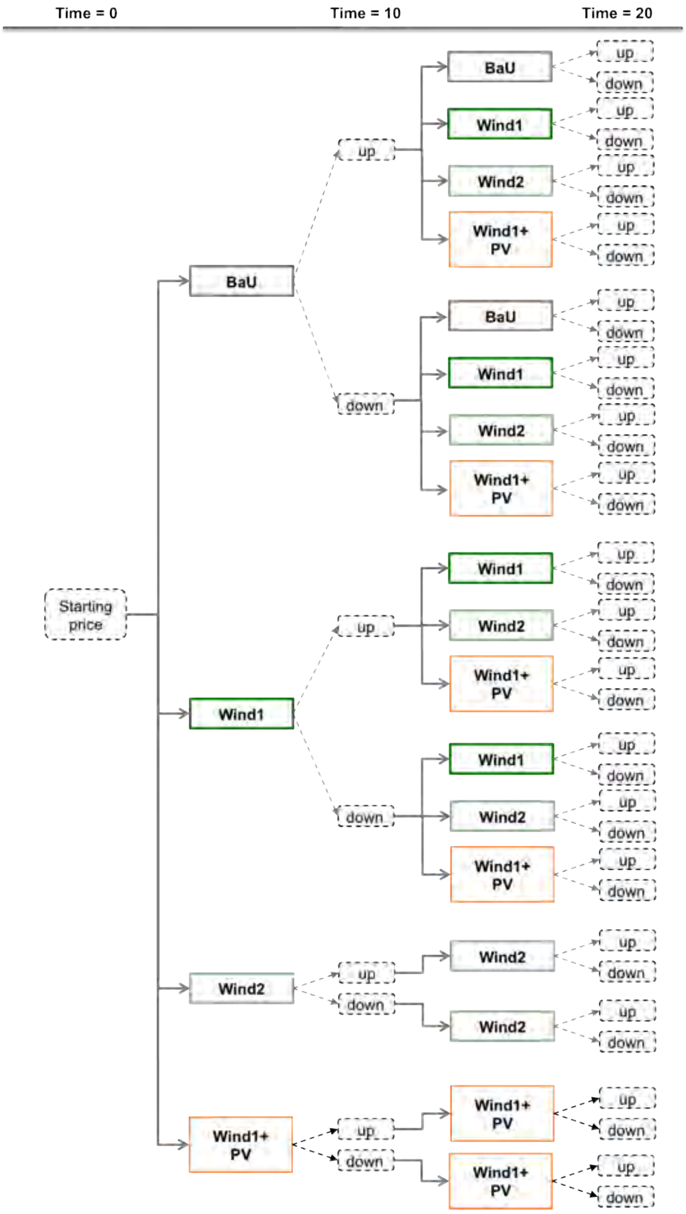

Fig. 6.22: *Two-step binomial decision tree of real option approach*

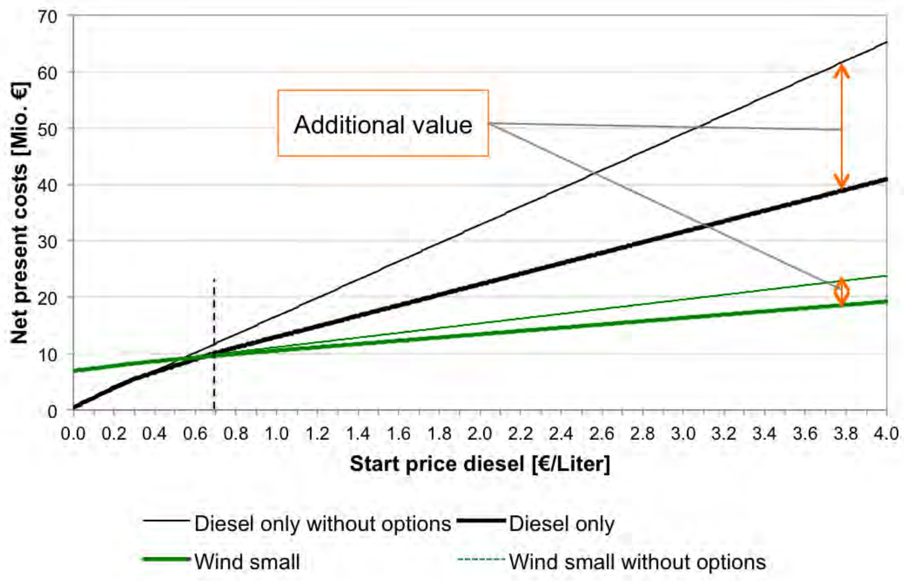

Fig. 6.23: *Comparison of costs without uncertainty with and without future options*

mined in respect to the matching diesel price from period twenty to period ten, and from ten to zero for the second decision point respectively. Detailed information concerning the calculation approach can be found in *Blechinger*'s description [126]. Benefits of the real option compared to the net present cost approach are recognizable in Fig. 6.23. Since only the two scenarios *BaU* and *Wind1* can be extended in later periods, these are the ones applied.

For identifying the best scenario and investment strategy at the beginning of the project and after ten years, the cash flows of each scenario are calculated for different fuel prices from 0 to 4 €/kWh with deviations from 0 to 0.1 to reflect a wide range of uncertain cases. This standard deviation means a hundred per cent variance leading to diesel prices of a quarter up to more than a tenfold. The results of the complex and not in detail discussed calculations are assembled in Fig. 6.24. It shows the optimality of the introduced scenarios as a function of diesel price volatility and the corresponding starting fuel price. The boxes recommend the investment proceeding at the beginning of the investment period.

The deviation of the fuel price has not any impact on scenario *BaU*, because from this status it is possible to react to any possible development. *Wind1* on the other hand, is favourable only because of the consideration of increasing deviations. That means that if the uncertainty and volatility of the oil price is assumed to be very high, the installation of only a few wind turbines can be profitable, although it would have never been part of an optimal solution without considering real options.

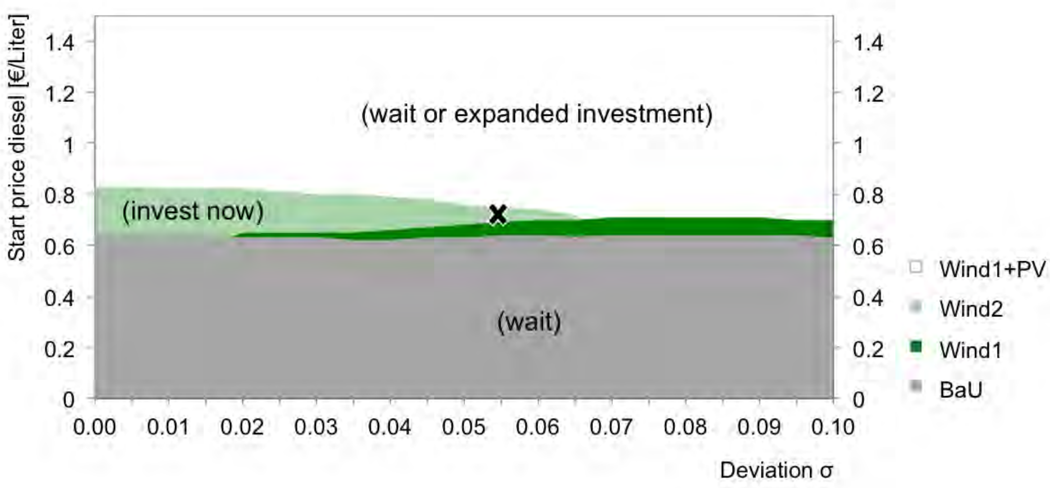

Fig. 6.24: *Result of real option approach for investment strategy*

Based on the current approach, marked with a cross in Fig. 6.24, the main question is, which volatility of the fuel price is assumed. High uncertainty would stand for investing only in a few wind turbines to keep the future option open to invest directly into photovoltaic systems after the first ten years (scenario *Wind1+PV*), low diesel price deviation would mean, to invest into a large wind farm (scenario *Wind2*). In theory, this would take away the chance of reinvesting into the *Wind1+PV* scenario. This is a decision, that needs to be made by governments, since not all background information are accessible.

6.7 Global reflection: Concepts for other islands

A scenario analysis has also been accomplished for additional islands: *Astypalia*, a Greek island in the Mediterranean Sea, *Petite Martinique*, one of the Grenada islands in the Caribbean Sea, and *Rotuma*, one of the Fiji islands in the Pacific ocean. Except Astypalia, all islands belong to the Small Island Developing States. Up to now, most of the research works concerning renewable energies and seawater desalination were accomplished for Greek islands, e.g. [46, 68, 103]. The simulation and analysis of Astypalia therefore was used as reference scenario to confirm the developed modeling and optimization approach.

Although the islands are located in different regions, they all have in common, that wind conditions are good or even very good, solar irradiation is high, the

Tab. 6.11: *Properties of other considered islands*

Island	Population	el. demand [MWh/day]	av. wind speed [m/s]	av. solar radiation [kWh/m^2/day]
Astypalia	1,200	18	6.1	4.6
Petite Martinique	1,000	2.2	7.7	6.6
Rotuma	2,000	1.7	5.2	5.0

current electricity supply is met by diesel generators and that all islands face water shortage problems either due to the lack of natural freshwater stocks or due to groundwater depletion. For all islands a scenario analysis was carried out, calculating energy supply systems with and without desalination and considering also variable desalination. Table 6.11 shows the relevant background information for each island. The energy demand presented in Tab. 6.11 contains only the electricity load on the island without considering the energy consumption of desalination.

The integration of renewable energies compared to the current electricity supply by diesel generators only is beneficial for all islands. The optimal supply system differs merely in the constellation of the components. Taking into account also the energy consumption of desalination, the optimal supply system in Astypalia consists out of a wind-PV-battery-diesel-system and the one in Petite Martinique of a wind-battery-diesel-system. For both the advantage of employing a variable operating desalination plant could be proven with using about 60 to 70 % of surplus wind energy and minimizing the dump load. On Rotuma the result differs. First of all, the energy demand on the island is significantly lower than on the other two islands and the inhabitants live in little villages, were decentralized photovoltaic solar panels have a higher impact to a cheaper price than to construct a new and robust electricity grid. Secondly Rotuma has a lot of coconut plantations and more coconuts than they use domestically. In addition to exports the energetic use of coconut oil offers the highest potential of diesel oil consumption, which is expensively imported. The reason for the freshwater shortage in Rotuma is the overuse of wells near to coastlines, where seawater streams make groundwater salty and unfit for human consumption. Rainwater harvesting and decentralized water filtrations seems to be a more constructive solution than implementing a centralized electricity grid with a centralized desalination plant.

Overall, the presented results for the Cape Verde island Brava can be confirmed by islands with comparable properties and are transferable to remote arid regions in a global perspective.

Chapter 7

Conclusions

7.1 Summary and conclusions

Using the modeling system GAMS a model for optimizing self-sufficient energy and water supply systems for remote regions has been developed. The central motivation of the research work has been to answer questions related to the following questions:

- How do various electricity storage technologies influence the optimal energy and water supply system?
- What effect does the integration of a deferrable desalination unit have on the system setup?
- How do changes of the diesel price, the energy demand or prices of components affect the system design?

Since no available model is able to answer these and related questions, an energy supply with integrated seawater desalination units is modeled and programmed. The model focuses on remote regions, where isolated island grids are in use. Basics of energy engineering and water supply are introduced and the Cape Verde island Brava identified as case study. Hourly measured data of one year are the base for realistic simulation results. Energy systems considering various generation technologies, energy storages and desalination processes are calculated, compared and a sensitivity analysis employed. In order to determine the robustness of a system, a global sensitivity analysis is applied using the simulation environment SimEnv within the GAMS model.

The effects of varying desalination processes and varying energy storage systems have been analyzed and discussed in detail. Focussing on the respective research objectives a number of results can be concluded:

The integration of renewable energies is beneficial in considered island grids.

The integration of renewable energy technologies to the current energy supply system on the investigated island is beneficial from an economic as well as from an ecological perspective even without considering freshwater production. The optimal energy supply system (at current conditions) is a hybrid wind-diesel-battery system. In case of increasing fuel prices and increasing energy consumption, the implementation of photovoltaics and concentrated solar power technologies would be beneficial, as the sensitivity analysis has shown. The current demand could be met with electricity prices of 0.21 €/kWh instead of 0.31 €/kWh for the investment period of twenty years. About 1 MW wind energy capacity should be installed on the Cape Verde island independently from any fuel price or demand change. Depending on the development strategy of the local government, additional photovoltaic capacities may be installed in case of enhancements, e.g. due to growing tourism.

The optimal energy and water supply system at current conditions is a wind-diesel-battery system with a reverse osmosis-desalination unit.

Integrating desalination to the island grid the optimal system, cf. section 6.2, consists out of four 275 kW Vergnet wind turbines, a diesel generator with the capacity of 800 kW_{el} and a sodium-sulphur battery with the peak discharge power of 1 MW and a storage capacity of 7.2 MWh. The desalination technology chosen within the optimization process is a conventional, constantly operating reverse osmosis unit producing 800 m^3 fresh water per day with an energy consumption of 4 kWh/m^3. The overall costs of the system are about 12.6 million Euros. With the assumption of constant diesel prices electricity costs could be kept on the level of 0.16 €/kWh and water costs at 1.53 €/m^3 for the period of twenty years.

The choice of the electricity storage system can change optimal capacities and components.

Depending on the energy storage technology used, the installed capacities of all components and the hourly dispatch behaviours change, and even PV systems can be part of the optimal solution. The lowest overall system costs can be reached by using pumped-hydro-storage systems or engine-coupled-hydrogen-storages. These two technologies though, are not applicable on Brava and hence the third optimal solution is employed, which is a sodium-sulphur battery bank. However, pumped-hydro and hydrogen storage devices should be considered for comparable island grids, where geographical requirements are given and higher demand loads need to be met.

A variable operating desalination unit can minimize the fuel consumption, dump load, energy storage capacity and specific electricity and water costs within an island grid.
Key findings of the scenario analysis are that the benefits of desalination as deferrable load in an island grid are:

- better capacity utilization of the fossil fuel-powered diesel generator engine,
- 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 levelized costs of electricity and water.

These results can be derived depending on the considered battery and dispatch strategy and can furthermore be proven by calculations also for the Caribbean island Petite Martinique [69]. Thermal desalination processes are never part of the optimal solution for the considered Cape Verde island. Only electrical processes as reverse osmosis and mechanical vapour compression are chosen within the optimization approach. Benefits for the energy grid could be shown by introducing the deferrable load as energy sink. The contribution to grid stability could not be proven and is beyond the scope of the work. To highlight effects of desalination as deferrable load in terms of frequency stabilization, an analysis with a higher temporal resolution (e.g. per seconds) is required. Results of such a research approach will be available soon in the dissertation accomplished by *Pohl*, cf. [54].

The membranes of the variable operating reverse osmosis desalination unit are able to tolerate occurring pressure changes.
Requirements of a flexible operating desalination plant have been determined based on analyzing the time series of the island Brava [57]. Interruptions of the energy supply as well as pressure changes up to 0.7 bar/s can theoretically be tolerated by the RO unit without damaging the modules and increasing operational costs. Nevertheless, an increase of the O&M costs above the assumed 1 €/m^3 makes variable desalination inefficient, at least in the framework of this study.

Depending on the considered electricity storage system, a variable operating reverse osmosis unit is the optimal desalination process in the given case.
Using most electricity storage systems, a variable operating desalination load is beneficial. For the lead-acid batteries an example has been presented, how a flexible RO unit disburdens diesel generators and batteries and adapts to load changes

dynamically. In combination with a NaS-battery a conventional RO-system is recommendable, because the battery has a very high minimal installed capacity and can deal with most load and even frequency changes. For almost all other electricity storage technologies demand side management is highly recommended. Within the model the variable RO unit is not always the optimal desalination process, because for guaranteeing the flexibility the capacity is up to 50 % higher than the one of the considered constantly operating RO plant. The higher costs due to this overcapacity are penalizing the variable system. At the same time it needs to be mentioned, that exactly this overcapacity allows more flexibility for future increases of the water demand. A decision of whether or not desalination as deferrable load should be implemented, is not only a technological and economic question, but also a strategic one. Variable operating desalination plants lead to lower fuel consumptions. For the current demand structure on Brava the conventional RO-desalination system is the optimal solution. The local sensitivity analysis has shown, that it is a robust optimum in the proximity of one per cent of relevant parameters. Of course, the installation of a desalination plant is only the optimal solution, if freshwater imports would be transported from the mainland. As soon as desalination capacities from neighbouring islands suffice to meet the demand of Brava as well, such a low-distance-import would be the most profitable water supply option.

Demand, diesel price as well as investment costs of wind energy converters and photovoltaic systems are the most sensitive parameters.
Next to these four parameters out of the sixteen that have been investigated in more detail, for the choice of desalination processes the energy consumptions and the O&M costs of each process are the most sensitive parameters. Except for the thermal processes, all electrical driven ones are represented within the solution space. It could be shown, that in the given case the installation of wind energy converters is always beneficial. Depending on the demand development and fuel prices, photovoltaic systems are the second best solution of installation. Small scale concentrated solar power technologies are implemented by the model as well, but not in the proximity of the optimal solution.

The global sensitivity analysis has shown a number of dependencies that were not clearly definable in advance.
Concerning the energy supply system it can be derived, that the implementation of wind converters is always beneficial, no matter how the external effects change. As long as the demand does not increase significantly aiming at keeping fuel consumption and energy storage capacities low, large scale PV-installations should be

avoided, since the installed capacity of ESS correlates with the installed capacity of PV and/or with the diesel consumption. A decentralized implementation of PV systems seems to be more profitable, since electricity demand can be minimized periodically without requiring additional centralized storage capacities. In case of significant energy demand increases, the additional installation of concentrated solar power capacity is recommendable, as can be concluded from the global sensitivity analysis.

The real option analysis applied is able to determine the robustness of a system facing the uncertainty of oil price developments.
The sensitivity and the real option analyses answer different questions. The global sensitivity analysis determines the optimal supply system for a given scenario considering specific impact factors, whereas the simplified real option approach applied can be used as decision tool between apparently indifferent supply scenarios. The uncertainty of a single specific parameter has been taken into account. Depending on the assumed volatility of the parameter, the most robust scenario can be determined for the entire investment period by considering the option to invest later as value, allowing to reinvest in a later period. Real options can help as decision tool if decision makers have assumptions concerning the volatility of considered impact factors.

The developed model is adaptive to varying input data and other case studies.
Geographical data, renewable energy potentials, demand structures as well as all technological and economic data can be applied to other regions and are also adjustable to alternative circumstances, if required. Detailed information concerning the structure of the model can be found in Appendix A.

7.2 Recommendations for further research

Although the interest in mid-scale desalination powered by renewable energies is large on the global market, the effects of desalination in an intermittent operation are still not available in real case projects. In theory it has been shown, that desalination (variable reverse osmosis) as deferrable load is beneficial in a micro-grid. But advantages of a variable operation depend significantly on the technical feasibility of realizing the presented energy consumptions and operation and maintenance costs. The question, whether seawater desalination can contribute as a deferrable load and storage technology to an electricity grid, is one that needs a confirmation by practical research. Finally a variable operating pilot plant has to be implemented operating load profile based on fluctuating energy sources. The company Synlift Systems GmbH is working on the installation of such an intermittent operating reverse osmosis desalination plant, which is supposed to approve calculated operation modes, energy consumptions and the robustness of the membranes.

It would also be interesting from an economic perspective, if volatile energy prices would enhance deferrable load. Related to this question is, whether a deferrable load of less than ten per cent of a primary load is large enough to be of interest for electricity systems with a high share of fluctuating renewable energy sources. Since the model simulates energy and water flows in an hourly resolution, dispatch strategies for battery-diesel-desalination behaviour cannot be derived. More detailed analysis in the range of minutes or even seconds would be required.

Not modeled and discussed, but decisive, is the local availability of reliable power grids. Integrating the power grid into the model would be a beneficial further development.

Concerning environmental costs the model could be used much more as a techno-economic-ecological decision tool than it has been done in the framework of this study. Although emission trading is hardly applicable to small islands, prices of CO_2 equivalents, costs of land-use, data from life cycle assessments for most technological components may be determined.

The global sensitivity analysis using SimEnv, as a somewhat oversized analysis tool for the given case, should be applied for other cases as well. The real option analysis should be developed, taking into consideration more than one of the unverified parameters. This could either be programmed as a quadrinomial decision tree, if one additional input parameter is looked at, or by even larger decision trees using an own developed or commercially available program.

Concerning the presented research work it needs to be clarified, that technological restrictions, high electricity or high water costs are hardly ever the main drawbacks of investigated concepts and configurations. High initial investment costs are a significant barrier, but even if they were carried by external investors, political and administrative aspects may inherit the implementation of new infrastructure systems. Often common law, privileges, pegged territories and subventions interfere with the project plan. Limitations within the education and transportation are also common difficulties realizing new energy and water supply strategies. These and further limits for implementing renewable energy supply systems in remote regions are going to be addressed in ongoing research projects, e.g. by *Blechinger*.

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Appendix A

Model Script

```
$TITLE     Techno-economic optimization model autonomous island
*-------------------------------------------------------
*           by KRISTINA BOGNAR and GABRIELE CALVO
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*-------------------------------------------------------
$oneolcom
$eolcom ##

*-------------------------------------------------------
*          MENU TO CONTROL THE MODEL SCENARIO
*-------------------------------------------------------
option MIP=osicplex;

Scalar
RunEstimate       0 if no - 1 if yes /0/
*         Runs the estimate part of 03_Bounderies in order to find
*         fast a first non-optimal solution where to start from

RunFromLastSave   0 if no - 1 if yes /0/
*         Start from the "LastSave.gdx" that was saved in the same
*         directory (manually by renaming the outcoming gdx file
*         TechnoEconOptimization_p.gdx). If RunEstimate=1, this is set to 0.

PrintXLS          0 if no - 1 if yes /0/
*         Toggles the possibility to create a Output.xls file

Consider_CSP          0 if no - 1 if yes /1/
*         Considers CSP subsystems in the model

Consider_ESS          0 if no - 1 if yes /1/
*         Considers ESS subsystems in the

Consider_Desal_ES3    0 if no - 1 if yes /1/
*         Considers the deferrable desalination input plants

Consider_Desal_ES2    0 if no - 1 if yes /1/
*         Considers the fixed desalination input plants
;
*--------------------------------------------------------------------------*



*_______________________SECONDARY AUTOMATIC SWITCHES______________________*
Scalar
 Consider_Desal    0 means no desalination - 1 means at least one kind of des»
al
;
Consider_Desal = 0 + 1$(Consider_Desal_ES2 eq 1 or Consider_Desal_ES3 eq 1);
RunFromLastSave$(RunEstimate eq 1) = 0;
*--------------------------------------------------------------------------*


$include 02_Demand.gms
*$include 02_Demand_TEST.gms
$include 01_Data.gms

*_____________________DECISION VARIABLES OF THE SYSTEM___________________*
Positive VARIABLEs
*                  ..:PHOTOVOLTAIC decision variable:..
P_PV(tech_PV)               kW    :Installed peak power for each PV technolo»
gy
*                  ..:CONCENTRATED SOLAR decision variable:..
P_CSP(tech_CSP)             kW    :Installed rated power for each CSP techno»
```

```
logy
*                    ..:WIND decision variable:..
P_W(tech_W)                   kW    :Installed rated power for each wind techn»
ology
*                    ..:EES decision variables:..
P_ess(tech_ess)               kW    :Rated power installed of each ess tech
E_ess(tech_ess)               kWh   :Rated capacity installed of each ess tech
*                    ..:Desal decision variables:..
Capacity_Desal(tech_Desal_tot)   m^3\d :Desalination capacity of each desalin»
ation tech
*                    ..:Thermal Storage decision variables:..
E_tss(tech_tss)               kWh   :Rated capacity installed of each thermal »
storage
*                    ..:Water Storage decision variables:..
V_wss(tech_wss)               m^3   :Water storage size
;
*-------------------------------------------------------------------------*

*_______________________DEFINING DUMPED ENERGY VARIABLES__________________*
Positive VARIABLEs
         Dump_el(t)       kWh   :Electrical wasted flux
         Dump_th(t)       kWh   :Thermal wasted flux
;
*------------------------------------------------------

*-----------------------.::INCLUDING OTHER FILES::.-----------------------*
$include 03_Bounderies.gms
$include 04_Renewables.gms
$include 05_Diesel.gms
$include 06_Desal.gms
$include 07_Storages.gms
$include 08_Optimization.gms
$include 09_Output.gms
$include 10_Output_SimEnv.gms

```

```
*----------------------------GENERAL MODEL DATA-----------------------------*
*---------------------------------------------------------------------------*
* For the SENSITIVITY ANALYSIS a big part of the model will not be used, in order to
* minimize computational capacity (under 3.5 GB RAM instead of current 4.8 GB)
*---------------------------------------------------------------------------*

SCALARs
*  General infos
         Tot_life                   y       :Life of the whole project
         Act_factor                 -       :The actualization factor for yearly expenses to convert in "year zero" money
         interest_rate              -       :interest rate of the project          /0.05/
         c_fuel                     €\kWh_f :Cost of fuel for CAES                 /0.0622/
         c_diesel                   €\kWh_f :Cost of fuel for Diesel               /0.0722/
*  0.7 €/liter, divided by 9.7 kWh/liter [Zittel and Wurster]
         c_CO2                      €\tCO2  :Cost of the CO2                       /20/
         c_land                     €\m^2   :Cost of the land on the island        /30/
         CO2_from_diesel            tCO2\kWh_f  :Amount of CO2_eq coming out from 1 kWh_diesel for diesel gen.    /0.000248498/
*  3,15 kg CO2-eq per Liter Diesel.
         CO2_from_fuel              tCO2\kWh_f  :Amount of CO2_eq coming out from 1 kWh_fuel for CAES (natural gas) /0.000178848/
         Height_anemometer          m :Height of the measuring anemometer          /10/
         Roughness                  m :Roughness index of the ground nearby        /0.0002/
         k_reserve                  - :Spinning reserve coeff to be sure to meet the load   /0.15/
         k_land_PV                  - :Multiplier to take into account structures and aux systems on land impact   /1.5/
         diesel_m_coeff             kW_f\kW_e  :Angular Coefficient of the linear approximation of the diesel curve         /2.44625/
         diesel_q_coeff             kW_f       :Abscissa Interseption of the linear approximation of the diesel curve       /95.7/
         RO_ES3_m_coeff             m^3\kW_e  :Angular Coefficient of the linear approximation of the deferrable RO curve   /0.5/
         RO_ES3_q_coeff             m^3\kW_e  :Abscissa Interseption of the linear approximation of the deferrable RO curve /-50/
         RO_ES3_maxP                kW_f      :Maximum power for RO (at k_desal=1)   /200/
         RO_ES3_minP                kW_f      :Minimum power for RO (at k_desal=1)   /133.33/
         min_diesel_load            - :Minimum load that the diesel generator can support   /0.3/
         Bignumber                  - :Number used in the mutually exclusive constriant     /10000000000/
*   It must be bigger than max value reachable by the excluded variables

* FACTORS added for the sensitivity analysis with SimEnv
         k_desal                    Factor for changing minP and maxP (energy consumption) of the deferrable desalination  /1/ ## included in 06_Desal.gms
         k_ess                      Factor for changing the costs of each ess technology                                  /1/ ## included in 07_Storages.gms
         k_demand                   Factor for changing the energy demand of each hour in the year                        /1/ ## included in 08_Optimization.gms
;
```

```
Tot_life = card(y);
Act_factor = sum(y,(1/(1+interest_rate))**(ord(y)));

SCALAR
         Industry_waste_heat          kWh   :The waste heat coming out of an hypotetic industry nearby   /0/
;


*----------------------------TECHNOLOGIES' DATA-----------------------------*
*---------------------------------------------------------------------------*
SETs
 tech_PV          /c-Si,a-Si,CdTe/
 prop_PV          /eta,Deration,c_P,M_om,land_use,minP,maxP,Resources,Emission_LCA/   ## @@ 2 methods to calculate land use in conflict
 tech_W           /Norwin225,Gyro10K,Vergnet275/
 prop_W           /coeff1*coeff7,P_nom,P_max_out,V_cut_in,V_flat,V_cut_off,Hub_height,c_P,M_om,land_use,minP,maxP,Resources,Emission_LCA/    ## for land_use I have 3.497
 tech_CSP         /Parabolic,SolarTower,Fresnel,Dish,ORC/
 prop_CSP         /eta_el,eta_th,Deration,c_P,M_om,land_use,minP,maxP,Resources,Emission_LCA/
 tech_ess         /LA_flood,NiCd,NaS,CAES_above,ZnBr,Li-ion,V-redox/    ## Regensys out
*                 before /LA_flood,VRLA,NiCd,NaS,CAES_under,CAES_above,PHS,PHS_as,ZnBr,Li-ion,V-redox,HS-flywheel,H2-PEMFC,H2-Engine/
 prop_ess         /c_P,c_E,eta,c_r_P,c_r_E,life,DOD,fuel_cons,OandM,Losses,land_use,H_autonomy,minP,maxP,Resources/  ## CO2_from_ESS not considered due to lack of data
 tech_diesel      /Caterpillar1,Caterpillar2/
 prop_diesel      /P_nom,c_P,eta_th,c_om,land_use,Resources,Emission_LCA/
 tech_Desal_tot   /HDH,MED,MD,MVC,RO,RO_ES3/
 tech_Desal_ES2(tech_Desal_tot)  /HDH,MED,MD,MVC,RO/
 tech_Desal_ES3(tech_Desal_tot)  /RO_ES3/
 prop_Desal       /E_cons_th,E_cons_el,c_plant,c_om,land_use,minCap,maxCap,Resources/           ## @@ LCA-CO2-emissions_from_Desal not considered
 tech_tss         /TS1/
 prop_tss         /spec_cost,eta,OandM,Losses,land_use,minE,maxE,Resources/
 tech_wss         /WS1/
 prop_wss         /spec_cost, land_use, minV, maxV, Resources/
;
TABLE Data_PV(tech_PV,prop_PV)    Data for PV systems
               eta          Deration      c_P           M_om        land_use         minP          maxP         Resources      Emission_LCA
  c-Si         0.16         0.8           2443          0.015       7.607            0             10000        0              1.4303
  a-Si         0.09         0.8           2000          0.02        7.607            0             10000        0              1.4303
  CdTe         0.11         0.8           2105          0.02        7.607            0             10000        0              1.4303
* Units        -            -             €/kW          -           m^2/kW_el        kW            kW           €/kW           tCO2/kW
;
TABLE Data_W(tech_W,prop_W)   Data for W systems
              coeff1       coeff2       coeff3       coeff4       coeff5       coeff6       coeff7       P_nom        P_max_out    V_cut_in     V_flat       V_cut_off    Hub_height   c_P          M_om         land_use     minP         maxP        Resources      Emission_LCA
 Norwin225    1.644E-05    -2.095E-03   1.065E-01    -2.674E+00   3.297E+01    -1.617E+02   2.668E+02    225          228          4            999          25           30           2051         0.02         0.93         0            100000      0              0.4274
 Gyro10K      3.949E-05    -2.406E-03   5.381E-02    -5.745E-01   3.233E+00    -8.928E+00   9.390E+00    10           12           3.5          14
```

```
  24.6          11            6278          0.01          0.93          0          1»
00000      0             0.4274
 Vergnet275   1.321E-03    -5.872E-02   9.616E-01    -7.406E+00    3.143E+01    »
  -6.602E+01   5.005E+01    275           275           3.5           13           »
  20            55            1818          0.02          0.93          0          1»
00000      0             0.4274
*Units        kW/(m/s)^6    kW/(m/s)^5    kW/(m/s)^4    kW/(m/s)^3    kW/(m/s)^2    »
 kW/(m/s)^1    kW            kW            kW            m/s           m/s           »
  m/s           m             €/kW          -             m^2/kW        kW          k»
W          €/kW            tCO2/kW
;
TABLE Data_CSP(tech_CSP,prop_CSP)    Data for CSP systems
              eta_el        eta_th        Deration      c_P           M_om          »
  land_use      minP          maxP        Resources   Emission_LCA
 Parabolic    0.141         0.38          0.9           5450          71.5          »
  11.04         10000         100000     0           0.000070
 SolarTower   0.138         0.40          0.9           6288          133.3         »
  12.39         10000         100000     0           0.000046
 Fresnel      0.1           0.32          0.9           2033          110.4         »
  8.62          10000         100000     0           0.000025
 Dish         0.167         0.65          0.9           8035          103           »
  25            10            100000     0           0.000025
 ORC          0.07          0.38          0.9           2538          100           »
  35            10            100000     0           0.000046
*Units        -             -             -             €/kW_el       €/kW/y        »
  m^2/kW_el     kW            kW          €/kW         tCO2/kW
;

TABLE Data_ess(tech_ess,prop_ess)    Data for ess systems
              c_P           c_E           eta           c_r_P         c_r_E         »
  life          DOD           fuel_cons     OandM         Losses        land_use    »
    H_autonomy    minP     maxP     Resources
 LA_flood     195.973       130.649       0.75          0             130.649       »
  6             0.75          0             15            8.333E-07     5.760E-02 »
          4        0        100000   0
*VRLA         195.973       174.199       0.75          0             174.199       »
  5             0.75          0             5             8.333E-07     5.760E-02 »
          4        0        100000   0
 NiCd         195.973       522.596       0.65          0             522.596       »
  10            1             0             25            1.667E-06     4.200E-02 »
          4        0        100000   0
 NaS          130.649       217.748       0.7           0             200.328       »
  15            1             0             20            8.342E-05     3.716E-02 »
          7.2      1000     100000   0
*Regenesys    239.523       130.649       0.65          130.649       0             »
  10            1             0             15            0.000E+00     8.806E-03 »
          4        0        100000   0     (company doesn't exist anymore, bought »
by RWE, source Nicolai Strauch)
*CAES_under   370.172       46.163        0.73          0             0             »
  30            0.625         1.2914        2.5           0.000E+00     1.022E-01 »
          8        10000    100000   0
 CAES_above   522.596       104.519       0.79          0             0             »
  30            0.625         1.2914        10            0.000E+00     2.137E-01 »
          8        50       100000   0
*PHS          870.993       12.194        0.75          0             0             »
  50            0.95          0             2.5           0.000E+00     1.858E-01 »
          8        1000     100000   0
 PHS_as       914.542       12.194        0.78          0             0             »
  50            0.95          0             2.5           0.000E+00     1.858E-01 »
          8        1000     100000   0
 ZnBr         152.424       348.397       0.6           0             87.099        »
  8             1             0             20            0.000E+00     2.323E-02 »
          4        0        100000   0
 Li-ion       152.424       435.496       0.85          0             435.496       »
```

```
 10          0.8          0            25           8.333E-07    1.000E-02 »
       4        0        100000   0
 V-redox      178.553      522.596      0.7          0            522.596      »
 10          1            0            20           0.000E+00    3.716E-02 »
       4        0        100000   0
*HS-flywheel  261.298      870.993      0.95         0            0            »
 15          0.775        0            67           4.188E-04    3.252E-01 »
       1        0        100000   0
 H2-PEMFC     1567.787     13.065       0.531        130.649      0            »
 6           0.9          0            3.8          0.000E+00    4.181E-02 »
       4        0        100000   0
 H2-Engine    261.298      13.065       0.44         95.809       0            »
 6           0.9          0            2.5          0.000E+00    5.110E-03 »
       4        0        100000   0
*Units        €/kW         €/kWh        -            €/kW         €/kWh        »
 y           -            kWh_f/kWh_e  €/kW/y       1/h          m^2/kWh_el»
       h        kW       kW       €/kW
;
TABLE Data_diesel(tech_diesel,prop_diesel)    Data for diesel systems
              P_nom        c_P          eta_th       c_om         land_use     »
    Resources        Emission_LCA
 Caterpillar1 800          270          0.6          0.01         0.02         »
    0                0.2179
 Caterpillar2 800          270          0.6          0.01         0.02         »
    0                0.2179
*Units        kW           €/kW         -            €/kWh        m^2/kW       »
    €/kW             tCO2/kW
;

TABLE Data_Desal(tech_Desal_tot,prop_Desal)    Data for Desal systems
              E_cons_th    E_cons_el    c_plant      c_om         land_use     »
 minCap       maxCap       Resources
 HDH          100          2.4          3000         0.18         0.6          »
 50           1000         0
 MED          110          1.7          3400         0.16         0.2          »
 50           1000         0
 MD           175          0.1          5000         0.2          0.3          »
 50           1000         0
 MVC          0            11           2350         0.29         0.3          »
 50           1000         0
 RO           0            4            2000         1.0385       0.3          »
 50           1000         0
 RO_ES3                                 2200         1.0385       0.3
*Units        kWh/m^3      kWh/m^3      €/(m^3/d)    €/m^3        m^2/(m^3/d)»
 m^3/d        m^3/d        €/(m^3/d)
## About RO_ES3: E_cons is calculated in 06_Desal.gms, here only the costs ar»
e defined
;

TABLE Data_tss(tech_tss,prop_tss)    Data for tss systems
             spec_cost    eta          OandM        Losses       land_use     »
 minE         maxE         Resources
TS1          115          0.9          5            0.00001      0            »
 0            100000       0
*Units       €/kWh        -            €/kWh/y      1/h          m^2/kWh_th   »
 kWh          kWh          €/kWh
;

TABLE Data_wss(tech_wss,prop_wss)    Data for wss systems
             spec_cost    land_use     minV         maxV         Resources
WS1          90           0.5          0            10000        0
*Units       €\m^3        m^2\m^3      €/m^3        €/m^3        €/m^3
;
```

```
*-----------------------------------DEMAND-------------------------------*
$ontext
  This part of the program sets:
  - The electric load for each hour
  - The water demand for each day
  - The hourly renewable potential in terms of solar irradiance and wind velocity
$offtext

*________________________________TIME SETS_______________________________*
SETs
         t  hour time set
                 /t1*t8760/
         d  days of the year (used for the water supply)
                 /d1*d365/
         y  years of the total project (discounted time)
                 /y1*y20/
;

*-------------------------------------------------------------------------*
*------------------------------..::DEMANDS::..----------------------------*
*-------------------------------------------------------------------------*

PARAMETERs
     Load(t)     kWh\h    :Hourly electric energy load of the island
        /t1         195.424
         t2         190.178
         t3         240.134
         t4         293.56
         t5         346.628
         t6         338.749
         t7         296.823
         t8         304.024
         t9         290.7
         t10        336.526
         t11        279.706
         t12        354.006
         t13        337.137
         t14        311.186
         t15        251.003
         t16        158.974
         t17        221.975
         t18        226.688
         t19        539.537
         t20        538.341
         t21        511.504
         t22        463.221
         t23        291.312
         t24        278.377
         t25        189.654
         t26        159.293
         t27        84.191
         t28        215.824
         t29        162.705
         t30        181.736
         t31        172.913
         t32        211.409
         t33        195.335
         t34        206.314
         t35        164.336
         t36        192.949
         t37        230.659
         t38        255.985
         t39        217.915
```

64	t40	149.429
65	t41	166.735
66	t42	214.94
67	t43	285.186
68	t44	344.851
69	t45	342.128
70	t46	225.932
71	t47	189.405
72	t48	235.196
73	t49	233.127
74	t50	185.557
75	t51	188.626
76	t52	260.33
77	t53	278.788
78	t54	312.274
79	t55	276.516
80	t56	237.264
81	t57	277.27
82	t58	303.555
83	t59	273.142
84	t60	358.441
85	t61	268.698
86	t62	274.392
87	t63	224.468
88	t64	222.718
89	t65	214.44
90	t66	322.154
91	t67	527.342
92	t68	389.01
93	t69	453.253
94	t70	403.731
95	t71	380.326
96	t72	304.502
97	t73	182.454
98	t74	236.485
99	t75	220.288
100	t76	178.402
101	t77	194.537
102	t78	231.532
103	t79	279.736
104	t80	208.956
105	t81	213.735
106	t82	211.385
107	t83	330.49
108	t84	278.365
109	t85	234.232
110	t86	255.418
111	t87	232.148
112	t88	170.747
113	t89	135.448
114	t90	201.819
115	t91	506.667
116	t92	443.504
117	t93	352.518
118	t94	358.757
119	t95	296.324
120	t96	266.886
121	t97	145.055
122	t98	173.026
123	t99	157.388
124	t100	231.021
125	t101	184.121
126	t102	259.534
127	t103	202.608

```
        t8744     259.624
        t8745     252.764
        t8746     294.054
        t8747     309.254
        t8748     176.248
        t8749     291.225
        t8750     281.174
        t8751     244.528
        t8752     310.246
        t8753     236.526
        t8754     280.518
        t8755     516.816
        t8756     507.19
        t8757     483.84
        t8758     349.617
        t8759     374.79
        t8760     238.389/

    Water_demand(d)      m^3\d   :Daily water demand of the island
        /set.d 800/
;


*--------------------------------------------------------------------------*
*---------------------------..::POTENTIALS::..-----------------------------*
*--------------------------------------------------------------------------*

SET
    meteo_type              type of meteorologic data
        /solar_radiation, wind_speed/
;
TABLE
Potentials(t, meteo_type)            solar and wind potentials
                            solar_radiation     wind_speed
*        [h]                [kW/m2]             [m/s]
        t1                  0                   6.056
        t2                  0                   5.2446
        t3                  0                   4.7676
        t4                  0                   1.603
        t5                  0                   2.2279
        t6                  0                   2.4148
        t7                  0                   2.189
        t8                  0.03599             3.6099
        t9                  0.11261             3.5651
        t10                 0.23142             3.1687
        t11                 0.04872             4.9879
        t12                 0.0294              2.5256
        t13                 0.24638             2.1327
        t14                 0.22011             3.3471
        t15                 0.09044             2.5868
        t16                 0.05099             5.6994
        t17                 0.10904             6.7818
        t18                 0.05378             6.5577
        t19                 0.00555             4.1159
        t20                 0                   6.5983
        t21                 0                   8.0782
        t22                 0                   6.8113
        t23                 0                   4.2318
        t24                 0                   4.9684
        t25                 0                   5.6106
        t26                 0                   5.3224
        t27                 0                   6.492
        t28                 0                   3.6051
        t29                 0                   5.2886
```

```
*______________________________SOLVING THE MINIMUM OR 0 PROBLEM______________________________*

Binary Variable   ## To solve "0 or in range" problem
         Exist_PV(tech_PV)          0 if csp not installed - 1 if installed
         Exist_W(tech_W)            0 if csp not installed - 1 if installed
         Exist_CSP(tech_CSP)        0 if csp not installed - 1 if installed
         Exist_ess(tech_ess)        0 if ess not installed - 1 if installed
         Exist_Desal(tech_Desal_ES2)    0 if Desal not installed - 1 if installed
;
Equations
         minimumPV(tech_PV)        sets the PV rated power to 0 or >= minP
         maximumPV(tech_PV)        sets the PV rated power to 0 or <= maxP
         minimumW(tech_W)          sets the CSP rated power to 0 or >= minP
         maximumW(tech_W)          sets the CSP rated power to 0 or <= maxP
         minimumCSP(tech_CSP)      sets the CSP rated power to 0 or >= minP
         maximumCSP(tech_CSP)      sets the CSP rated power to 0 or <= maxP
         minimumEss_P(tech_ess)    sets the Ess rated power to 0 or >= minP
         maximumEss_P(tech_ess)    sets the Ess rated power to 0 or <= maxP
         minumumDesal(tech_Desal_ES2) sets the Desal capacity to 0 or >= minP
         maximumDesal(tech_Desal_ES2) sets the Desal capacity to 0 or <= maxP
;

minimumPV(tech_PV)..
         P_PV(tech_PV) =g= Exist_PV(tech_PV)*Data_PV(tech_PV,'minP');
maximumPV(tech_PV)..
         P_PV(tech_PV) =l= Exist_PV(tech_PV)*Data_PV(tech_PV,'maxP');
minimumW(tech_W)..
         P_W(tech_W) =g= Exist_W(tech_W)*Data_W(tech_W,'minP');
maximumW(tech_W)..
         P_W(tech_W) =l= Exist_W(tech_W)*Data_W(tech_W,'maxP');
minimumCSP(tech_CSP)$(Consider_CSP eq 1)..
         P_CSP(tech_CSP) =g= Exist_CSP(tech_CSP)*Data_CSP(tech_CSP,'minP');
maximumCSP(tech_CSP)$(Consider_CSP eq 1)..
         P_CSP(tech_CSP) =l= Exist_CSP(tech_CSP)*Data_CSP(tech_CSP,'maxP');
minimumEss_P(tech_ess)$(Consider_ESS eq 1)..
         P_ess(tech_ess) =g= Exist_ess(tech_ess)*Data_ess(tech_ess,'minP');
maximumEss_P(tech_ess)$(Consider_ESS eq 1)..
         P_ess(tech_ess) =l= Exist_ess(tech_ess)*Data_ess(tech_ess,'maxP');
minumumDesal(tech_Desal_ES2)$(Consider_Desal_ES2 eq 1)..
         Capacity_Desal(tech_Desal_ES2) =g= Exist_Desal(tech_Desal_ES2)*Data_Desal(tech_Desal_ES2,'minCap');
maximumDesal(tech_Desal_ES2)$(Consider_Desal_ES2 eq 1)..
         Capacity_Desal(tech_Desal_ES2) =l= Exist_Desal(tech_Desal_ES2)*Data_Desal(tech_Desal_ES2,'maxCap');

* Fixed water storage: 2 days autonomy
V_wss.fx('WS1')=2*Water_demand('d1');    ##To be changed if water demand not constant

$ontext
*No CSP
P_CSP.fx('Dish') = 0;
P_CSP.fx('ORC') = 0;

*Only RO (constant)
Capacity_Desal.fx('MVC') = 0;

*Only NaS
Exist_ess.fx('VRLA') = 0;
Exist_ess.fx('NiCd') = 0;
Exist_ess.fx('ZnBr') = 0;
Exist_ess.fx('Li-ion') = 0;
```

```
Exist_ess.fx('Li-ion') = 0;
$offtext



$ontext
*///////////////////////// RUN ESTIMATE VALUES //////////////////////
*__________ESTIMATE SCRIPT to find a first solution fast (not optimal)__________
If (RunEstimate eq 1,
*////////////////////////////PHOTOVOLTAIC SYSTEM\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
P_PV.fx('c-Si')=0;
P_PV.fx('a-Si')=0;
P_PV.fx('CdTe')=0;
*////////////////////////////////WIND SYSTEM\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
P_W.fx('Norwin225')=0;
P_W.fx('Gyro10k')=0;
P_W.fx('Vergnet275')=1200;
*/////////////////////CONCENTRATED SOLAR POWER SYSTEM\\\\\\\\\\\\\\\\\\\\\\\\\\
P_CSP.fx('Dish')=0;
P_CSP.fx('ORC')=0;
*//////////////////////////DESALINATION SYSTEM\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
Exist_Desal.fx('HDH')=0;         Capacity_Desal.fx('HDH')=0;
Exist_Desal.fx('MED')=0;         Capacity_Desal.fx('MED')=0;
Exist_Desal.fx('MD')=0;          Capacity_Desal.fx('MD')=0;
Exist_Desal.fx('MVC')=0;         Capacity_Desal.fx('MVC')=0;
Exist_Desal.fx('RO')=1;          Capacity_Desal.fx('RO')=800;
*//////////////////////ELECTRIC STORAGE SYSTEM\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
Exist_ess.fx('LA_flood')=0;      P_ess.fx('LA_flood')=0;
Exist_ess.fx('CAES_above')=0;    P_ess.fx('CAES_above')=0;
Exist_ess.fx('PHS')=1;           P_ess.fx('PHS')=1000;
Exist_ess.fx('HS-flywheel')=0;   P_ess.fx('HS-flywheel')=0;
Exist_ess.fx('Regenesys')=0;     P_ess.fx('Regenesys')=0;
Exist_ess.fx('H2-Engine')=1;     P_ess.fx('H2-Engine')=100;
*/////////////////////////THERMAL STORAGE SYSTEM\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
E_tss.fx('TS1')=0;
*//////////////////////////WATER STORAGE SYSTEM\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
V_wss.l('WS1')=0;
);
$offtext


$ontext
*_______________________________________ESS SCREANING__________________________________________*
* If scenario = 1 all the ess' are set to 0, so no ess are taken into consideration.
*P_ess.fx('LA_flood')$(Count_ESS eq 0) = Data_ess('LA_flood','minP');     Exist_ess.fx('LA_flood')$(Count_ESS eq 0)=0;
*P_ess.fx('Regenesys')$(Count_ESS eq 0) = Data_ess('Regenesys','minP');     Exist_ess.fx('Regenesys')$(Count_ESS eq 0)=0;
*P_ess.fx('PHS')$(Count_ESS eq 0) = Data_ess('PHS','minP');     Exist_ess.fx('PHS')$(Count_ESS eq 0)=0;
*P_ess.fx('CAES_above')$(Count_ESS eq 0) = Data_ess('CAES_above','minP');     Exist_ess.fx('CAES_above')$(Count_ESS eq 0)=0;
*P_ess.fx('HS-flywheel')$(Count_ESS eq 0) = Data_ess('HS-flywheel','minP');     Exist_ess.fx('HS-flywheel')$(Count_ESS eq 0)=0;
```

```
*P_ess.fx('H2-Engine')$(Count_ESS eq 0) = Data_ess('H2-Engine','minP'); Exist_ess.fx('H2-Engine')$(Count_ESS eq 0)=0;

         ##Adjustments made to exclude PHS and include NaS (19/3/12)
*Exist_ess.fx('PHS')=0;
P_ess.fx('NaS')$(Count_ESS eq 0) = Data_ess('NaS','minP'); Exist_ess.fx('NaS')$(Count_ESS eq 0)=0;


*________.::ESS After prescreening::.
if (Prescreen_ESS eq 1 or Count_ESS eq 0,
P_ess.fx('VRLA') = 0;           E_ess.fx('VRLA') = 0;          Exist_ess.fx('VRLA') =0;
P_ess.fx('NiCd') = 0;           E_ess.fx('NiCd') = 0;          Exist_ess.fx('NiCd') =0;
*P_ess.fx('NaS') = 0;           E_ess.fx('NaS') = 0;           Exist_ess.fx('NaS') =0;
*P_ess.fx('CAES_under') = 0;    E_ess.fx('CAES_under') = 0;    Exist_ess.fx('CAES_under') =0;
*P_ess.fx('PHS_as') = 0;        E_ess.fx('PHS_as') = 0;        Exist_ess.fx('PHS_as') =0;
P_ess.fx('ZnBr') = 0;           E_ess.fx('ZnBr') = 0;          Exist_ess.fx('ZnBr') =0;
P_ess.fx('Li-ion') = 0;         E_ess.fx('Li-ion') = 0;        Exist_ess.fx('Li-ion') =0;
P_ess.fx('V-redox') = 0;        E_ess.fx('V-redox') = 0;       Exist_ess.fx('V-redox') =0;
*P_ess.fx('H2-PEMFC') = 0;      E_ess.fx('H2-PEMFC') = 0;      Exist_ess.fx('H2-PEMFC') =0;
);

if (CountBigCSP eq 0,
*We already know that these techs are too big for PM
*P_CSP.fx('Parabolic') = 0;
*P_CSP.fx('SolarTower') = 0;
*P_CSP.fx('Fresnel') = 0;
)
*/////////////////////////INITIAL_SETTINGS_end/////////////////////
$offtext

```

```
*---------------.:: Renewable Energy Production Systems ::.---------------*
*------------------------------------------------------------------------*
*------------------------------------------------------------------------*

*______________________SETTING PARAMETERS AND VARIABLES__________________*
PARAMETERs
         PV_out_spec(t,tech_PV)    [kW\m^2]  :specific output of the photovoltaic system
         V_hubheight(t,tech_W)     [m\s]     :wind speed calculated at hubheight
         W_out_spec(t,tech_W)      [kW\turbine]  :output of the wind turbine system
         CSP_out_el_spec(t,tech_CSP) [kW\m^2]  :specific electricity output of the concentrated solar system
         CSP_out_th_spec(t,tech_CSP) [kW\m^2]  :specific thermal output of the concentrated solar system
;
Positive VARIABLEs
         E_W_out(t,tech_W)        [kWh\h]    :The electric energy produced by each wind tech at each time step
         E_PV_out(t,tech_PV)      [kWh\h]    :The electric energy produced by each PV tech at each time step
         E_CSP_out(t,tech_CSP)    [kWh\h]    :The electric energy produced by each CSP tech at each time step
         Th_CSP_out(t,tech_CSP)   [kWh\h]    :The thermal energy produced by each CSP tech at each time step
         TC_PV(tech_PV)           €          :Total cost of the PV systems
         TC_W(tech_W)             €          :Total cost of the W systems
         TC_CSP(tech_CSP)         €          :Total cost of the CSP systems
;

*_________________________CALCULATING SPECIFIC OUTPUTS___________________*
*                                 ...:::PV system:::...
loop( (tech_PV,t),
         PV_out_spec(t,tech_PV) = Potentials(t,'solar_radiation')*Data_PV(tech_PV,'Deration');
);       ## The kW_out/kW_p of each tech of PV is modeled as Incoming_radiation*Deration_factor*(efficiency/specific_area) but the (..)=1

*                                 ...:::Wind system:::...
V_hubheight(t,tech_W) = Potentials(t,'wind_speed') * (log(Data_W(tech_W,'Hub_height')/Roughness) / log(Height_anemometer/Roughness))    ## This is to say: v2 = v1 * (ln(h2/z0) / ln(h1/z0))
loop( (t,tech_W),
      W_out_spec(t,tech_W) $ ( V_hubheight(t,tech_W) < Data_W(tech_W,'V_cut_in') ) = 0;
      W_out_spec(t,tech_W) $ ( (V_hubheight(t,tech_W)>=Data_W(tech_W,'V_cut_in')) and (V_hubheight(t,tech_W)<=Data_W(tech_W,'V_cut_off')) and (V_hubheight(t,tech_W)<Data_W(tech_W,'V_flat')) ) =
                                 Data_W(tech_W,'coeff1')*V_hubheight(t,tech_W)**6 + Data_W(tech_W,'coeff2')*V_hubheight(t,tech_W)**5
                               + Data_W(tech_W,'coeff3')*V_hubheight(t,tech_W)**4 + Data_W(tech_W,'coeff4')*V_hubheight(t,tech_W)**3
                               + Data_W(tech_W,'coeff5')*V_hubheight(t,tech_W)**2 + Data_W(tech_W,'coeff6')*V_hubheight(t,tech_W)
                               + Data_W(tech_W,'coeff7');
      W_out_spec(t,tech_W) $ ( (V_hubheight(t,tech_W) >= Data_W(tech_W,'V_flat')) and (V_hubheight(t,tech_W)<=Data_W(tech_W,'V_cut_off')) ) = Data_W(tech_W,'P_max_out');
      W_out_spec(t,tech_W) $ (V_hubheight(t,tech_W) > Data_W(tech_W,'V_cut_off') ) = 0;
);    ## This is implementing the given power curve into the model,cf.:
         ## V<V_ci E=0;
         ## V>=V_ci & V<V_flat & V<=V_co E=f(V);
```

```
        ## V>=V_flat & V<=V_co   E=E_max;
        ## V>V_co E=0;

*                                  ...:::CSP system:::...
loop( (tech_CSP,t),
         CSP_out_el_spec(t,tech_CSP) = Potentials(t,'solar_radiation')*Data_C»
SP(tech_CSP,'Deration');
         CSP_out_th_spec(t,tech_CSP) = Potentials(t,'solar_radiation')*Data_C»
SP(tech_CSP,'Deration')*( Data_CSP(tech_CSP,'eta_th')/Data_CSP(tech_CSP,'eta_»
el') );
);       ## The kW_out/kW_p of each tech of CSP is modeled as Incoming_radiat»
ion*Deration_factor*(efficiency/specific_area), in case of eta_el the (..)=1



*_________________CALCULATING ENERGY OUTPUTS & COSTS______________________*
* Energy outputs are the specific outputs multiplied by the extensive variabl»
e
* Costs are specific cost of the extensive variable increased by O&M and actu»
alized

EQUATIONs
      ## Energy
         EnergyPV(t,tech_PV)        E_PV_out = PV_out_specific * P_PV
         EnergyW(t,tech_W)          E_W_out  = W_out_specific * P_W\P_W_nom
         EnergyCSP(t, tech_CSP)     E_CSP_out = CSP_out_el_specific * P_CSP
         ThermalCSP(t,tech_CSP)     Th_CSP_out = CSP_out_th_specific * P_CSP
      ## Costs
         TotCostPV(tech_PV)         TC_PV = c_P*P_PV * (1+ f_O&M*(1\(1+i))^n  )»
   + c_land*(P_PV\eta)*coeff_LU
         TotCostW(tech_W)           TC_W = c_P*P_W * (1+ f_O&M*(1\(1+i))^n  )  »
   + c_land*LU_specific*P_W
         TotCostCSP(tech_CSP)       TC_CSP = c_P*P_CSP + c_O&M * P_CSP * (1\(1+»
i))^n  + c_land*LU_specific*P_CSP
;

EnergyPV(t,tech_PV)..       ##Electrical energy coming out of each tech of PV »
system
         E_PV_out(t,tech_PV) =e=  PV_out_spec(t,tech_PV)*P_PV(tech_PV);

EnergyW(t,tech_W)..         ##Electrical energy coming out of each tech of Win»
d system
         E_W_out(t,tech_W)   =e=  W_out_spec(t,tech_W)*P_W(tech_W)/Data_W(tec»
h_W,'P_nom');

EnergyCSP(t,tech_CSP)$(Consider_CSP eq 1)..    ##Electrial energy coming out »
of each tech of CSP system
         E_CSP_out(t,tech_CSP) =e=  CSP_out_el_spec(t,tech_CSP)*P_CSP(tech_CS»
P);

ThermalCSP(t,tech_CSP)$(Consider_CSP eq 1)..   ##Thermal energy coming out of»
 each tech of CSP system
         Th_CSP_out(t,tech_CSP) =e=  CSP_out_th_spec(t,tech_CSP)*P_CSP(tech_C»
SP);

TotCostPV(tech_PV)..        ##Total cost of each PV system technology
         TC_PV(tech_PV) =e=  Data_PV(tech_PV,'c_P')*P_PV(tech_PV)*( 1+Data_PV»
(tech_PV,'M_om')*Act_factor ) + c_land*(P_PV(tech_PV)/Data_PV(tech_PV,'eta')*»
k_land_PV) + P_PV(tech_PV)*Data_PV(tech_PV,'Resources') + P_PV(tech_PV)*Data_»
PV(tech_PV,'Emission_LCA')*c_CO2;

TotCostW(tech_W)..          ##Total cost of each Wind system technology
         TC_W(tech_W) =e=  Data_W(tech_W,'c_P')*P_W(tech_W)*( 1+Data_W(tech_W»
,'M_om')*Act_factor ) + c_land*Data_W(tech_W,'land_use')*P_W(tech_W) + P_W(te»
```

```
ch_W)*Data_W(tech_W,'Resources') + P_W(tech_W)*Data_W(tech_W,'Emission_LCA')*»
c_CO2;

TotCostCSP(tech_CSP)$(Consider_CSP eq 1)..       ##Total cost of each CSP sys»
tem technology
         TC_CSP(tech_CSP) =e=  Data_CSP(tech_CSP,'c_P')*P_CSP(tech_CSP) + Dat»
a_CSP(tech_CSP,'M_om')*P_CSP(tech_CSP)*Act_factor  + c_land*Data_CSP(tech_CSP»
,'land_use')*P_CSP(tech_CSP) + P_CSP(tech_CSP)*Data_CSP(tech_CSP,'Resources')»
 + P_CSP(tech_CSP)*Data_CSP(tech_CSP,'Emission_LCA')*c_CO2;

```

```
*-------------------------.:: Diesel generator  model::.------------------*
*-------------------------------------------------------------------------*

*_________________________PROBLEM SETTING_________________________________*
Positive VARIABLEs
     ## Inputs and outputs
          Fuel_diesel_in(t,tech_diesel)    kWh\h :Flux of fuel energy input in the diesel generator
          E_diesel_out(t,tech_diesel)      kWh\h :Flux of electrical energy from the diesel generator
          Th_diesel_out(t,tech_diesel)     kWh\h :Flux of thermal energy from the diesel generator
     ## Costs
          TC_diesel(tech_diesel)           €     :Total cost of the diesel generator
;

Binary VARIABLEs
          Csi_diesel(t,tech_diesel)        0 if diesel is off. 1 if diesel is on.
;

*_____________________________EQUATIONS WRITING___________________________*
EQUATIONs
          TotCost_Diesel(tech_diesel)             c_O&M*E_diesel_out*(1\(1+i))^n + (c_diesel+ c_CO2*specific_CO2)*(Fuel_diesel_in)*actualization
          E_Diesel_production(t,tech_diesel)      Fuel_diesel_in = linearized function of E_diesel_out
          Th_Diesel_production(t,tech_diesel)     Th_diesel_out = Fuel_diesel_in*eta_th
          maxDieselPower(t,tech_diesel)           E_diesel_out <= P_diesel
          minDieselPower(t,tech_diesel)           E_diesel_out >= 0.4 * P_diesel
;


*-------------------------.::DIESEL EQUATIONS::.--------------------------*
*-------------------------------------------------------------------------*

TotCost_Diesel(tech_diesel)..   ##Total cost of the diesel generator system
          TC_diesel(tech_diesel) =e= Data_diesel(tech_diesel,'c_P') * Data_diesel(tech_diesel,'P_nom')
                                 + Data_diesel(tech_diesel,'c_om') * Act_factor * sum(t,E_diesel_out(t,tech_diesel))
                                 + (c_diesel + c_CO2*CO2_from_diesel) * Act_factor * sum(t,Fuel_diesel_in(t,tech_diesel))
                                 + c_CO2 * Data_diesel(tech_diesel,'Emission_LCA') * Data_diesel(tech_diesel,'P_nom')
                                 + c_land*Data_diesel(tech_diesel,'land_use')*Data_diesel(tech_diesel,'P_nom')
                                 + Data_diesel(tech_diesel,"P_nom")*Data_diesel(tech_diesel,"Resources")
;
E_Diesel_production(t,tech_diesel)..  ##If diesel is on, linear approximation: Fin = 2.44625*Eout + 95.7
  Fuel_diesel_in(t,tech_diesel) =e=  diesel_m_coeff*E_diesel_out(t,tech_diesel) + diesel_q_coeff*Csi_diesel(t,tech_diesel)
;
Th_Diesel_production(t,tech_diesel)..  ##Thermal energy production of diesel generator
  Th_diesel_out(t,tech_diesel) =e= Fuel_diesel_in(t,tech_diesel)*Data_diesel(tech_diesel,'eta_th')
;
maxDieselPower(t,tech_diesel).. ##The maximum energy that the diesel can prod
```

```
uce in one hour
  E_diesel_out(t,tech_diesel) =l= Csi_diesel(t,tech_diesel)* Data_diesel(tech_diesel,"P_nom")
;
minDieselPower(t,tech_diesel).. ##The minimum energy load is 40%
  E_diesel_out(t,tech_diesel) =g= Csi_diesel(t,tech_diesel)* min_diesel_load * Data_diesel(tech_diesel,"P_nom")
;
* maxDieselPowerBasedOnConsumption(t,tech_diesel).. ##The maximum energy that the diesel can produce in one hour
*  E_diesel_out(t,tech_diesel) =l= Csi_diesel(t,tech_diesel)* VERBRAUCH ZUM ZEITPUNKT T + maximale Entsalzung (Variable, die bereits definiert ist
;
```

```
*--------------------.:: Desalination plant model::.----------------------*
*------------------------------------------------------------------------*

*_________________________PROBLEM SETTING_________________________________*
Positive VARIABLEs
     ## Inputs and outputs
         E_Desal_in(t,tech_Desal_tot)        kWh\h :Flux of electrical energy to the desalination plant
         Th_Desal_in(t,tech_Desal_ES2)       kWh\h :Flux of thermal energy to the desalination plant
         Water_generation(d,tech_Desal_tot)  m^3   :Water generated by the desalination plant
     ## Costs
         TC_Desal(tech_Desal_tot)            €     :Total cost of the desalination plant
;
Binary VARIABLEs
         OnOff_Desal(t)                  0 if Desal is off. 1 if is in range.
         ES3_zeroing                     0 if ES3 Desal not installed. 1 if installed.
;
SCALARs
         h_per_d                         h\d   :hours per day (so 24 - during testing can be different)
;
h_per_d=card(t)/card(d);

*____________________________EQUATIONS WRITING_____________________________*
EQUATIONs
         TotCost_Desal(tech_Desal_tot)      c_plant*Capacity_Desal + c_om*WaterProduction*actualization + c_land*LU_specific*Capacity_Desal

         ##ES2
         WaterGen_ES2(d,tech_Desal_ES2)         Generation(d)  = sum_t(d)[E_Desal_in\E_cons_el]
         ThermalNeed(t,tech_Desal_ES2)          Th_Desal_in = E_Desal_in\E_cons_el*E_cons_th
         maxProduction(d,tech_Desal_ES2)        WaterProduction(t) < Capacity_Desal
         Desal_ES2(t,tech_Desal_ES2)            Sets Desal load as constant

         ##ES3
         WaterGen_ES3(d)                    Sets Desal load as deferrable
         minimumE_desal_ES3(t)              Sets the Desal E_in to 0 or >= minP
         maximumE_desal_ES3(t)              Sets the Desal E_in to 0 or <= maxP
         ZeroingProduction(t)               Sets production to 0 if not installed
         InstallES3                         Sets the capacity to 0 or the one set (indirectly) in the Data
;

*----------------------.::DESALINATION EQUATIONS::.---------------------*
*----------------------------------------------------------------------*

TotCost_Desal(tech_Desal_tot)$(Consider_Desal eq 1)..    ##Total cost of the desalination plant
         TC_Desal(tech_Desal_tot) =e= Data_Desal(tech_Desal_tot,'c_plant')*Capacity_Desal(tech_Desal_tot)
                                  + Data_Desal(tech_Desal_tot,'c_om') * Act_factor * sum(d,Water_generation(d,tech_Desal_tot))
                                  + c_land*Data_Desal(tech_Desal_tot,"land_use")*Capacity_Desal(tech_Desal_tot)
```

```
                                + Capacity_Desal(tech_Desal_tot)*Data_Desal(tech_Desal_tot,"Resources")
;

## .::Fixed water production plants::.
ThermalNeed(t,tech_Desal_ES2)$(Consider_Desal_ES2 eq 1)..    ##For every kWh of electricity, the Desal plant also needs (1*eta_el/eta_th) kWh of thermal energy
         Th_Desal_in(t,tech_Desal_ES2)*Data_Desal(tech_Desal_ES2,'E_cons_el') =e= E_Desal_in(t,tech_Desal_ES2)*Data_Desal(tech_Desal_ES2,'E_cons_th')
;
maxProduction(d,tech_Desal_ES2)$(Consider_Desal_ES2 eq 1)..
         Water_generation(d,tech_Desal_ES2) =l= Capacity_Desal(tech_Desal_ES2)
;
WaterGen_ES2(d,tech_Desal_ES2)$(Consider_Desal_ES2 eq 1)..      ##Desalted water produced by the plant in each day
         Water_generation(d,tech_Desal_ES2)*Data_Desal(tech_Desal_ES2,'E_cons_el') =e=
                 sum( t$( (ord(t)>(ord(d)-1)*h_per_d)and(ord(t)<ord(d)*h_per_d+1)  ),E_Desal_in(t,tech_Desal_ES2))
;
Desal_ES2(t,tech_Desal_ES2)$(Consider_Desal_ES2 eq 1).. ##costant load at each timestep
         E_Desal_in(t,tech_Desal_ES2) =e= E_Desal_in(t++1,tech_Desal_ES2);
;
*In case fixed output desalination is not considered
Capacity_Desal.fx(tech_Desal_ES2)$(Consider_Desal_ES2 eq 0) = 0;
Water_generation.fx(d,tech_Desal_ES2)$(Consider_Desal_ES2 eq 0)=0;

## .::Deferrable water production plants::.
WaterGen_ES3(d)$(Consider_Desal_ES3 eq 1).. ##deferrable load
         Water_generation(d,'RO_ES3') =e=
                 sum( t$( (ord(t)>(ord(d)-1)*h_per_d)and(ord(t)<ord(d)*h_per_d+1) ), RO_ES3_m_coeff*E_Desal_in(t,'RO_ES3')+ (k_desal*RO_ES3_q_coeff)* OnOff_Desal(t) )
;
minimumE_desal_ES3(t)$(Consider_Desal_ES3 eq 1)..
         E_Desal_in(t,'RO_ES3') =g= OnOff_Desal(t)*(RO_ES3_minP+(RO_ES3_q_coeff/RO_ES3_m_coeff)*(1-k_desal))
;
maximumE_desal_ES3(t)$(Consider_Desal_ES3 eq 1)..
         E_Desal_in(t,'RO_ES3') =l= OnOff_Desal(t)*(RO_ES3_maxP+(RO_ES3_q_coeff/RO_ES3_m_coeff)*(1-k_desal))
;
ZeroingProduction(t)..
        OnOff_Desal(t) =l= ES3_zeroing;
;
InstallES3$(Consider_Desal_ES3 eq 1)..
         Capacity_Desal('RO_ES3') =e= ES3_zeroing*(RO_ES3_m_coeff*RO_ES3_maxP+RO_ES3_q_coeff)*24  ##already in [m^3/d]
;

*Setting generation and capacity to 0 if RO_ES3 not considered
Capacity_Desal.fx('RO_ES3')$(Consider_Desal_ES3 eq 0) = 0;
Water_generation.fx(d,'RO_ES3')$(Consider_Desal_ES3 eq 0) = 0;

```

```
*-----------------------.:: Storage Systems::.-------------------------------------*
*------------------------------------------------------------------------------------*

*______________________SETTING PARAMETERS AND VARIABLES______________________*

Positive VARIABLEs
     ## Energy storage
         E_ess_in(t,tech_ess)       kWh\h :Flux of energy to the ESSs
         E_ess_out(t,tech_ess)      kWh\h :Flux of energy from the ESSs
         Stored_elec(t,tech_ess)    kWh   :Electrical energy stored in ESSs (i.e. what can be given)
         TC_ess(tech_ess)           €     :Total cost of the electricity storage systems
     ## Water storage
         Water_reserve(d)           m^3   :Water stored in the water storage
         TC_wss                     €     :Total cost of the water storage
     ## Thermal storage
         Th_tss_in(t,tech_tss)        kWh\h :Flux of thermal energy to the tss'
         Th_tss_out(t,tech_tss)       kWh\h :Flux of thermal energy from the tss'
         Stored_therm(t,tech_tss)     kWh   :Thermal energy stored in tss' (i.e. what can be given)
         TC_tss(tech_tss)             €     :Total cost of the theraml storage systems
;
set flux_ess   /EssIn, EssOut/;

*Binary VARIABLEs
*          Csi_ess(t,tech_ess,flux_ess)  Binary variable to set either incoming or outgoing flux from ess
*;

*____________________________EQUATIONS______________________________________*

EQUATIONs
     ## Electricity storage
         TotCost_ESS(tech_ess)        TC_ess= c_P*P+c_E*E + REPLACEMENTS + O&M + FUEL + LAND
         Charge_balance(t,tech_ess)  S_el(t+1)-S_el(t) = -E_ess_out +E_ess_in*eta - LOSSES
         max_SOC(t,tech_ess)          S_el(t) < E_ess
         min_SOC(t,tech_ess)          S_el(t) > E_ess*(1-DOD)
         powerlimit_in(t,tech_ess)    E_ess_in  < dt * Pmax
         powerlimit_out(t,tech_ess)   E_ess_out < dt * Pmax
         HourAutomomy(tech_ess)        E = P*h
*          FluxDirectionIn(t,tech_ess)  E_ess_in  - 10e10*Csi_ess_in <= 0
*          FluxDirectionOut(t,tech_ess) E_ess_out - 10e10*Csi_ess_out <= 0
*          DecideDirection(t,tech_ess)  Csi_ess_in + Csi_ess_out <= 1
     ## Thermal storage
         TotCost_ThStorage(tech_tss)           TC_tss= c_E*E + c_O&M*E*(1\(1+i))^n +c_land*LU_tss*E
         Thermal_storage_balance(t,tech_tss)   S_th(t+1)-S_th(t) = -Th_tss_out +Th_tss_in - LOSSES
         max_Stored_th(t,tech_tss)             S_th(t) < E_tss(tech_tss)
     ## Water storage
         TotCost_Water_Storage(tech_wss)       TC_wss = c_wss*V_wss + c_land*LU_wss*V_wss
         WaterTank(d)                          Reserve(d+1) = Reserve(d) + Generation(d) - Demand(d)
         maxWaterReserve(d)                    Reserve(d) <= V_wss
```

```
;

*...........................ELECTRICITY STORAGE...............................
TotCost_ESS(tech_ess)$(Consider_ESS eq 1)..     ##Total cost of the system for each technology
         TC_ess(tech_ess) =e= ( k_ess*Data_ess(tech_ess,"c_P")*P_ess(tech_ess)+ k_ess*Data_ess(tech_ess,"c_E")*E_ess(tech_ess) )
                          + ( k_ess*Data_ess(tech_ess,"c_r_P")*P_ess(tech_ess)+ k_ess*Data_ess(tech_ess,"c_r_E")*E_ess(tech_ess) ) * sum(y, (  (1/(1+interest_rate))**ord(y)  )$(  mod(ord(y), Data_ess(tech_ess,"life"))=0  )        )
                          + Data_ess(tech_ess,"OandM") * P_ess(tech_ess) * Act_factor
                          + (c_fuel+c_CO2*CO2_from_fuel) * Act_factor * Data_ess(tech_ess,"fuel_cons") * sum(t,E_ess_out(t,tech_ess))
                          + c_land*Data_ess(tech_ess,"land_use")*E_ess(tech_ess)
                          + P_ess(tech_ess)*Data_ess(tech_ess,"Resources")
;

Charge_balance(t,tech_ess)$(Consider_ESS eq 1)..     ##Calculate the new state of charge from the old one and fluxes, taking into account the efficiency
         Stored_elec(t++1,tech_ess)
         =e=     + Stored_elec(t,tech_ess)
                 - E_ess_out(t,tech_ess)
                 + E_ess_in(t,tech_ess)*Data_ess(tech_ess,"eta")
                 - Stored_elec(t,tech_ess)*Data_ess(tech_ess,"Losses")
;

max_SOC(t,tech_ess)$(Consider_ESS eq 1)..    ##The maximum charge of a system is 100%
         Stored_elec(t,tech_ess) =l= E_ess(tech_ess);
;
min_SOC(t,tech_ess)$(Consider_ESS eq 1)..    ##The State Of Charge can't go under the level imposed by the maximum Depth of Discharge
         Stored_elec(t,tech_ess) =g= E_ess(tech_ess)*(1-Data_ess(tech_ess,'DOD'));
;
powerlimit_in(t,tech_ess)$(Consider_ESS eq 1).. ##The maximum charge or discharge is the P_ess
         E_ess_in(t,tech_ess) =l= P_ess(tech_ess)
;
powerlimit_out(t,tech_ess)$(Consider_ESS eq 1).. ##The maximum charge or discharge is the P_ess
         E_ess_out(t,tech_ess) =l= P_ess(tech_ess)
;
HourAutomomy(tech_ess)$(Consider_ESS eq 1)..   ##The minimum amount of hours in which an ess system should provide energy is 1h
         E_ess(tech_ess) =e= P_ess(tech_ess)*Data_ess(tech_ess,'H_autonomy')
;
*FluxDirectionIn(t,tech_ess)$(Consider_ESS eq 1)..    ##The flux can be incoming if the outgoing is zero
*         E_ess_in(t,tech_ess)- Bignumber*Csi_ess(t,tech_ess,'EssIn') =l= 0
*;
*FluxDirectionOut(t,tech_ess)$(Consider_ESS eq 1)..   ##The flux can be outgoing if the incoming is zero
*         E_ess_out(t,tech_ess) - Bignumber*Csi_ess(t,tech_ess,'EssOut') =l= 0
*;
*DecideDirection(t,tech_ess)$(Consider_ESS eq 1)..    ##Setting mutual exclusivity
*         Csi_ess(t,tech_ess,'EssIn')+Csi_ess(t,tech_ess,'EssOut') =l= 1
*;

```

```

*............................THERMAL STORAGE..................................
TotCost_ThStorage(tech_tss)$(Consider_Desal eq 1)..    ##Total cost of each thermal storage technology
         TC_tss(tech_tss) =e= Data_tss(tech_tss,"spec_cost")*E_tss(tech_tss)
                          + Data_tss(tech_tss,"OandM")*E_tss(tech_tss) * Act_factor
                          + c_land*Data_tss(tech_tss,"land_use")*E_tss(tech_tss)
                          + E_tss(tech_tss)*Data_tss(tech_tss,"Resources")
;
Thermal_storage_balance(t,tech_tss)$(Consider_Desal eq 1)..    ##Calculate the new state of charge from the old one and fluxes, taking into account the efficiency
         Stored_therm(t++1,tech_tss)
         =e=     + Stored_therm(t,tech_tss)
                 - Th_tss_out(t,tech_tss)
                 + Th_tss_in(t,tech_tss)*Data_tss(tech_tss,"eta")
                 - Stored_therm(t,tech_tss)*Data_tss(tech_tss,"Losses")
;
max_Stored_th(t,tech_tss)$(Consider_Desal eq 1)..   ##The maximum thermal enegy that can be stored is the installed capacity
         Stored_therm(t,tech_tss) =l= E_tss(tech_tss);
;
E_tss.fx(tech_tss)$(Consider_Desal eq 0) = 0; ##In case thermal storage is not considered

*............................WATER STORAGE..................................
TotCost_Water_Storage(tech_wss)$(Consider_Desal eq 1)..  ## Cost of the water storage
         TC_wss(tech_wss) =e= V_wss(tech_wss)*Data_wss(tech_wss,"spec_cost") + c_land*V_wss(tech_wss)*Data_wss(tech_wss,"land_use") + V_wss(tech_wss)*Data_wss(tech_wss,"Resources")
;
WaterTank(d)$(Consider_Desal eq 1)..    ##Calculate the new volume of water in the storage from the old one and the production, taking into account the efficiency
         Water_reserve(d++1)
         =e= Water_reserve(d)
             + sum(tech_Desal_ES2,Water_generation(d,tech_Desal_ES2))$(Consider_Desal_ES2 eq 1)
             + sum(tech_Desal_ES3,Water_generation(d,tech_Desal_ES3))$(Consider_Desal_ES3 eq 1)
             - Water_demand(d)
;
maxWaterReserve(d)$(Consider_Desal eq 1)..    ##The reserve cannot be greater than the size of the storage tank
         Water_reserve(d) =l= sum(tech_wss,V_wss(tech_wss))
;
V_wss.fx(tech_wss)$(Consider_Desal eq 0) = 0; ##In case water part of the model is not considered

```

```
*----------.:: Overall system optimization setting and running ::.-----------»
--*
*----------------------------------------------------------------------------»
--*

*______________________________PROBLEM SETTING_______________________________»
__*
VARIABLEs
         TC                €      :Total cost of the entire systems
*         dummy            dummy variable for testing script
;

*_____________________________EQUATIONS_______________________________________»
__*

EQUATIONs
total_cost                      OBJECTIVE FUNCTION: Total cost of the whole s»
ystem (installation + O&M + fuel)
electricity_balance(t)          System electrical energy balance for all time»
 steps
thermal_balance(t)              System thermal energy balance for each day
*eq_dummy                         dummy equation to test the script
;

total_cost..  ##Total cost of the overall system is the sum of the total cost»
s of each part of the system
         TC   =e= sum(tech_PV,   TC_PV(tech_PV)    )
             +    sum(tech_W,    TC_W(tech_W)      )
             +    sum(tech_CSP, TC_CSP(tech_CSP) )                $(Consider_C»
SP eq 1)
             +    sum(tech_diesel, TC_diesel(tech_diesel) )
             +    sum(tech_ess, TC_ess(tech_ess) )                $(Consider_E»
SS eq 1)
             +    sum(tech_tss, TC_tss(tech_tss) )                $(Consider_D»
esal eq 1)
             +    sum(tech_Desal_tot, TC_Desal(tech_Desal_tot) )  $(Consider_D»
esal eq 1)
             +    sum(tech_wss, TC_wss(tech_wss) )                $(Consider_D»
esal eq 1)
;
electricity_balance(t)..  ##The difference of energy between Load, Renewables»
, Diesel and Desalination has to be covered by ESSs
         Load(t)*(1+k_reserve)*k_demand =e= sum(tech_PV,   E_PV_out(t,tech_PV)»
     )
                         +     sum(tech_W,         E_W_out(t,tech_W)          »
     )
                         +     sum(tech_CSP,       E_CSP_out(t,tech_CSP)      »
     )$(Consider_CSP eq 1)
                         +     sum(tech_diesel,    E_diesel_out(t,tech_diesel)»
     )
                         +     sum(tech_ess,       E_ess_out(t,tech_ess)      »
     )$(Consider_ESS eq 1)
                         -     sum(tech_ess,       E_ess_in(t,tech_ess)       »
     )$(Consider_ESS eq 1)
                         -     sum(tech_Desal_tot, E_Desal_in(t,tech_Desal_tot»
)    )$(Consider_Desal eq 1)
                         -     Dump_el(t)
;
thermal_balance(t)..
          sum(tech_Desal_ES2,  Th_Desal_in(t,tech_Desal_ES2)) =e=
                 + sum(tech_diesel, Th_diesel_out(t,tech_diesel) )
                 + sum(tech_CSP,    Th_CSP_out(t,tech_CSP)        )$(Consider_»
CSP eq 1)
                 + sum(tech_tss,    Th_tss_out(t,tech_tss)        )$(Consider_»
```

```
Desal_ES2 eq 1)
                  - sum(tech_tss,    Th_tss_in(t,tech_tss)        )$(Consider_»
Desal_ES2 eq 1)
                  + Industry_waste_heat
                  - Dump_th(t)
;
*eq_dummy..        dummy  =e=  0;      ##Equation just to test script

Model TechnoEconOptimization /all/ ;
TechnoEconOptimization.optfile=1;        ##enable use of option file
TechnoEconOptimization.holdfixed=1;
option solvelink=0;
*TechnoEconOptimization.reslim= 150000;  ##time limit (overruled by osicplex.»
opt settings)
*Option Bratio=0;                        ##Let the model start from initial v»
ariables
If (RunEstimate eq 1,
  Option Integer4=1;                       ##Start from the given initial var»
iables
);
If (RunFromLastSave eq 1,
  execute_loadpoint 'LastSave'; ##Read the initial variables in this gdx file
);
Option Savepoint=1;                      ##Save model variables calculated in»
 TechnoEconOptimization_p

SOLVE TechnoEconOptimization minimizing TC using MIP;


##____Displaying___
*display k_desal;

```

```
*________________________________Preparing output datas________________________________

SCALAR
 Tot_E_renew       amount of electric energy produced from renewable sources
 Tot_E_fossil      amount of electric energy produced from fossil sources
 epsilon_el        percentage of electic energy produced by renewable sources
;

Tot_E_renew = sum(t, sum(tech_PV,E_PV_out.l(t,tech_PV)) + sum(tech_W,E_W_out.l(t,tech_W)) + sum(tech_CSP,E_CSP_out.l(t,tech_CSP)) );
Tot_E_fossil = sum((t,tech_diesel),E_diesel_out.l(t,tech_diesel));
epsilon_el= (Tot_E_renew/(Tot_E_renew+Tot_E_fossil)*100)$((Tot_E_renew+Tot_E_fossil)>0);

*-------------.:: Writing a report and saving the log file ::.------------------*
*------------------------------------------------------------------------------*

SETs
 LoadTech         /Load, PV, W, CSP_el, diesel_el, ees, Desal_el, Dump_el/
 ThermTech        /Desal_th, CSP_th, diesel_th, tss, Dump_th/
 WaterTech        /Demand, Generation, Reserve_pre, Reserve_post/
* CapacitySet      /a-Si, Vergnet275, ORC, NaS, Caterpillar2, MVC, RO, RO_ES3, TS1, WS1/
;
PARAMETERs
 TabellaLoad(t,LoadTech)
 TabellaTherm(t,ThermTech)
 TabellaWater(d,WaterTech)
* Capacities(CapacitySet)
;

If (PrintXLS eq 1,
*Capacities(CapacitySet)$(ord(CapacitySet)=1)   =       P_PV.l('a-Si');
*Capacities(CapacitySet)$(ord(CapacitySet)=2)   =       P_W.l('Vergnet275');
*Capacities(CapacitySet)$(ord(CapacitySet)=3)   =       P_CSP.l('ORC');
*Capacities(CapacitySet)$(ord(CapacitySet)=4)   =       P_ess.l('NaS');
*Capacities(CapacitySet)$(ord(CapacitySet)=5)   =       Data_diesel('Caterpillar2','P_nom');
*Capacities(CapacitySet)$(ord(CapacitySet)=6)   =       Capacity_Desal.l('MVC');
*Capacities(CapacitySet)$(ord(CapacitySet)=7)   =       Capacity_Desal.l('RO');
*Capacities(CapacitySet)$(ord(CapacitySet)=8)   =       Capacity_Desal.l('RO_ES3');
*Capacities(CapacitySet)$(ord(CapacitySet)=9)   =       E_tss.l('TS1');
*Capacities(CapacitySet)$(ord(CapacitySet)=10)  =       V_wss.l('WS1');

TabellaLoad(t,LoadTech)$(ord(LoadTech)=1)   =       (-1*Load(t));
TabellaLoad(t,LoadTech)$(ord(LoadTech)=2)   =       sum(tech_PV, E_PV_out.l(t,tech_PV));
TabellaLoad(t,LoadTech)$(ord(LoadTech)=3)   =       sum(tech_W,  E_W_out.l(t,tech_W));
TabellaLoad(t,LoadTech)$(ord(LoadTech)=4)   =       sum(tech_CSP, E_CSP_out.l(t,tech_CSP));
TabellaLoad(t,LoadTech)$(ord(LoadTech)=5)   =       sum(tech_diesel, E_diesel_out.l(t,tech_diesel));
TabellaLoad(t,LoadTech)$(ord(LoadTech)=6)   =       sum(tech_ess, E_ess_out.l(t,tech_ess)-E_ess_in.l(t,tech_ess));
TabellaLoad(t,LoadTech)$(ord(LoadTech)=7)   =       sum(tech_Desal_tot, -E_Desal_in.l(t,tech_Desal_tot));
TabellaLoad(t,LoadTech)$(ord(LoadTech)=8)   =       -Dump_el.l(t);
```

```
TabellaTherm(t,ThermTech)$(ord(ThermTech)=1)   =    (-1* sum(tech_Desal_ES2,Th_Desal_in.l(t,tech_Desal_ES2)) );
TabellaTherm(t,ThermTech)$(ord(ThermTech)=2)   =    sum(tech_CSP, Th_CSP_out.l(t,tech_CSP) );
TabellaTherm(t,ThermTech)$(ord(ThermTech)=3)   =    sum(tech_diesel, Th_diesel_out.l(t,tech_diesel) );
TabellaTherm(t,ThermTech)$(ord(ThermTech)=4)   =    sum(tech_tss, Th_tss_out.l(t,tech_tss)-Th_tss_in.l(t,tech_tss) );
TabellaTherm(t,ThermTech)$(ord(ThermTech)=5)   =    -Dump_th.l(t);
TabellaWater(d,WaterTech)$(ord(WaterTech)=1)   =    (-1*Water_demand(d));
TabellaWater(d,WaterTech)$(ord(WaterTech)=2)   =    sum(tech_Desal_tot, Water_generation.l(d,tech_Desal_tot));
TabellaWater(d,WaterTech)$(ord(WaterTech)=3)   =    Water_reserve.l(d);
TabellaWater(d,WaterTech)$(ord(WaterTech)=4)   =    Water_reserve.l(d+1);
Execute_Unload "tmp.gdx",TabellaLoad,TabellaTherm,TabellaWater,E_PV_out,E_W_out,E_CSP_out,Th_CSP_out,E_diesel_out,Th_diesel_out,Fuel_diesel_in,E_ess_in,E_ess_out,E_Desal_in,Th_Desal_in,Th_tss_in,Th_tss_out; ##,Capacities;
Execute 'GDXXRW.EXE tmp.gdx O=Output.xls @WritingXLS.txt';
);

*______________________________WRITING REPORT LOG FILE______________________________*
file Report /Report.log/;
put Report;
Report.pw=100;
put @15,'..:: TECHNOLOGIES CHOSEN BY THE MODEL ::..'/;
put 'Elapsed time: ',TechnoEconOptimization.Resusd, ' seconds'/;
put 'Solver status: ',TechnoEconOptimization.Solvestat,' (1=ok)'/;
*put 'Optimality gap reached: ',TechnoEconOptimization.optcr,' %'/;
put 'Number of infeasabilities: ', TechnoEconOptimization.numinfes:4:0//;
put /'Photovoltaic technologies'/;
put @3, 'Tech', @15, 'Power'/;
loop(tech_PV, put @3, tech_PV.tl, @15, P_PV.l(tech_PV):6:2,'kW'/);
put /'Wind Energy technologies'/;
put @3, 'Tech', @15, 'Power'/;
loop(tech_W, put @3, tech_W.tl, @15, P_W.l(tech_W):6:2,'kW'/);
put /'Concentrated Solar technologies'/;
put @3, 'Tech', @15, 'Power'/;
loop(tech_CSP, put @3, tech_CSP.tl, @15, P_CSP.l(tech_CSP):6:2,'kW'/);
*put /'Diesel generator'/;
*put @3, 'Tech', @15, 'Rated Power'/;
*loop(tech_diesel, put @3, tech_diesel.tl, @15, P_diesel.l(tech_diesel):6:2,'kW'/);
put /'Water storage system'/;
put @3, 'Tech', @15, 'Size'/;
loop(tech_wss, put @3, tech_wss.tl, @15, V_wss.l(tech_wss):6:2,'m^3'/);
put /'Desalination system'/;
put @3, 'Tech', @15, 'Capacity'/;
loop(tech_Desal_tot, put @3, tech_Desal_tot.tl, @15, Capacity_Desal.l(tech_Desal_tot):6:2,'m^3/d'/);
put /'Energy Storage System'/;
put @3, 'Tech', @15, 'Power', @25, 'Energy'/;
loop(tech_ess, put @3, tech_ess.tl, @15, P_ess.l(tech_ess):6:2,'kW', @30, E_ess.l(tech_ess):6:2,'kWh' /);
put /'Thermal Storage System'/;
put @3, 'Tech', @15, 'Capacity'/;
loop(tech_tss, put @3, tech_tss.tl, @15, E_tss.l(tech_tss):6:2,'kWh'/);
put /'Total Cost'/;
put @3, 'Total cost', @16, TC.l:6:2, '€'/;
*put /'Renewable Fraction'/;
*put @3, 'Epsilon_electric', @20, epsilon_el:6:2 '%'/;

put //@15, '..:: TOTAL COSTS ::..'//;
put 'Tech', @15,'Total Cost', @40, 'Marginal Costs'/;
```

```
loop(tech_PV, put tech_PV.tl, @15,  TC_PV.l(tech_PV), '€', @35,  P_PV.m(tech_PV):8:2, '€'/);
loop(tech_W, put tech_W.tl, @15,  TC_W.l(tech_W), '€', @35,  P_W.m(tech_W):8:2, '€'/);
loop(tech_CSP, put tech_CSP.tl, @15,  TC_CSP.l(tech_CSP), '€', @35,  P_CSP.m(tech_CSP):8:2, '€'/);
loop(tech_ess, put tech_ess.tl, @15,  TC_ess.l(tech_ess), '€', @35,  P_ess.m(tech_ess):8:2, '€ (P)', @50,  P_ess.m(tech_ess):8:2, '€ (E)'/);   ##ESS
*loop(tech_diesel, put tech_diesel.tl, @15,  TC_diesel.l(tech_diesel), '€', @35,  P_diesel.m(tech_diesel):8:2, '€'/);
loop(tech_Desal_tot, put tech_Desal_tot.tl, @15,  TC_Desal.l(tech_Desal_tot), '€', @35,  Capacity_Desal.m(tech_Desal_tot):8:2, '€'/);
loop(tech_wss, put tech_wss.tl, @15,  TC_wss.l(tech_wss), '€', @35,  V_wss.m(tech_wss):8:2, '€'/);
put '-------------------------------'/;
put 'Total', @15, TC.l, '€'/;
putclose Report;




*___________________________COSTS REPORT LOG FILE______________________________*
file CostReport /CostReport.log/;
put CostReport;
CostReport.pw=120;
put @15, '..:: ECONOMIC ANALISYS ::..'//;
put @4, 'Tech', @16,'IC', @28, 'O&M', @40, 'Land', @52, 'Fuel', @64, 'CO2', @76, 'Replac.', @88, 'Resources', @100, 'Total'/;

loop(tech_PV, put tech_PV.tl, @12, (Data_PV(tech_PV,'c_P')*P_PV.l(tech_PV)):8:0,'€',
                              @24, (Data_PV(tech_PV,'c_P')*P_PV.l(tech_PV)*Data_PV(tech_PV,'M_om')*Act_factor):8:0,'€',
                              @36, (c_land*P_PV.l(tech_PV)/Data_PV(tech_PV,'eta')*1.5):8:0, '€',
                              @84, (P_PV.l(tech_PV)*Data_PV(tech_PV,"Resources")):8:0, '€',
                              @100, TC_PV.l(tech_PV):8:0, '€'
     /);
loop(tech_W, put tech_W.tl, @12,  (Data_W(tech_W,'c_P')*P_W.l(tech_W)):8:0, '€',
                            @24,  (Data_W(tech_W,'c_P')*P_W.l(tech_W)*Data_W(tech_W,'M_om')*Act_factor):8:0, '€',
                            @36,  (c_land*Data_W(tech_W,'land_use')*P_W.l(tech_W)):8:0, '€',
                            @84,  (P_W.l(tech_W)*Data_W(tech_W,"Resources")):8:0, '€',
                            @100, TC_W.l(tech_W):8:0, '€'
     /);
loop(tech_CSP, put tech_CSP.tl, @12,  (Data_CSP(tech_CSP,'c_P')*P_CSP.l(tech_CSP)):8:0, '€',
                                @24,  (Data_CSP(tech_CSP,"M_om")*P_CSP.l(tech_CSP)*Act_factor):8:0, '€',
                                @36,  (c_land*Data_CSP(tech_CSP,'land_use')*P_CSP.l(tech_CSP)):8:0, '€',
                                @84,  (P_CSP.l(tech_CSP)*Data_CSP(tech_CSP,"Resources")):8:0, '€',
                                @100, TC_CSP.l(tech_CSP):8:0, '€'
     /);
loop(tech_diesel, put tech_diesel.tl, @12,  (Data_diesel(tech_diesel,'c_P')*Data_diesel(tech_diesel,'P_nom')):8:0, '€',
                                      @24,  (Data_diesel(tech_diesel,'c_om')* Act_factor *sum(t,E_diesel_out.l(t,tech_diesel))):8:0, '€',
```

```
                                            @36,  (c_land*Data_diesel(tech_diesel,'land_use')*Data_diesel(tech_diesel,'P_nom')):8:0, '€',
                                            @48,  (c_diesel * Act_factor * sum(t,Fuel_diesel_in.l(t,tech_diesel))):8:0, '€',
                                            @60,  (c_CO2*CO2_from_diesel * Act_factor * sum(t,Fuel_diesel_in.l(t,tech_diesel))):8:0, '€',
                                            @84,  (Data_diesel(tech_diesel,"P_nom")*Data_diesel(tech_diesel,"Resources")):8:0, '€',
                                            @100, TC_diesel.l(tech_diesel):8:0, '€'
     /);
loop(tech_Desal_tot, put tech_Desal_tot.tl, @12,  (Data_Desal(tech_Desal_tot,'c_plant')*Capacity_Desal.l(tech_Desal_tot)):8:0, '€',
                                          @24,  (Data_Desal(tech_Desal_tot,'c_om') * Act_factor * sum(d,Water_generation.l(d,tech_Desal_tot))):8:0, '€',
                                          @36,  (c_land*Data_Desal(tech_Desal_tot,"land_use")*Capacity_Desal.l(tech_Desal_tot)):8:0, '€',
                                          @84,  (Capacity_Desal.l(tech_Desal_tot)*Data_Desal(tech_Desal_tot,"Resources")):8:0, '€',
                                          @100, TC_Desal.l(tech_Desal_tot):8:0, '€'
     /);
loop(tech_ess, put tech_ess.tl, @12,  (Data_ess(tech_ess,'c_P')*P_ess.l(tech_ess)+Data_ess(tech_ess,'c_E')*E_ess.l(tech_ess)):8:0, '€',
                                @24,  (Data_ess(tech_ess,'OandM')*P_ess.l(tech_ess)*Act_factor):8:0, '€',
                                @36,  (c_land*Data_ess(tech_ess,'land_use')*E_ess.l(tech_ess)):8:0, '€',
                                @48,  (c_fuel*Data_ess(tech_ess,'fuel_cons')*Act_factor* sum(t,E_ess_out.l(t,tech_ess))):8:0, '€',
                                @60,  (c_CO2*CO2_from_fuel*Data_ess(tech_ess,'fuel_cons')*Act_factor*sum(t,E_ess_out.l(t,tech_ess))):8:0, '€',
                                @72,  ((Data_ess(tech_ess,'c_r_P')*P_ess.l(tech_ess)+Data_ess(tech_ess,'c_r_E')*E_ess.l(tech_ess))*sum(y,((1/(1+interest_rate))**ord(y))$(mod(ord(y),Data_ess(tech_ess,'life'))=0))):8:0, '€',
                                @84,  (P_ess.l(tech_ess)*Data_ess(tech_ess,"Resources")):8:0, '€',
                                @100, TC_ess.l(tech_ess):8:0, '€'
     /);
loop(tech_tss, put tech_tss.tl, @12,  (Data_tss(tech_tss,'spec_cost')*E_tss.l(tech_tss)):8:0, '€',
                                @24,  (Data_tss(tech_tss,'OandM')*E_tss.l(tech_tss) * Act_factor):8:0, '€',
                                @36,  (c_land*Data_tss(tech_tss,'land_use')*E_tss.l(tech_tss)):8:0, '€',
                                @84,  (E_tss.l(tech_tss)*Data_tss(tech_tss,"Resources")):8:0, '€',
                                @100, TC_tss.l(tech_tss):8:0, '€'
     /);
loop(tech_wss, put tech_wss.tl, @12,  (Data_wss(tech_wss,'spec_cost')*V_wss.l(tech_wss)):8:0, '€',
                                @36,  (c_land*Data_wss(tech_wss,'land_use')*V_wss.l(tech_wss)):8:0, '€',
                                @84,  (V_wss.l(tech_wss)*Data_wss(tech_wss,"Resources")):8:0, '€',
                                @100, TC_wss.l(tech_wss):8:0, '€'
     /);

put '------------------------------------------------------------------------------------------------------------'/;
put 'Total', @100, TC.l:8:0, '€'/;
putclose CostReport;
```

```
*---------------.:: Preparing output data for SimEnv ::.--------------------*
*--------------------------------------------------------------------------*

SCALAR
 out_p_pv                 kW
 out_p_w                  kW
 out_p_csp                kW
 out_p_ess                kW
 out_p_diesel             kW_el            /800/
 out_tc                   €
 out_tc_pv                €
 out_tc_w                 €
 out_tc_csp               €
 out_tc_diesel            €
 out_tc_ess               €
 out_tc_ro_es3            €
 out_tc_mvc               €
 out_tc_ro                €
 out_tc_tss               €
 out_tc_wss               €
 out_e_sum_pv             kWh
 out_e_sum_w              kWh
 out_e_sum_csp            kWh
 out_e_sum_diesel         kWh
 out_e_sum_ess            kWh
 out_e_sum_desal          kWh
 out_w_sum                m^3
 out_flh_pv               h
 out_flh_w                h
 out_flh_csp              h
 out_flh_diesel           h
 out_flh_ess              h
 out_capacity_desal       m^3\h
 out_flh_desal            h
 out_capacity_ro_es3      m^3\h
 out_capacity_mvc         m^3\h
 out_capacity_ro          m^3\h
;

PARAMETERS
 out_e_pv_out(t)          kWh\h
 out_e_w_out(t)
 out_e_csp_out(t)
 out_e_diesel_out(t)
 out_e_ess_out(t)
 out_e_ro_es3(t)
 out_e_mvc(t)
 out_e_ro(t)
 out_e_desal_in(t)
;

* Installed capacity
out_p_pv = P_PV.l('a-Si');
out_p_w = P_W.l('Vergnet275');
out_p_csp = P_CSP.l('ORC');
out_p_ess = P_ess.l('NaS');
out_capacity_ro_es3 = Capacity_Desal.l('RO_ES3');
out_capacity_mvc = Capacity_Desal.l('MVC');
out_capacity_ro = Capacity_Desal.l('RO');

* Annual energy generation /energy stored / water production
out_e_pv_out(t) = E_PV_out.l(t,'a-Si') ;
out_e_sum_pv = sum(t,out_e_pv_out(t)) ;
```

```
out_e_w_out(t) = E_W_out.l(t,'Vergnet275') ;
out_e_sum_w = sum(t,out_e_w_out(t)) ;
out_e_csp_out(t) = E_CSP_out.l(t,'ORC') ;
out_e_sum_csp = sum(t,out_e_csp_out(t)) ;
out_e_diesel_out(t) = E_diesel_out.l(t,'Caterpillar2') ;
out_e_sum_diesel = sum(t,out_e_diesel_out(t)) ;
out_e_ess_out(t) = E_ess_out.l(t,'NaS') ;
out_e_sum_ess = sum(t,out_e_ess_out(t)) ;
out_e_ro_es3(t) = E_Desal_in.l(t,'RO_ES3') ;
out_e_mvc(t) = E_Desal_in.l(t,'MVC') ;
out_e_ro(t) = E_Desal_in.l(t,'RO') ;

out_e_sum_desal = sum((t,tech_Desal_tot),E_Desal_in.l(t,tech_Desal_tot));
out_w_sum = sum((d,tech_Desal_tot),Water_generation.l(d,tech_Desal_tot));

* Full load hours per year
*out_flh_pv = out_E_sum_PV.l 'divided by' out_P_PV ;
*out_flh_w = out_E_sum_W.l 'divided by' out_P_W ;
*out_flh_csp = out_E_sum_CSP.l 'divided by' out_P_CSP ;
*out_flh_diesel = out_E_sum_diesel.l 'divided by' out_P_diesel ;
*out_flh_ess = out_E_sum_ess.l 'divided by' out_P_ess ;
*out_capacity_desal = Capacity_Desal.l('RO_ES3');
*out_flh_desal =e= out_W_sum.l 'dividied by' out_Capacity_Desal ;

* Total costs
 out_tc = TC.l;
 out_tc_pv = TC_PV.l('a-Si');
 out_tc_w = TC_W.l('Vergnet275');
 out_tc_csp = TC_CSP.l('ORC');
 out_tc_diesel = TC_diesel.l('Caterpillar2');
 out_tc_ess = TC_ess.l('NaS');
 out_tc_ro_es3 = TC_Desal.l('RO_ES3');
 out_tc_mvc = TC_Desal.l('MVC');
 out_tc_ro = TC_Desal.l('RO');
 out_tc_tss = TC_tss.l('TS1') ;
 out_tc_wss = TC_wss.l('WS1') ;


*__________________________SimEnv Output file_____________________________*
* Test
*file SimEnv_Report /SimEnv.log/;
*put SimEnv_Report;
*put @15, '..:: Sim Env Data ::..'//;
*put @15, out_TC//;
*put @15, out_TC_PV//;
*putclose SimEnv_Report;

```

Appendix B

Renewable energy technologies not modeled

B.1 Hydro power

Hydropower plants harness the potential energy within falling water and use classical mechanics to convert that energy into electricity. The theoretical water power between two specific points on a river depends on the water density, the volumetric flow rate through the power station on the height of the fall and the geodetic level of head and tailwater.

A hydroelectric power station works principally as shown in Fig. B.1. The flow is led to the turbine via the intake structure, the headrace and penstock. Afterwards it streams through the draft tube into the tailrace [127].

Mainly three turbines can be used: The Kaplan turbine, the Francis turbines or the Pelton turbine, and derived designed from the original turbine types respectively. The **Kaplan turbine** works in principle like a reverse operating propeller. The flow runs almost through all Kaplan-derived turbines axially. Vertical, horizontal and slanting axis positions can occur. Additionally, Kaplan turbines and their derivatives have adjustable runner blades. They allow a better adjustment to different flow rates and thus an efficiency improvement for various operating conditions. **Francis turbines** are reaction turbines. The water flows radially from the guide vanes over the runner blades and flows out axially again. In contrast to the Kaplan turbine Francis turbine runner blades are not movable. It needs to be decided previously, if low-speed or high-speed runners are required. Francis turbines can normally be run from 40 % of their maximum power. The **Pelton turbine** is an impulse turbine and has a runner, a so called Pelton wheel, with fixed buckets. It is regulated by one or several nozzles that control the flow and direct the water jet tangentially to the wheel into the buckets. During this process the entire pressure energy of the water is converted into kinetic energy when leaving the nozzle. This energy is converted into mechanical energy by the Pelton wheel; the water then drops more or less without energy into the reservoir underneath the runner [127]. Kaplan turbines are the most commonly used turbines in hydropower plants.

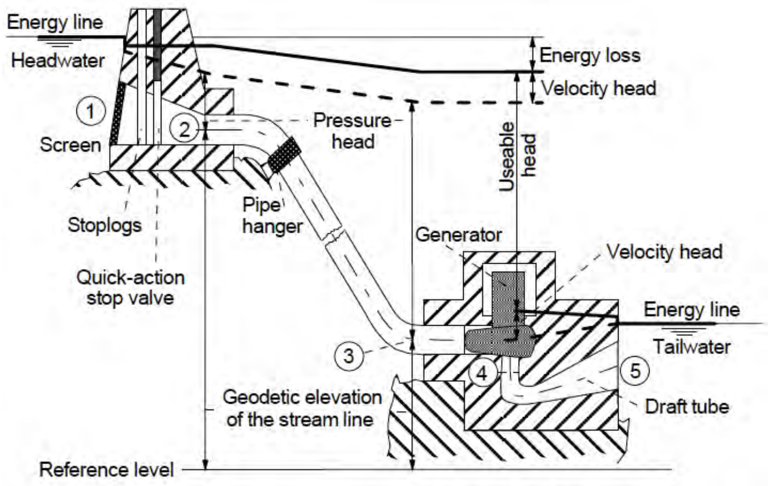

Fig. B.1: *Physical correlations in a hydroelectric power station [127]*

B.2 Ocean powers

Ocean energy has many forms: tides, surface waves, ocean circulation, salinity, and thermal gradients. The ocean offers a lot of intriguing energy sources. Since some plants can also be implemented in the range of one megawatt, the state-of-the-art of some oceanic power generators will be addressed briefly.

Wave power

Wind-driven waves derive ultimately from solar energy. Because of its considerable energy potential, for several decades wave energy has been investigated with regard to power generation. Waves of the height of two meters and a period of six seconds for example, as typical for the German North Sea coast, could theoretically generate approximately 14 kW/m and 3.6 GW in a coast length of about 250 km[128]. Only for using wave energy various technologies have been developed: tapered channel systems, float systems, oscillating water column systems, underwater turbines etc. Similar to hydroelectric dams, channel systems raise the intake water higher than sea level and let the water run down through a turbine. Float systems lay on the sea surface and waves run hydraulic pumps or pistons that power a turbine. Oscillating water column systems let waves enter a chamber to push air up with the same goal, to power a turbine. Underwater turbines work like wind mills. Instead of wind though, they use the water current to turn the blades in the ocean. The most common energy capture methods are surface-following attenuators and oscillating water column buoys. The most recent plants were built and are still planned in the United Kingdom, Australia, Belgium, Korea and China [129]. Up to now very few facilities of wave energy conversion to electricity operate commercially. Most of them are publicly funded pilot plants. For economical reasons they were not commercialized yet. Wave energy converters though could combine power generation and coastline protection (since kinetic energy is taken from the waves) and enhance the economic attractiveness of wave energy exploitation [128].

Tidal Energy
Driven by gravitational effects the ocean level rises and falls. Marine currents are predictable and the change of the sea level can be exploited. Tides can be used in two different ways for power generation: The potential energy of backwaters or marine currents can be used by tidal power stations.

The first one works similar to the hydroelectric dam generation method, filling a bay with seawater and releasing it through turbine systems. Its advantage is the simple turbine design, its disadvantage though the relatively short time period in which electricity can be generated. Tidal power stations can also be designed as a two-basin system, but are more demanding and the two basins require more space. The exploitation method based on the high and low tide stream, and thus on water motion caused by low and high tides faces the challenge of relatively low energy densities. Savonius or Darrieus rotors are used for these slow current speeds. Up to now, first prototypes are in operation, but projects of pure high and low tide stream exploitation have not been put into practice yet.

A tidal energy facility performs most effective, if the minimum tidal level difference between high and low tide is approximately 5 meters. Not many areas of the oceans meet this requirement, therefore only few applications were implemented until now [129]. The largest tidal energy facility is at La Rance in France and has been in operation since 1967. It has a capacity of 180 million m^3 with a tidal range of approximately 8.5 meters and an installed capacity of 240 MW, producing 600 GWh a year. This amount supplies enough energy for 250,000 households. Another smaller facility with a capacity of 20 MW is located in Annapolis Royer, Canada, producing 30 GWh yearly. The third tidal energy plant is at Kislaya Guba in Russia with 0.5 MW capacity. Two further plants were constructed in China. An economical breakthrough could not be achieved yet [128].

Thermal gradient Ocean Thermal Energy Conversion (OTEC) is based on driving a power conversion cycle by the temperature difference between surface seawater and seawater at a depth of around 1000 meters or even more. In principle, this type of thermal energy could be used for power generation by means of open or closed Rankine processes. The warm seawater flashes in a low pressure or vacuum chamber, where after expansion it condenses through a heat exchanger, cooled by surrounding seawater. The water temperature difference ranges from a maximum of 22 to approximately 28 °C and the cold deep waters of approximately 4 to 7 °C. These power plants can only achieve very low efficiencies of under 5 % [128]. Research is in progress but up to date, no system has been implemented yet. Its commercial development is limited due to economic aspects.

A combination of this technology with geothermal power plants, increasing the temperature differences between warm areas near volcanic structures and cold ocean water are conceivable. However, it is unlikely that this method will be put into practice in the near future due to considerable technical problems.

B.3 Geothermal energy

Compared to fluctuating solar, wind or oceanic energy, geothermal energy is able to assure a constant energy supply, making it applicable as source for base load. Geothermal energy is thermal energy stored in high-pressure water zones, steam, or hot stones below the earth's surface. It consists partly of the permanent heat flow from the earth's core (about 30 %); the other part originates from natural radioactive decay processes taking place in the mantle. Near to the surface geothermal energy can supply buildings with heat and warm water by earth heat collectors in combination with heat pumps in a depth of approximately 15 to 150 meters. The temperature in the earth's mantle increases by around 3 °C every 100 meter depths [130].

For generating electricity in a direct way geothermal reservoirs above 130 °C are required. Volcanic regions or layers in great depth from 2000 to 5000 meters need usually to be found. The "coldest" geothermal power plant of the world is located in Germany (Neustadt-Glewe), operating at a temperature of approximately 98 °C. The provision of electrical energy is possible but not efficient. Currently the plant is not in operation. Geothermal energy of temperatures above 150 °C is currently used especially in Iceland, New Zealand and Italy [131]. The first geothermal power plant was built in 1904 in Tuscany, Italy at a place where natural steam was erupting from the earth.

There are different methods of collecting geothermal energy: the fluid-dominated, the vapour (steam)-dominated and the Hot-Dry-Rock (HDR) process. At the fluid-dominated system high-pressure hot water is transported through wells from deep inside the earth and converted/flashed into steam. If steam itself is found in a geothermal reservoir, it is used directly to turn generator turbines in so called dry steam plants. When the steam cools, it condenses to water and is injected back into the ground to be used over and over again. The Hot-Dry-Rock method works similar: Wells are drilled into the granite layer, which has temperatures over 200 °C. Through one of the wells water is injected down into the granite layer where it is heated. The hot water returns back to the surface through another well, where it is kept under pressure and therefore in liquid form, in order to run a turbine system. Most geothermal power plants are flash plants. Binary power plants transfer heat from geothermal hot water to another liquid. The heat causes the second liquid to turn to steam, which is used to drive a generator turbine. Today production rates up to 10 MW of thermal energy are common [131].

Although in the past approaches have been done to implement slim holes for small off-grid power generation [132] they could not be asserted. Geothermal power plants can only operate effectively and beneficial as large-scale applications. Especially the expensive drillings in the preparation-phase increase costs tremendously, because it is not secure, whether or not the required sediment or hydrothermal conditions

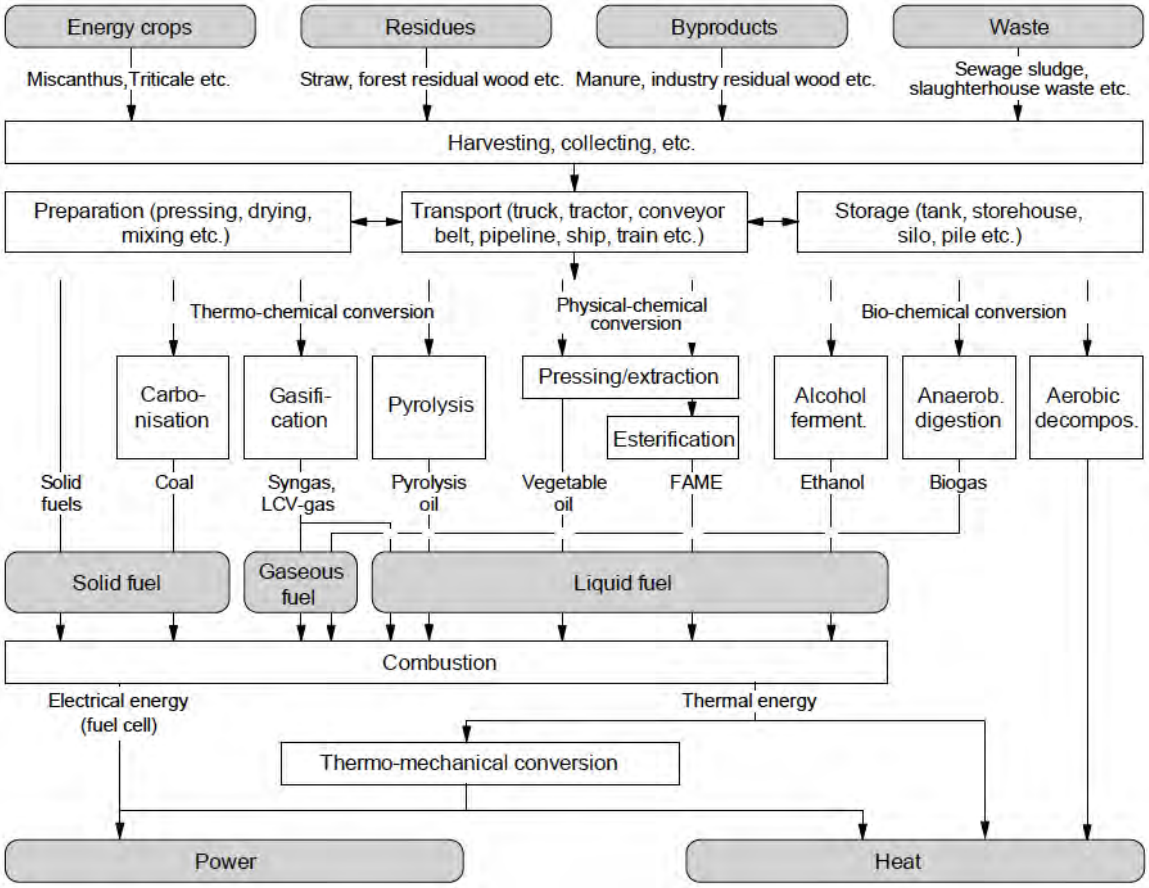

Fig. B.2: *Energy conversion options from biomass [128]*

are given in the investigated region. Further drawbacks in volcanic regions are the danger of geological reactions to the intervention of drilling.

Since in this work mainly remote mini-grids are considered, power generation by geothermal energy is not considered and modeled. However, even for desalination purposes geothermal energy has been tried to be implemented in Greece, France and Tunisia [133].

B.4 Energetic use of biomass

In arid regions with freshwater shortage biomass will hardly be available en masse. But since there are still some options using this energetic source, main principles of biomass utilization are briefly addressed. Biomass can energetically used in various forms and is usually based on combustion processes. An overview of conversion processes is shown in Fig. B.2. Energy carriers are shaded grey.

In thermo-chemical conversion processes, such as gasification, pyrolysis, and carbonization, solid biofuels are transformed into solid, liquid or gaseous secondary energy carriers primarily using heat. Physical-chemical conversion considers all processes based on oil seeds, vegetable oil or fat, e.g. rape seeds, sunflower seeds or coconuts. Running through a number of separation and conversion steps, the obtained vegetable oil can be used as a fuel for engines and CHP plants and is applied either in its pure form or after chemical conversion to Fatty Acid Methyl Ester (FAME). Bio-chemical processes use micro-organisms or bacteria to convert biomass into secondary energy carriers or useful energy. Fermentation into alcohol, aerobic fermentation and aerobic digestion are such bio-chemical processes. The most common process used in remote regions is the anaerobic digestion with biogas as final product [128, 134].

The identification of applicable processes depends highly on the biomass potential in the considered region. A collection of biomass potentials in Small Island Developing States is listed in Fig. B.3. The dark marked arrays stand for high potentials, light marked arrays for low or no potential.

Only secondary or tertiary biomass is considered. The potentials are divided into biomass from forestry, agriculture, animal husbandry, tourism and organic waste.

As mentioned before, remote regions with freshwater scarcity will hardly have large amounts of surplus biomass. Some dry regions though have a good potential of growing specific energy plants, whose oil can supplement diesel fuel with biofuel, such as canola, oil palm, soy or jatropha. *Jatropha curcas* is one of the few drought resistant and perennial oil plants. It is a tropical plant that can be grown in dry and humid areas. The soil conditions should be around pH 4.5. The plants have a useful life of about 30 years and have a 30 % oil content in their seeds. Annually two to four tons per hectare of the oily nut seeds can be harvested, resulting in approximately up to 4000 to 8000 litres biofuel. Biodiesel can be produced by extraction of the seeds with an oil mill. The properties of jatropha curcas oil are a density of 884 kg/m^3 (at 15 °C), a phosphorus and sulphur content of less than 1 mg/kg and a cetane number of 60, which is a relatively high and good with respect to its usability in engines (rape oil 54) [135].

A further approach growing biomass is to use algae. **Algae** are an attractive way to harvest solar energy and turn carbon dioxide into biofuel. A lot of resources are thus being put into the idea of turning algae into mini oil wells. Algae can grow in salt water, freshwater or even in contaminated water at sea or in ponds. But the challenges are many. Algae use carbon dioxide to produce oil molecules via photosynthesis. The greatest challenge of algal biofuel is the production of oil on a much larger scale but at much lower costs. As per one estimate the scale of production needs to increase at least three orders of magnitude, with a decrease in the cost of production by a factor of ten. The main distinction between algae-concepts is the cultivation system; both open pools and closed tubular reactor systems are investigated. Significant research results will be needed for large scale applications. Up to now a technological breakthrough is not conceivable.

SIDS / Biomass indicators	Forestry	Agriculture	Animal husbandry	Tourism waste	Waste
Niue	9.40	2.50	1.18	1.87	na
Vanuatu	1.88	0.80	1.28	0.35	0.85
Belize	4.69	0.50	0.45	0.84	0.74
Guyana	19.93	2.20	0.72	0.16	2.61
Fiji	1.19	0.51	0.95	0.67	0.14
Guinea-Bissau	1.30	1.03	1.08	0.01	0.31
Montserrat	0.42	0.50	3.95	1.28	na
New Caledonia	3.41	1.02	0.62	0.42	0.24
Palau	2.02	0.25	na	4.38	na
Dominica	0.67	0.34	0.56	1.23	2.36
Samoa	0.96	0.37	1.38	0.67	0.64
Cook Islands	0.78	0.15	1.72	4.81	na
Timor-Leste	0.70	0.34	0.81	na	0.18
Cuba	0.25	0.59	0.92	0.20	0.52
Micronesia (Federated States of)	0.58	0.20	0.48	0.20	na
Suriname	24.87	0.15	0.29	0.31	0.53
Papua New Guinea	4.41	0.17	0.30	0.02	na
British Virgin Islands	0.16	0.36	na	15.59	na
Anguilla	0.37	na	na	5.09	na
French Polynesia	0.55	0.17	0.23	0.81	0.11
Marshall Islands	0.21	0.21	na	0.11	na
Solomon Islands	4.35	0.16	0.14	0.03	0.12
Saint Kitts and Nevis	0.22	0.10	0.57	2.54	0.11
Dominican Republic	0.20	0.25	0.53	0.41	0.32
Antigua and Barbuda	0.11	0.15	0.90	3.03	0.12
Bahamas	1.52	0.04	0.16	4.58	0.08
Cape Verde	0.17	0.19	0.70	0.54	0.20
Grenada	0.16	0.12	0.30	1.22	0.51
Saint Lucia	0.28	0.06	0.34	1.75	0.79
Sao Tome and Principe	0.17	0.36	0.13	0.08	1.52
Guam	0.15	0.11	0.05	6.88	na
Saint Vincent and the Grenadines	0.24	0.09	0.35	0.83	0.69
Tonga	0.09	0.30	0.86	0.43	na
Tuvalu	0.10	0.18	1.42	0.11	na
Jamaica	0.12	0.17	0.29	0.64	0.34
Northern Mariana Islands	0.36	0.04	na	4.79	na
Seychelles	0.48	0.05	0.22	1.84	0.11
Kiribati	0.13	0.35	0.18	0.05	0.10
American Samoa	0.27	0.08	0.17	0.38	na
Haiti	0.01	0.18	0.55	0.03	0.57
Comoros	0.00	0.18	0.24	0.03	0.16
United States Virgin Islands	0.19	0.04	0.17	5.24	na
Aruba	0.00	0.02	na	7.35	na
Barbados	0.03	0.07	0.35	2.23	0.13
Puerto Rico	0.13	0.05	0.15	0.94	na
Trinidad and Tobago	0.17	0.04	0.33	0.34	0.15
Bahrain	0.00	0.01	0.10	6.22	na
Mauritius	0.03	0.08	0.15	0.69	0.07
Maldives	0.00	0.03	na	2.17	0.10
Nauru	0.00	0.04	0.30	na	na
Singapore	0.00	0.00	0.07	1.73	na
Netherlands Antilles	0.01	0.04	0.16	3.61	0.15

Fig. B.3: Biomass potential on SIDS

Appendix C

Renewable energy powered desalination

	TYPICAL CAPACITY	ENERGY DEMAND	WATER GENERATION COST	TECHNICAL DEVELOPMENT STAGE
SOLAR STILL	< 0.1 m³/d	solar passive	1–5 €/m³	applications
SOLAR MEH	1–100 m³/d	thermal: 100 kWh/m³ electrical: 1.5 kWh/m³	2–5 €/m³	applications/ advanced R&D
SOLAR MD	0.15–10 m³/d	thermal: 150–200 kWh/m³	8–15 €/m³	advanced R&D
SOLAR/CSP MED	> 5,000 m³/d	thermal: 60–70 kWh/m³ electrical: 1.5–2 kWh/m³	1.8–2.2 €/m³ (prospective cost)	advanced R&D
PV-RO	< 100 m³/d	electrical: BW: 0.5–1.5 kWh/m³ SW: 4–5 kWh/m³	BW: 5–7 €/m³ SW: 9–12 €/m³	applications/ advanced R&D
PV-EDR	< 100 m³/d	electrical: only BW: 3–4 kWh/m³	BW: 8–9 €/m³	advanced R&D
WIND-RO	50–2,000 m³/d	electrical: BW: 0.5–1.5 kWh/m³ SW: 4–5 kWh/m³	units under 100 m³/d BW: 3–5 €/m³ SW: 5–7 €/m³ about 1,000 m³/d 1.5–4 €/m³	applications/ advanced R&D
WIND-MVC	< 100 m³/d	electrical: only SW: 11–14 kWh/m³	4–6 €/m³	basic research
WAVE-RO	1,000–3,000 m³/d	pressurised water: 1.8–2.4 kWh/m³ electrical: 2.2–2.8 kWh/m³	0.5–1.0 €/m³ (prospective cost)	basic research

Fig. C.1: *Possible combinations of renewable energy with desalination technologies [46]*